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**EVALUATION AND DESIGN OF
SUSTAINABLE ENERGY POLICIES:
AN APPLICATION TO THE
CASE OF SPAIN**

Ph.D. Thesis / Tesis Doctoral

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NOTIFICACIÓN AL INTERESADO DE LA CALIFICACIÓN
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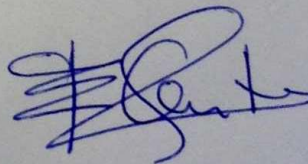
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El Secretario del Tribunal

A Bea y Tom, mis padres, por la Educación que me han dado.

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Me tengo que ir que pierdo el avión...nos vemos pronto!

Álvaro,

Abu Dhabi, 10 de Mayo de 2014

**EVALUATION AND DESIGN OF
SUSTAINABLE ENERGY POLICIES:
AN APPLICATION TO THE
CASE OF SPAIN**

As we watch the sun go down, evening after evening, through the smog across the poisoned waters of our native Earth, we must ask ourselves seriously whether we really wish some future universal historian on another planet to say about us: "With all their genius and with all their skill, they ran out of foresight and air and food and water and ideas" (...)"

U Thant, UN Secretary General,
addressing the General Assembly, New York (1970)

It is better to be vaguely right than exactly wrong

Carveth Read, British philosopher and logician,
Logic: deductive and inductive (1898)

RESUMEN

El actual sistema energético mundial, mayoritariamente basado en el uso de combustibles fósiles, es claramente insostenible desde los puntos de vista ambiental, económico, social y de equidad. El caso de España no es una excepción. Hay consenso, entre los más prestigiosos organismos internacionales e instituciones de investigación, en que se necesitan ambiciosas *políticas energéticas sostenibles* para hacer frente a esta situación. Por otro lado, el uso de modelos matemáticos informatizados es necesario para evaluar dichas políticas antes de su aplicación, con el fin de simular sus efectos, su eficacia, los costes y beneficios de las medidas, sus sinergias e interacciones, o sus posibles consecuencias inesperadas, entre otros.

Esta tesis doctoral propone una metodología mejorada para el modelizado de políticas energéticas sostenibles que, creemos, aborda las debilidades de los modelos actuales: son a veces demasiado detallados, lo que hace su lógica interna a menudo difícil de entender; los resultados que producen pueden ser contraintuitivos dadas las hipótesis de entrada; y sus salidas son a veces muy pesadas, con extensas bases de datos llenas de cifras presentadas en unidades diferentes y poco habituales. Creemos que los responsables de las políticas energéticas requieren una perspectiva amplia sobre el sistema energético estudiado, una comprensión útil y general sobre el efecto de las políticas analizadas, y una metodología transparente que puedan entender y en la que confíen. Esto es especialmente necesario en España, uno de los pocos países europeos sin una estrategia energética más allá de 2020 y donde el debate público energético necesita basarse en cifras sólidas y transparentes.

Esta tesis doctoral define, desarrolla e implementa una metodología que trata de responder a estas necesidades y carencias. Propone una metodología para el análisis de políticas energéticas a nivel nacional, y la aplica al caso de España. La idea central es proporcionar un mejorado, y hasta ahora inexistente, conjunto de herramientas, basadas en datos públicos y fiables, con un modelizado matemático sólido pero también simple y transparente, que permita simular la evolución de un sistema energético bajo diferentes políticas y medir su sostenibilidad desde los puntos de vista económico, social y ambiental. El objetivo es mostrar que la verdadera dificultad no reside en comprender el modelo en sí, sino en discernir las implicaciones de las políticas, sus posibles contraprestaciones, o el peso relativo de cada política para lograr un sistema más sostenible; y que un enfoque cuantitativo amplio pero simple podría facilitar considerablemente esta tarea.

Una extensa revisión del estado del arte permite justificar la metodología propuesta. Se ha llevado a cabo un meticuloso proceso de recopilación y abstracción de datos. Se proponen los modelos "MASTER": dos modelos *bottom-up* de equilibrio parcial complementarios, uno estático y otro que considera la evolución temporal del sistema energético. Sus resultados se presentan de manera intuitiva utilizando diagramas de Sankey para representar el sistema energético simulado bajo cada escenario de políticas. Los modelos han sido aplicados a asuntos relevantes para la política energética en España, como los costes de reducir emisiones con energías renovables o con eficiencia energética; o como las distintas evoluciones del sistema energético bajo diferentes estrategias de eficiencia energética.

ABSTRACT

The present world energy system, largely based on the use of fossil fuels, is clearly unsustainable from environmental, economic, social and equity perspectives. The Spanish case is no exception. There is consensus, among the most renowned international organisations and research institutions, that ambitious *sustainable energy policies* are needed to address this situation. Computer-based mathematical models are necessary to evaluate these policies prior to their implementation. This enables the analysis of their effects, of whether they can achieve the desired goals, of their costs and benefits, of their synergies and interactions, or of their possible unexpected consequences.

This PhD thesis proposes an improved methodology for sustainable energy policy modelling that, we believe, addresses real gaps present in current models: they are sometimes too detailed, which makes their internal logic often complex to understand; outcomes are produced which are counterintuitive given the inputs; and results are often cumbersome, with large databases full of numbers presented in inconsistent and unfamiliar units. We think that policymakers need information about the *big picture* of the energy system in question, they need useful insights and conclusions which allow them to obtain broad understanding about the studied policies, and they need a transparent methodology that they can understand and trust. This is especially needed in Spain, one of the few European countries without an energy strategy beyond 2020, and where the public energy debate needs to be guided by transparent and sound figures.

This PhD thesis defines, develops and implements a methodology that tries to address these needs and gaps. It proposes a methodology that is specifically focused on energy policy analysis at country level and applies it to the case of Spain. The central idea is to provide an improved, and so far inexistent, set of tools based on public and reliable data, with a sound but simple and transparent mathematical representation, which allows to simulate an energy system's evolution under different policy assumptions and to measure its sustainability from the economic, social and environmental perspectives. The aim is to show that the real difficulty is not in understanding the model itself but in discerning the implications of policies, their potential trade-offs, or the relative weight of each policy in making the system more sustainable; and that a comprehensive but simplified quantitative approach could significantly ease this task.

An extensive review of the state of the art allows justifying the proposed methodology. A meticulous process of data collection and abstraction has been carried out. The "MASTER" models are proposed: they are two complementary partial equilibrium *bottom-up* models, one under static conditions and a second that considers the temporal evolution of the energy system. Their results are intuitively presented, using Sankey diagrams to represent the simulated energy system under each policy scenario. The models have been applied to actual energy policy questions in Spain, such as the costs of reducing emissions with renewables and energy efficiency; or the different evolutions of the energy system under several energy efficiency strategies.

CONTENTS

CHAPTER I. INTRODUCTION, MOTIVATION, OBJECTIVES AND STRUCTURE.....	1
I.1. INTRODUCTION.....	3
I.2. MOTIVATION	6
I.3. OBJECTIVES.....	11
I.3.1. General objective.....	11
I.3.2. Specific objectives.....	11
I.4. STRUCTURE OF THE THESIS.....	13
CHAPTER II. CONTEXT OF THE THESIS	15
II.1. OUTLINE OF THIS CHAPTER	17
II.2. SUSTAINABILITY	17
II.2.1. A conceptual approach to Sustainability	18
II.2.2. Sustainability: related aspects	20
II.2.3. Facts and figures.....	23
II.3. ENERGY SUSTAINABILITY.....	29
II.3.1. Global trends	29
II.3.2. Energy sustainability: natural capital perspective.....	34
II.3.3. Energy sustainability: social and human capital perspective.....	37
II.3.4. Energy sustainability: economic capital perspective	38
II.3.5. Energy sustainability: equity perspective.....	40
II.3.6. Energy sustainability: conclusion and outlook.....	42
II.4. ENERGY SUSTAINABILITY IN SPAIN	43
II.4.1. Main trends of energy supply and demand in Spain	43
II.4.2. The <i>big picture</i> of the Spanish energy system: Sankey diagrams.....	48
II.4.3. Energy sustainability in Spain: natural capital perspective.	61
II.4.4. Energy sustainability in Spain: social and human capital perspective.	62
II.4.5. Energy sustainability in Spain: economic capital perspective.....	62
II.4.6. Energy sustainability in Spain: equity perspective.	64
II.4.7. Energy sustainability in Spain: conclusion and outlook.	64

II.5. NARROWING THE FOCUS: SUSTAINABLE ENERGY POLICIES.....	64
II.6. SUSTAINABLE ENERGY POLICY ASSESSMENT	72
CHAPTER III. ENERGY MODELLING STATE OF THE ART	73
III.1. OUTLINE OF THIS CHAPTER	75
III.2. KEY CONCEPTS AND TECHNIQUES.....	75
III.2.1. Economic representation and environmental feedbacks.....	76
III.2.2. Modeling techniques: optimization vs. simulation.....	78
III.2.3. Technological detail: bottom-up vs. top-down	80
III.2.4. Geographic perspective	82
III.2.5. Time representation	82
III.2.6. Uncertainties and future foresight.....	83
III.2.7. Technological change	84
III.2.8. International energy markets	85
III.2.9. Summary.....	85
III.3. MAINSTREAM ENERGY MODELS	86
III.3.1. Bottom-up partial equilibrium optimization modeling: the MARKAL/TIMES family	87
III.3.2. Bottom-up partial equilibrium simulation modeling: POLES.....	95
III.3.3. Bottom-up partial equilibrium simulation modeling: World Energy Model.	99
III.3.4. Bottom-up partial equilibrium optimization modeling: PRIMES.....	102
III.3.5. Bottom-up general equilibrium simulation modeling: NEMS	105
III.3.6. Top-down general equilibrium optimisation modelling: the EPPA Family.	108
III.3.7. Top-down general equilibrium optimisation modelling: WITCH	114
III.3.8. Summary table	117
III.4. OTHER ENERGY MODELS	119
III.4.1. Review of other models and techniques.....	119
III.4.2. Summary.....	122
III.5. CONCLUSIONS OF THE STATE OF THE ART: THE GAP TO BE COVERED BY THIS THESIS.	123
CHAPTER IV. METHODOLOGICAL JUSTIFICATION AND PROPOSAL	127
IV.1. OUTLINE OF THIS CHAPTER	129
IV.2. METHODOLOGICAL JUSTIFICATION	129
IV.2.1. Main conclusions from previous chapters.....	129
IV.2.2. Justifying our methodology	130
IV.3. METHODOLOGICAL PROPOSAL	131
IV.3.1. Our proposal: overview	131

IV.3.2. Our proposal: energy sector representation	132
IV.3.3. Our proposal: data, magnitudes and units	157
IV.3.4. Our proposal: energy sustainability indicators.....	161
IV.3.5. Our proposal: modelling framework	163
IV.3.6. Our proposal: the static model	173
IV.3.7. Our proposal: the dynamic model.....	173
IV.3.8. Our proposal: output	175
CHAPTER V. MASTER_SO: A STATIC OPTIMISATION MODEL FOR SUSTAINABLE ENERGY POLICY ASSESSMENT.....	179
V.1. OUTLINE OF THIS CHAPTER	181
V.2. MODEL OVERVIEW	181
V.3. PREVIOUS EXPLANATIONS, CONVENTIONS AND NOTATION	182
V.4. SETS.....	183
V.4.1. Time definition	183
V.4.2. Processes.....	184
V.4.3. Main demand characterization sets	189
V.4.4. Auxiliary sets	191
V.4.5. Possible energy flows	192
V.5. PARAMETERS.....	193
V.5.1. General parameters	193
V.5.2. DS Parameters.....	194
V.5.3. TE Parameters	198
V.5.4. CE Parameters.....	199
V.5.5. PE Parameters.....	203
V.5.6. EI Parameters.....	204
V.6. DECISION VARIABLES	205
V.7. CONSTRAINTS	209
V.7.1. Constraints in DS.....	209
V.7.2. Constraints in TE	215
V.7.3. Constraints in CE.....	216
V.7.4. Constraints in PE.....	224
V.7.5. Constraints in EI.....	225
V.7.6. Constraints to avoid unrealistic solutions.....	227
V.7.7. Policy constraints	228

V.8. OBJECTIVE FUNCTION.....	230
V.8.1. Domestic primary energy production cost.....	231
V.8.2. Domestic primary energy production emissions social cost.....	231
V.8.3. Primary energy imports cost.....	232
V.8.4. Primary energy exports revenue.....	232
V.8.5. Energy conversion variable cost.....	232
V.8.6. Energy conversion emissions social cost.....	232
V.8.7. Cost of the provision of electricity reserves by generators.....	233
V.8.8. Active conversion capacity fixed O&M cost	233
V.8.9. New CE capacity investment cost (annuity)	234
V.8.10. Energy transportation cost	234
V.8.11. Energy transportation emissions social cost.....	235
V.8.12. Final energy imports cost	236
V.8.13. Final energy exports revenue.....	236
V.8.14. Final energy use emissions social cost.....	236
V.8.15. Energy service variation measures promotion costs.....	237
V.8.16. Utility losses associated to load shifting in ESSTs	237
V.8.17. Non-energy usage costs of ESSTs	238
V.8.18. Non supplied energy cost.....	240
V.9. UTILIZATION MODES, OTHER OPTIONS AND COMPUTER IMPLEMENTATION	240
V.9.1. Execution modes	240
V.9.2. Other utilization options.....	241
V.9.3. Computer implementation.....	241
V.10. MAIN OUTPUTS	242

CHAPTER VI. MASTER_SO STUDY: RENEWABLES VS. ENERGY EFFICIENCY, THE COST OF CARBON EMISSIONS REDUCTION IN SPAIN..... 243

VI.1. OUTLINE OF THIS CHAPTER	245
VI.2. CONTEXT OF THE STUDY.....	245
VI.3. THE METHODOLOGY, THE MODEL AND ITS MAIN PARAMETERS.....	246
VI.3.1. Overview	247
VI.3.2. Data used.....	247
VI.3.3. Demand and DSM characterization.....	248
VI.3.4. Energy sector representation.....	250

VI.4. CONSIDERED SCENARIOS	251
VI.5. RESULTS	252
VI.5.1. Carbon emissions.....	252
VI.5.2. Investments.....	254
VI.5.3. Shadow prices	255
VI.5.4. Sankey diagrams of the energy system in different scenarios.....	256
VI.5.5. Energy supply costs	264
VI.6. CAVEATS AND SHORTCOMINGS	266
VI.7. CONCLUSIONS.....	267
CHAPTER VII. MASTER_DS: A PROTOTYPE DYNAMIC SIMULATION MODEL.	271
VII.1. OUTLINE OF THIS CHAPTER.....	273
VII.2. MODEL OVERVIEW	273
VII.3. OUR MODELLING METHODOLOGY	274
VII.4. DESCRIPTION OF THE LOGIC WITHIN THE MODEL	278
VII.4.1. Agents in the system	278
VII.4.2. Agent's interaction: final energy markets and the role of networks.....	280
VII.4.3. The proposed causal loop diagram	281
VII.4.4. The energy markets within each year	283
VII.4.5. Utilities forecasts.....	284
VII.4.6. Utilities investment decisions	286
VII.5. MAIN OUTPUTS.....	289
CHAPTER VIII. AN ILLUSTRATIVE CASE STUDY WITH MASTER_DS: PATHWAYS FOR THE SPANISH ENERGY SYSTEM.	291
VIII.1. OUTLINE OF THIS CHAPTER	293
VIII.2. RESEARCH QUESTION, ENERGY SECTOR REPRESENTATION, DATA AND SCENARIOS ...	293
VIII.3. RESULTS AND DISCUSSION	297
VIII.3.1. Energy use.....	298
VIII.3.2. Prices for final energy	304
VIII.3.3. Energy conversions.....	305
VIII.3.4. Emissions	308
VIII.3.5. Costs	309

VIII.4. CONCLUSIONS	312
CHAPTER IX. SUMMARY, CONCLUSIONS, MAIN CONTRIBUTIONS AND FUTURE RESEARCH. 313	
IX.1. OUTLINE OF THIS CHAPTER.....	315
IX.2. SUMMARY	315
IX.3. CONCLUSIONS	319
IX.3.1. Energy and sustainability conclusions	319
IX.3.2. Methodological conclusions	319
IX.3.3. Policy conclusions	325
IX.4. MAIN CONTRIBUTIONS	326
IX.5. FUTURE RESEARCH.....	328
IX.5.1. Energy and sustainability. Energy sustainability indicators.	328
IX.5.2. Representation of the energy system, with a special focus on Spain.....	328
IX.5.3. Methodological framework	330
IX.5.4. MASTER_SO.....	330
IX.5.5. MASTER_DS.....	331
IX.5.6. Sustainable energy policy analysis.....	331
IX.5.7. Others	332
REFERENCES OF THE PHD THESIS	333
ANNEX 1. “BACK OF THE ENVELOPE” EXAMPLES	377
ANNEX 2. FUTURE RESEARCH LINES: POTENTIALLY USEFUL DETAILS.....	383
Energy and sustainability. Energy sustainability indicators.....	385
Representation of the energy system, with a special focus on Spain	386
Methodological framework.....	390
MASTER_SO	391
MASTER_DS	392
Sustainable energy policy analysis	395
Others.....	396
ANNEX 3. DATA DOCUMENTATION.....	397
ANNEX 4. REFERENCE GUIDE FOR THE MASTER_SO AND MASTER_DS MODELS	451

LIST OF FIGURES

Figure 1: parody of the current use of the word “Sustainable” Source: xkcd webcomic	18
Figure 2: graphical representation of the idea of sustainable development. Source: own elaboration.....	20
Figure 3: development diamonds for selected countries. Source: (Subbotina, 2004).....	22
Figure 4: evolution of global population in the last 5000 years, expressed in billions Source: adapted from the original figure in (United Nations Environment Programme, 2011).	23
Figure 5: evolution of GDP per capita in developed and developing countries, and world average Source: adapted from the original figure in (United Nations Environment Programme, 2011)	24
Figure 6: evolution of global population, GDP, material intensity and resource extraction in the last two decades. Source: adapted from the original figure in (United Nations Environment Programme, 2011)	24
Figure 7: global material extraction in the last century, billion tonnes Source: (United Nations Environment Programme, 2012)	25
Figure 8: evolution of the prices of global resources, as measured by the GMO Commodity Index. Source: adapted from the original figure in (Grantham, 2011).....	26
Figure 9: evolution of oil prices since 1900, measured in US dollars per barrel (constant 2011\$ the light green graph, current US\$ the dark one). Source: adaptation from the original figure in (BP, 2012).....	27
Figure 10: atmospheric CO ₂ concentrations in the last 800,000 years, in parts-per-million (ppm). Source: adaptation from the original figure in (United Nations Environment Programme, 2012).....	28
Figure 11: Global anthropogenic GHG emissions in terms of CO ₂ -equivalent: a) evolution, b) share of gasses in 2004 and c) share of sectors in 2004 (forestry includes deforestation). Source: (Intergovernmental Panel on Climate Change, 2007).....	28
Figure 12: Human Development Index vs. per capita electricity use (in kWh) for selected countries Source: (Deutch et al., 2009).....	30
Figure 13: global evolution of population, income (GDP in PPP), primary energy consumption (measured as TPES), CO ₂ emissions and the associated intensities. Source: (International Energy Agency, 2009a).....	31
Figure 14: energy consumption per use and per capita (GJ/year-person) in different historic moments. Source: (Smil, 2013a).....	33
Figure 15: spending on net imports of fossil fuels in the New Policies Scenario. Source: (International Energy Agency, 2012a).....	39
Figure 16: evolution of primary energy use in Spain (ktoe). Source: (Ministerio de Industria, Energía y Turismo, 2012).....	44

Figure 17: evolution of primary energy intensity (GJ/million constant 2000 US\$) in selected regions. Source: own elaboration with data from (The World Bank, 2013).....	46
Figure 18: evolution of per capita primary energy consumption (GJ/cap) in selected regions. Source: own elaboration with data from (The World Bank, 2013).....	47
Figure 19: evolution of selected indicators of sectoral final energy use Source: own elaboration based on data from (Eurostat, 2013) and (The International Monetary Fund, 2013)	47
Figure 20: Sankey diagram of the Spanish energy sector in 2011. Source: own elaboration, originally published in (López-Peña, Linares, Pérez-Arriaga, et al., 2013).....	51
Figure 21: Sankey diagram of the Spanish energy-related CO ₂ in 2011. Source: own elaboration, originally published in (López-Peña, Linares, Pérez-Arriaga, et al., 2013).....	54
Figure 22: Sankey diagram of the monetary flows in the Spanish energy sector in 2011. Source: own elaboration, originally published in (López-Peña, Linares, Pérez-Arriaga, et al., 2013).	57
Figure 23: Sankey diagram of the monetary flows in the Spanish energy sector in 2011, discounting the external costs to society that emissions from CO ₂ , SO ₂ , NO _x and particles create. Source: own elaboration, originally published in (López-Peña, Linares, Pérez-Arriaga, et al., 2013).....	60
Figure 24: conceptual illustration of relations in models: partial equilibrium (top left), general equilibrium (top right) and integrated assessment models (bottom). Source: own elaboration.	78
Figure 25: introductory table containing the main features of the MARKAL/TIMES family of models. Source: own elaboration.....	87
Figure 26: introductory table containing the main features of the POLES model. Source: own elaboration.	95
Figure 27: introductory table containing the main features of the WEM model. Source: own elaboration.	99
Figure 28: introductory table containing the main features of the PRIMES model. Source: own elaboration.	102
Figure 29: introductory table containing the main features of the NEMS model. Source: own elaboration.	105
Figure 30: introductory table containing the main features of the EPPA model. Source: own elaboration.	108
Figure 31: introductory table containing the main features of the WITCH model. Source: own elaboration.	114
Figure 32: summary table with the main information about the reviewed models. Source: own elaboration.	118
Figure 33: level of treatment of each assessed features in the reviewed models. Source: own elaboration.	123

Figure 34: level of treatment of each assessed features in this thesis's main model (MASTER_SO) versus the reviewed models in the literature. Source: own elaboration.	126
Figure 35: Sankey diagram of the Spanish energy sector in 2011. Source: own elaboration, originally published in (López-Peña, Linares, Pérez-Arriaga, et al., 2013).....	133
Figure 36: illustration of the concept of “process”, as will be used within this PhD thesis. Source: own elaboration.....	134
Figure 37: illustration of the reference energy system concept in TIMES. Source: (Loulou et al., 2005).....	135
Figure 38: columns that can be identified within the Sankey diagram. Source: own elaboration	136
Figure 39: simplified energy system representation, including processes and possible energy flows. Source: own elaboration	138
Figure 40: the “proc” set in our example, including elements and their description. Source: own elaboration.....	138
Figure 41: the different subsets in our example. Source: own elaboration.....	138
Figure 42: the double sets in our example. Source: own elaboration.....	139
Figure 43: Sankey representation of our example. Source: own elaboration	140
Figure 44: generalized representation of the allowed power flows within our modeling framework. Source: own elaboration	141
Figure 45: illustration of the concept of activity within an ESST (energy service supply technology). Source: own elaboration.....	142
Figure 46: numerical example of our ESST modeling. Part I/II: schema. Source: own elaboration	144
Figure 47: numerical example of our ESST modeling. Part II/II: numerical implementation. Source: own elaboration	144
Figure 48: example of several ESSTs providing a single ES. Source: own elaboration.....	145
Figure 49: example of the number of units used in the energy sector. Source: (CORES, 2012) ..	158
Figure 50: introductory table containing the main features of the MASTER models. Source: own elaboration.....	165
Figure 51: table placing the MASTER models within the family of mainstream models reviewed. Source: own elaboration.	167
Figure 52: level of treatment of each assessed features in this thesis's main model (MASTER_SO) versus the reviewed models in the literature. Source: own elaboration.	168
Figure 53: proposed sequential use of the two models. Step 1 out of 2. Source: own elaboration.	170

Figure 54: proposed sequential use of the two models. Step 2 out of 2. Source: own elaboration.	172
Figure 55: Sankey representation of our example. Policy scenario: reference. Source: own elaboration	176
Figure 56: Sankey representation of our example. Policy scenario: no nuclear. Source: own elaboration	177
Figure 57: Sankey representation of our example. Policy scenario: efficiency and wind. Source: own elaboration	177
Figure 58: example of elements in the “te” subset.	186
Figure 59: example of elements in the “ce” subset.	187
Figure 60: example of elements in the “pe” subset.	188
Figure 61: example of elements in the “rg” subset.	188
Figure 62: example of elements in the “ds” set.	189
Figure 63: example of elements in the “es” set.	190
Figure 64: example of elements in the “esvm” set.	191
Figure 65: generalized representation of the allowed power flows within our modeling framework. Source: own elaboration.	209
Figure 66: example of how a demand sector DS is composed of a number of ESs and ESSTs. Source: own elaboration.	210
Figure 67: Demand side management policies database. Source: own elaboration.	249
Figure 68: 2008 final energy demands per type and demanding sector, in PetaJoules. Source: own elaboration.	250
Figure 69: Considered scenarios. Source: own elaboration.	252
Figure 70: Carbon emissions in the different scenarios. Source: own elaboration.	253
Figure 71: Capacity additions decided by the model for the studied period (1996-2008). Source: own elaboration.	254
Figure 72: Shadow prices of the capacity constraints in €/kW, when applied. Source: own elaboration.	255
Figure 73: Sankey diagram, “Actual case” scenario. Source: own elaboration.	258
Figure 74: Sankey diagram, “No RE” scenario. Source: own elaboration.	259
Figure 75: Sankey diagram, “Efficiency” scenario. Source: own elaboration.	260
Figure 76: Sankey diagram, “Actual case_low CC” scenario. Source: own elaboration.	261
Figure 77: Sankey diagram, “No RE_low CC” scenario. Source: own elaboration.	262
Figure 78: Sankey diagram, “Efficiency_low CC” scenario. Source: own elaboration.	263

Figure 79: Cost components and total energy supply cost in each scenario. Source: own elaboration.....	264
Figure 80: Demand side management policies chosen by the model. Source: own elaboration.	265
Figure 81: Overview of the Simulink implementation of MASTER_DS. Source: own elaboration.	277
Figure 82: representation of our idea of operating profit for an energy conversion plant. Source: own elaboration.....	279
Figure 83: representation of the main agents in our prototype model and their interaction. Source: own elaboration.	281
Figure 84: main causal loop diagram in our proposed model. Source: own elaboration.....	282
Figure 85: Simulink block representing energy markets. Source: own elaboration.	284
Figure 86: Simulink block representing utilities' forecasts. Source: own elaboration.	285
Figure 87: Simulink block representing utilities' investment decisions. Source: own elaboration.	286
Figure 88: investment decisions as a function of profitability. Source: own elaboration.	288
Figure 89: maximum investment decisions calculation. Source: own elaboration.....	289
Figure 90: primary energy types considered for the MASTER_DS model. Source: own elaboration.....	294
Figure 91: energy conversion technologies considered for the MASTER_DS model. Source: own elaboration.....	294
Figure 92: final energy types considered for the MASTER_DS model. Source: own elaboration.	294
Figure 93: evolution of energy conversion capacity investment costs considered (€/kW output). Source: own elaboration.	295
Figure 94: evolution of the import prices of primary and final energy (€/2010/MWh) for all the scenarios. Source: own elaboration.....	295
Figure 95: final energy demand sectors considered for the MASTER_DS model. Source: own elaboration.....	296
Figure 96: scenarios considered for this case study. Source: own elaboration.....	297
Figure 97: evolution of final energy used per type (measured in EJ) in the four scenarios. Source: own elaboration.....	299
Figure 98: evolution of the national energy matrix (in EJ) in the four scenarios. Source: own elaboration.....	300
Figure 99: evolution of the energy dependence (%) for the four scenarios. Source: own elaboration.....	301

Figure 100: Sankey diagram of the Spanish energy system in 2010, common for the four scenarios. Source: own elaboration.....	302
Figure 101: Sankey diagrams of the Spanish energy system in 2015, 2020 2025 and 2030 under each case. Source: own elaboration.....	303
Figure 102: evolution wholesale and retail energy prices (€'2010/MWh) in the four scenarios. Source: own elaboration.....	304
Figure 103: evolution of conversion capacity per technology (measured in GW) in the four scenarios. Source: own elaboration.....	306
Figure 104: investment decisions in conversion capacity per technology (GW) in the four scenarios. Source: own elaboration.....	307
Figure 105: profitability (NPV) of each conversion capacity (M€'2010/MW) in the four scenarios. Source: own elaboration.....	308
Figure 106: emissions from all sources, conversions and final use, (MtCO ₂) in the four scenarios. Source: own elaboration.....	309
Figure 107: energy-related costs (billion €'2010) in the four scenarios. Source: own elaboration.	310
Figure 108: energy- and non energy-related costs (billion €'2010) in the four scenarios. Source: own elaboration.	311
Figure 109: energy- related costs per unit of final energy demand (€'2010/MWh) in the four scenarios. Source: own elaboration.....	311
Figure 110: summary table with the main information about the reviewed models, and placing the developed MASTER models. Source: own elaboration.	321
Figure 111: cars' electrification example. Source: own elaboration.....	380
Figure 112: private commuting example. Source: own elaboration.....	380
Figure 113: representation of the main agents in our prototype model and their interaction. Source: own elaboration.....	393
Figure 114: representation of the possible future research regarding the main agents in our prototype model and their interaction. Source: own elaboration.....	394

Chapter I.

INTRODUCTION, MOTIVATION, OBJECTIVES AND STRUCTURE

I.1	Introduction	3
I.2	Motivation	6
I.3	Objectives	11
I.4	Structure of the Thesis	13

I.1. INTRODUCTION

We all live in the Earth. It is a planet, a finite mass in our Solar System with ample, diverse but also limited resources. The global population is growing exponentially and is expected to reach 9 billion by 2050, while the world average per capita use of resources and pollution production are growing as life conditions improve. This is perfectly fair for many developing countries, but it is happening with the same unsustainable development model that has been followed in developed countries. This unsustainable process of large-scale use of resources, with its associated environmental impact, is bringing enormous challenges to our civilization.

This unsustainability is already becoming clear for some sectors and resources that are key to our societies, such as energy¹. Our economies are largely based on the intensive (and normally inefficient) use of limited fossil fuels, whose demand has grown significantly in the last decades as global economic activity increased, mainly in western countries. This has implied a large increase in associated pollution, mainly atmospheric emissions. This trend is forecasted to continue, in this case, mainly driven by the well-deserved economic development from developing countries.

At the same time, the global supply of fossil resources is becoming tight, due not only to geological or technological reasons, but as well to geopolitical or environmental ones. The combination of a growing global demand and a tighter global supply is causing fossil fuel prices to increase, bringing great economic challenges for countries both in the importing and in the exporting side. Importing countries spend growing shares of their wealth in energy, what reduces their available income for investment or consumption and what worsens their current account balances. In addition, as energy is a key input in their economies, growing energy prices are passed to the rest of the economy, increasing inflation and hence reducing competitiveness. From the perspective of exporting countries, fossil fuels trade allows them to receive enormous amounts of wealth. This can be a blessing if the country has strong institutions who make a sensible use of these funds, but if not, this wealth can become a great liability, or even a *curse* as some authors have put it (Auty, 1993), creating growing inequality, social unrest and political instability.

This energy model based on fossil fuels is not only challenging from the economic perspective. From the social perspective, as energy becomes more and more expensive, poor people cannot afford to use it for basic human needs such as cooking, heating, lighting or productive uses. What is more, a very significant proportion of humanity cannot access modern energy sources and hence they rely on traditional biomass, what poses great risks to their health, economy and human development. Ironically, these or similar problems exist even in countries with large energy reserves, with huge differences in energy use and access between rich people in large cities and poor people in rural areas. Access to energy presents the same inequality patterns as does access to other forms of wealth, what is a great obstacle for the development of many people worldwide.

¹ Detailed definitions of *sustainability* and *energy sustainability* are given later in this thesis.

Last, but certainly not least, the world energy system being largely based on fossil fuels is creating large environmental problems. Climate change could be considered the main one: using fossil fuels with energy purposes releases large amounts of carbon dioxide and other greenhouse gasses to the atmosphere. This reinforces the greenhouse effect, and hence global warming and climate change, which are considered to be one of the main challenges for human well-being in our planet in the medium to long term. Climate change is not the only environmental impact of the way we use energy: burning fossil fuels also creates local and regional pollution, which causes respiratory diseases, allergies and other health problems leading to premature death to many millions of people worldwide (Anenberg et al., 2010). Besides, another issue can also be considered a consequence of our energy use: energy resources depletion, which is not only an economic issue (as described above), but also an environmental and equity one, because it means that less natural assets are left to be used by next generations, which can be a problem if no suitable alternatives are developed.

All of the above allows us to reach a preliminary conclusion: our energy model, mainly based on fossil fuels, is clearly unsustainable. Left to themselves, market forces are not able to properly address this problem. This is partly due to the fact that energy markets are not perfect: many externalities² and other market imperfections exist in the energy sector and markets fail to price them correctly. Hence policy intervention is needed to correct these market failures. The latest predictions and forecasts from highly reputed international organizations, such as the United Nations or the International Energy Agency, point at the fact that, unless aggressive policy action is put in place as soon as possible, the world energy system is going to continue along the path of unsustainability (International Energy Agency, 2012a). In the past, this has been mainly due to the economic development of western countries. In the future, this will be caused by the same (and unquestionable) process, but now applied to developing countries that are, even more worryingly, vastly populated. If we do not implement aggressive policies, our energy system will continue to be clearly unsustainable in the future, causing great risks for humankind.

A key concept in this PhD thesis can be now introduced: *sustainable energy policy*. Sustainable energy policies are those aiming at making the energy system evolve towards greater sustainability³. Sustainable energy policies are an important part of the context of this PhD thesis, which tries to improve the methods used for their assessment.

Energy policies are nowadays defined from several governance scales: global, regional, national and, in certain countries like Spain, sub-national. Of all these levels, this PhD thesis concentrates on the national one. Given that the policies that must be specifically put in place

² The definition of *externality* is given in the next chapter.

³ *Sustainability* is a complex concept, incorrectly used in many occasions, and often simplistically associated with (only) environmental issues. A comprehensive definition of what is understood by *sustainability* in the context of this thesis is given in Chapter 2. Here, however, a compact and widely used definition is given. It was proposed by the "Brundtland Report" in 1987 and we believe it to be adequate for this Introduction: "Sustainable development [i.e. sustainability] is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

very much depend on the physical, economical and social characteristics of the country to which they are applied, this thesis will be focused on Spain or countries with similar characteristics. That is, industrialized and market-oriented countries from the OECD with well-developed energy systems and infrastructures, but facing serious problems of economic and environmental lack of sustainability, such as high energy dependence on fossil fuels, which also happen to be mostly imported. In these countries, energy sustainability from a social perspective is less of an issue (although energy poverty does exist). Hence social aspects of sustainability will not be treated in this thesis. In conclusion, this thesis will set a basis to examine sustainable energy policies that focus on the economical and environmental aspects of sustainability and are applied at a national level to Spain or similar countries (although the methodologies developed could be applied to almost every country).

More precisely, this research is framed within sustainable energy policy *analysis*, that is, the process of analyzing and designing sustainable energy policies. *Policy analysis* in the context of this thesis refers to the quantitative and qualitative assessment of different policies in order to decide which of them best fulfils the desired objectives, and therefore allow policy-makers to make correctly informed decisions about the expected outcomes of their regulations.

Energy policy analysis is a very complex job. Energy systems are very intricate, they are integrated by a large set of economic agents with different interests, technologically complicated infrastructures, and strong interrelations internally and with other sectors, both domestic and international. Added to this, the outputs of energy systems (modern forms of energy ready for final use) are vital inputs for economic activity. Therefore, relations between the energy sector and the rest of the economy are very important and of great complexity. This becomes even more entangled if the environment is included. In a simplistic way, economic activity drives energy use, which creates environmental impacts, which in turn can affect the economy and the energy sector.

Luckily, modern computation technologies make complex mathematical calculations largely accessible at affordable prices. This brings the possibility of representing intricate energy-economic-environmental systems and their evolution under different assumptions with computer-based numerical models.

This thesis will focus on sustainable energy policy evaluation and design for Spain, and computer-based energy models will be used in this evaluation.

To summarize: (i.) global energy unsustainability needs urgent and ambitious policy action; (ii.) our energy-economic-environmental systems are very complex and interrelated, and sustainable energy policies significantly affect them in complex ways; (iii.) policymakers need some means of analyzing policy measures thoroughly, before adopting them; (iv.) computer-based mathematical models for energy policy assessment are key in this process; (v.) this PhD thesis focuses on the design and evaluation of sustainable energy policy assessment models and methodologies applicable to Spain (or similar countries) and will deal mainly with the economic and environmental aspects of energy sustainability.

I.2. MOTIVATION

There are already, in the literature, a number of energy policy analysis models and methodologies that are currently being used by policymakers worldwide. Just to cite a few, the MARKAL/TIMES family of models that has been extensively used, the PRIMES and POLES models employed by the European Commission, the NEMS model used in the United States, or the Massachusetts Institute of Technology's EPPA model in its many versions. We will later review, in detail, all of these and others.

Why is there the need for another energy policy assessment methodology? Why are new models required? What is the added value of the research carried out in this PhD thesis?

The key issue here is *which should be the purpose of the modeling process*. As Huntington, Weyant and Sweeney wrote in their 1982 paper, “the primary goal of policy modeling should be the insights quantitative models can provide, not the precise-looking projections—i.e. numbers—they can produce for any given scenario”. The title of their paper represents very clearly the idea: “Modeling for Insights, Not Numbers (...)”. The paper describes one of the most relevant energy policy modeling community ever created, the Energy Modeling Forum, established at Stanford University in the 1970s as a consequence of the Oil Crisis.

We are completely in line with this philosophy and this thesis is inspired by it. Many models have been developed, especially since computing has become cheap and accessible. Some of these models represent, in great technological detail but in isolation, certain aspects of the energy system, for instance the hourly operation of the power sector. Others include the complete energy systems and their main economic and technical details. Still others represent the energy-economy-environment interrelations, but at the expense of technical detail.

All of these models have their own purpose. However, we think that many of them are not adequate in order to provide the insights needed for sustainable energy policy analysis. They sometimes produce large databases full of numbers, but the main policy interactions, trade-offs and effects are sometimes hard to extract from them. What is more, some of these models can become black boxes, where the user is not able to understand the internal logic and how the outputs are derived from the inputs. We should not forget that the users of these models are government officials, business managers, or lobbyists, among others, who have to make important policy or strategy decisions with a limited time for analysis. They need clear and understandable conclusions about the *big picture* of the studied energy system. Details are irrelevant, because we are interested in energy policy *design*, not in its implementation.

We believe that the real difficulty of energy policymaking is not in the adopted model itself, but in understanding the policies' mutual implications and trade-offs, how a policy can be counterproductive with another, the relative weight of each policy in achieving the main high level goal (in our case, making the system more sustainable), the value of policy anticipation or wait-to-see, or the policies' sensitivity to uncertainties.

The need for such models, able to analyze main policy interactions, synergies and trade-offs, is for instance clearly seen in the recent European Commission's Green Paper “A 2030

Framework for Climate and Energy Policies”, published in March 2013. This document, which launches a public consultation on the European 2030 targets/policies on climate and energy, clearly states the vital need to understand policy interactions and to take them into account when designing specific regulations. Citing literally from this document:

(...) The current climate and energy targets for GHG [greenhouse gasses] reduction, the share of renewable energy sources and energy savings were designed to be mutually supporting and there are indeed interactions between them. Higher shares of renewable energy can deliver GHG reductions so long as these do not substitute other low-carbon energy sources while improved energy efficiency can help reduce GHG emissions and facilitate attainment of the renewables target. There are obvious synergies but there are also potential trade-offs. For example, more than anticipated energy savings and greater than expected renewable energy production can lower the carbon price by weakening the demand for emission allowances in the ETS [emissions trading scheme]. This in turn can weaken the price signal of the ETS for innovation and investments in efficiency and the deployment of low-carbon technologies whilst not affecting attainment of the overall GHG reduction target. A 2030 framework with multiple targets will have to recognize these interactions explicitly. (...)

More precisely, in our opinion, a useful model for national sustainable energy policymaking should incorporate the following characteristics:

- It should be comprehensive enough and include the entire energy system under study, its main components and interactions, and a fair level of technical detail. But without going too much into details that may require excessive mathematical complexity or too many internal parameters, which could muddle the main relations and conclusions and create the feeling that the results are dominated by the more or less arbitrary choice of these parameters. By including the complete energy sector, the model should be able to represent the relations between the different energy subsectors (electricity, gas, oil products, etc.) and the fact that a policy applied to one subsector can produce unexpected, synergic or counterproductive effects in another.
- It should allow the user to measure and account for energy sustainability, that is, it should make use of some type of *energy sustainability indicators*. Most of the models existing in the literature only provide results about aspects such as the system’s costs, quantity and type of the energy carriers used, infrastructure capacities and investments, or emissions. But they do not include explicit metrics on energy sustainability. We think that a useful sustainable energy policy analysis methodology should incorporate quantitative metrics on energy sustainability. Once these metrics are introduced in a model, it could be formulated so that its objective function, which represents the overall policy aim, consists on *maximizing energy sustainability*⁴. This would allow the user to

⁴ Even if this terminology (objective function, maximization, etc.) comes from the mathematical programming/optimization discipline, we use it here only for illustrative purposes: it adequately represents the idea. However this does not imply that this methodology can only use optimization techniques.

understand how each precise policy affects this overall objective of evolving towards a sustainable energy model, the purpose of sustainable energy policymaking.

- It should be able to address global high-level policy questions about the studied system. Some examples of these types of questions could be: (i.) Is it cheaper to reduce CO₂ emissions through renewables or through energy efficiency?; (ii.) Is it possible to achieve ambitious levels of emissions reduction without nuclear energy? (iii.) How should be decarbonization efforts distributed among different sectors such as power generation, transportation or buildings?; (iv.) How large should be the contribution of electric mobility, if any?; (v.) In which sectors is it better to introduce renewables, in power generation, in transportation through biofuels or in buildings through biomass or solar heating?; (vi.) In order to achieve energy savings, is it preferable to subsidize hybrid cars, more efficient appliances or better insulation in households? The type of model that this PhD thesis proposes should be able to give general answers to this type of questions, even if it is not with a very detailed numerical result but, instead, with ballpark figures and sensitivity analysis.
- It should be as transparent as possible, with simple but sound mathematical techniques, so that all its underlying calculations are intuitive and easy to understand for any user, even if she does not have a very advanced mathematical training. Very complex mathematical formulations can be counterproductive for our purpose. We believe that simple optimization or simulation techniques, which in general yield intuitive results and present understandable behaviors, are enough to represent energy systems with an adequate level of detail. Modularity can help in achieving this transparency, if the user can see and understand the information that, within the model, is available to different agents (represented as separated modules interconnected by information flows) and the decisions that they take based on it.
- It should take into account that the energy sector is a very policy-driven one. By this, we mean that it is subject to significant regulatory intervention and many of its developments are consequences of these regulations. They affect issues such as the quantity and type of installed electricity generation capacity (e.g. renewables support schemes or nuclear policy largely affect investment decisions in these technologies), the fuels used by cars (e.g. the large dieselization of car fleet in some European countries is due mainly to tax reasons) or the energy efficiency of buildings (e.g. building codes or refurbishing programs can be very influential on the energy demand for space heating). The precise way these regulations affect the decisions of the different agents can be complex to understand and model, but one could be confident in the fact that, if policymakers want some developments to take place, they will pursue the objective until they do. For instance, if a premium on wind energy is established, it can be difficult to model the way wind power investors make their investment decisions, but if wind power is not coming into the system, the regulator will act (increasing the premium) until it

happens⁵. In some cases, for the sake of transparency and in the context of this thesis, a useful energy policy assessment model could represent if an effect is desirable, and not how to achieve it, since this can be much more complex to model and is less relevant to our case⁶. In the wind power example, the model could only represent how a given installed capacity affects system's costs, emissions or reliability, but not how a premium affects investment decisions. The model would be more of a *calculator*, allowing the user to answer *what if* questions about a given policy, sometimes without worrying about how to make that policy happen (once again, in the context of this PhD thesis). This can be understood as a sort of alternative option for the sake of transparency: given the complexities of correctly modelling the internal decision-making processes of agents, and the amount of hypotheses and internal parameters that it would entail, we just skip them by modelling the produced effect. This idea is what, in the context of this PhD thesis, will be called "direct policy effect modelling".

- It should reflect energy markets' imperfections and their influences on the effectiveness, costs and outcomes of energy policies. As said, many externalities are present in the energy sector and most of them are not correctly priced (climate change, resources depletion or pollution, amongst others). Furthermore, there may be information asymmetries and competition problems. Strategic and market-positioning behaviours are common within energy utilities. Risk aversion and uncertainties play very important roles in agents' decisions, sometimes making implicit discount rates to take unusually high values and causing myopia in decisions. In many cases, other non-economic or qualitative aspects may play important roles in the decisions of energy consumers, aspects hard to quantify in the type of utility functions that are normally used in existing models. In other words, energy markets are not perfect. This can cause energy policies to have unexpected results and costs. For instance, the large investment in combined cycle gas turbines (CCGTs) that has taken place in Spain as a result of utilities' growing demand expectations or strategic behaviours (a possible fight for market shares) may be causing the current cost of renewables support (from the perspective of the complete Spanish energy system) to be higher than in the case of optimal CCGT capacity (López-Peña, Pérez-Arriaga, et al., 2012a). Other example could be the fact that many energy efficiency investments, which would be cost-effective under perfect energy market assumptions, are not taking place due to myopia and other bounded rational behaviours of the decision-makers (mainly consumers), which result in high discount rates when evaluating their investment decisions. Subsidies may be needed to bring these investments, which is an extra cost of the policy due to market imperfections. These

⁵ Of course this may not be necessarily true in real life. This somehow extreme example is only used for illustrative purposes.

⁶ Modeling policies or regulations to understand how they affect the regulated sector is a very important and relevant topic within regulatory analysis. We certainly do not intend to underestimate it, even more because much of the research done by the Directors of this thesis and many colleagues and friends is linked to it. We are just saying that it is less relevant *within this thesis*.

types of effects are not represented in those models that assume perfect energy markets and perfect rational decisions, and we believe that these issues should be also included in a sound energy policy assessment methodology.

- It should use public and contrasted data obtained from widely available and recognized sources. Data hypothesis must be made clear and explicit. This would allow us to be confident on the used data, but at the same time, it can be made completely open and available to the wide public, so that anyone not agreeing with some results could fully analyze the data and perform her own calculations. If the user/modeler is not confident about the value given to a parameter, this should be clearly stated so that it is well identified, easing the process of redoing the calculations with a new value or performing a sensitivity analysis.
- It should present the results in ways that allow the user to comprehend the *big picture* of the policy effects and that foster the extraction and understanding of conclusions and insights. Sankey diagrams allow for very graphical and intuitive representations of all energy flows within a country, which can be very useful in order to present the effects of different policy interventions. Also, all results should be presented in coherent and uniform units where the different orders of magnitudes are easily understandable. For example, it is very useful to express all energy price magnitudes in the same units, e.g. €/MWh, instead of using these units for electricity, €/liter for liquid fuels, and €/m³ for natural gas. This can be easily done just by using average energy densities and performing some change of units.
- It should also include decision support techniques. As said above, many uncertainties are present in the energy system. They affect not just utilities and consumers, but as well the policymaker. Hence it is useful for her to understand the value of policy anticipation or wait-to-see (until more complete information is available), or the policies' sensitivity to uncertainties. It can be interesting to choose strategies that are robust and flexible to unexpected developments and that minimize the regret value. Hence some type of decision support scheme (e.g. approaches such "minimax regret" or "robust decision making") would be needed too.

This approach is supported by an extensive review of the state-of-the-art (Chapter 3) as well as by an extensive although informal consultation to energy decision makers and policy analysts⁷, obtaining always very positive feedback.

⁷ We have consulted: (i.) Spanish Government high level officials at the Energy and Environment Ministries; (ii.) politicians from different parties with previous responsibilities in energy; (iii.) energy regulators from the Spanish National Energy Regulatory Commission (Comisión Nacional de Energía, CNE); (iv.) high executives from energy companies; (v.) academics from various universities across Spain, in Europe and in the United States, working in issues related to energy and climate policies, consulted in international conference and during a research visit at MIT in 2012; (vi.) executives from energy consulting firms; (vii.) members of international organisations in the fields of energy and sustainable development, or (viii.) members of other organisations such as NGOs or lobbies defending various interests, always related to energy

The Energy Modeling Forum (EMF), mentioned above, was created with a somehow similar objective. One of its main purposes was to serve as a platform for energy policy modeling experts to meet and share the results and conclusions obtained from their different models and methodologies in order to reach common insights. A similar goal is sought with the overall approach and the models that have been developed in this PhD thesis, which may be seen as a contribution to building such an overall methodology, setting the basis for continued future research. In the next section, the precise objectives of this thesis are described.

I.3. OBJECTIVES

I.3.1. General objective

This thesis' main objective is to define, develop and implement a methodology that is specifically focused on energy policy analysis at country level and to apply it to Spain.

The central idea is to provide an improved and so far inexistent set of tools based on public and contrasted data, with a sound –but at the same time simple and transparent– methodology, which allows to represent an energy model's evolution under different policy assumptions and to measure its sustainability. The aim is to show that the real difficulty is not in the model itself but in understanding, with a comprehensive but simplified quantitative analysis, the policies' mutual implications and trade-offs, how a policy can be counterproductive with another or the relative weight of each policy in making the system more sustainable. An extensive review of the state of the art allows justifying the proposed methodology, along the lines exposed in the Motivation section. An extensive process of abstraction, representation and data collection has been done in order to characterise the studied energy system with public and contrasted data; and two models are proposed and used to evaluate actual energy policy issues for the case of Spain, one under static conditions and a second one that considers the temporal evolution of the energy system.

Two *complementary* models are needed, as will be thoroughly justified in the Methodological Proposal chapter. As said, one represents static conditions and the second takes into account temporal evolution, but this is not the only reason. It is also because the static one will be optimisation-based and will provide *normative* information (e.g. how should the energy system be in 2030?), whereas the dynamic one could be simulation-based and provide *descriptive* information, in a second step (e.g. how to get from where we are now to that 2030 system that we have decided, with the static model, to be the goal?).

I.3.2. Specific objectives

I.3.2.a. Methodology definition and data structuring and acquisition

The thesis proposes, develops and implements a methodology for sustainable energy policy making that incorporates most of the issues mentioned in the Motivation section above. This objective has been carried out taking into account the review of the state of the art and the

availability of public data for Spain. Models are proposed, specifying which should be their main inputs and outputs, how they should be used, their underlying hypothesis and methodologies, and the way they relate to each other and how the user (the policymaker) should use them. An extensive process of abstraction, representation and data collection has been done in order to characterise the studied energy system with public and contrasted information.

I.3.2.b. Development of a full-fledged static optimisation model

This specific objective consists of the development of a bottom-up, partial equilibrium, static optimization model for sustainable energy policy analysis that:

- Contains a complete representation of the energy system under study, typically at single country level, including all energy vectors and all energy demanding sectors. It makes use of a fair but not excessive level of technological detail.
- Has as main input the demand for energy services⁸ in energy demanding sectors and optimises the complete upstream energy sector (energy use devices, energy transportation and distribution, energy conversion, energy trade and primary energy production).
- It is modular, leaving open to future research the possibility of improving sectoral models (electricity, transport, specific industries, etc.).
- The objective function can be flexibly modified in order to represent, if desired, a quantitative measure of the sustainability of the studied energy system. For now, special emphasis will be put on economic private⁹ cost.
- Clearly identifies the trade-offs or synergies between policies.
- Represents the fact that the energy sector is "policy-driven", as mentioned in the Motivation section above.
- Uses public and contrasted data. The process of obtaining data (sources, hypothesis, previous calculations, etc.) is well documented and made public so that anyone could criticize the values or perform her own calculations with different ones.
- Represents the results in a clear and easy to understand manner, using uniform units and easily comprehensible Sankey diagrams.

I.3.2.c. Development of a prototype of a dynamic simulation model

For the completion of this specific objective, a prototype for a dynamic simulation model for sustainable energy policy making has been developed. More precisely:

⁸ *Energy services* refers to the actual services that energy is used for, such as lighting, space heating, industrial production, passengers mobility, etc., in opposition to final energy such as electricity, gas, coal or gasoline.

⁹ As opposed to *public* or *social* costs, which include externalities.

- Given that it is only a prototype, it will be the basis for a modular simulation model where *realistic* aspects of energy markets (i.e. externalities, bounded rationality, imperfect competition, etc.) could be represented. By *modular*, as said above, we imply that it leaves open to future research the possibility of improving specific sectoral models (electricity, transport, specific industries, etc.).
- It would allow for the representation of realistic evolutions of the energy system under study under a set of policies, for example, between 2010 and 2030.
- In each of its yearly steps, it has a representation and level of detail similar to the static model in Specific Objective 2.

I.3.2.d. Applications to actual policy-relevant cases in Spain

Our models will be applied to the examination of some energy policy questions relevant to the Spanish case. These questions will be:

- Assuming that the dominant policy goal in Spain was to reduce carbon emissions in the years prior to the present economic crisis, would it have been better to prioritize renewables and support (through subsidies) energy efficiency or renewables for electricity generation? What would have been the economic savings in the best alternative? How would have changed the emissions, installed power generation capacity, energy flows throughout the complete energy system, and distribution of energy supply costs?
- What would be the foreseeable advantages that strongly pursuing end-use energy efficiency and savings could bring? How would the energy matrix in Spain look? And the evolution of CO₂ emissions? Which level of energy dependence would be reached?

I.4. STRUCTURE OF THE THESIS

Chapter I of the thesis first introduces its context, then the motivation section presents the main driver of this PhD thesis (i.e. the identified need for improved tools and models for sustainable energy policy analysis), and describes the key features that, in our opinion, such tools should incorporate (which are, later, backed by an extensive literature review). Finally, Chapter I presents both the general and specific objectives of this PhD thesis.

Chapter II presents in greater detail the context of this thesis, which sits within the energy and sustainability problem (first at a global level and then particularised for Spain), the need for sustainable energy policies to complement markets, and the need for mathematical models to analyse these policies. This allows us to focus, in the remaining of the thesis, on such models.

Chapter III presents the literature review of this PhD thesis. We first introduce the key concepts and techniques for energy modelling. Then, we perform a review of the mainstream energy models, whose selection also tries to cover a diverse representation of techniques and modelling approaches. Then, some other models are also reviewed, all of which have interesting

features from the point of view of this PhD thesis, and finally, the main gaps in the literature are identified, some of which are covered by this thesis.

Chapter IV contains the detailed methodological justification and proposal of this PhD thesis. First we give an overview on our methodology. Then we describe our proposed detailed representation of the energy sector. Later, we explain our approach to data, magnitudes and units, which is key in achieving some of our main methodological purposes such as being able to analyse the big picture of the studied energy system and to understand well the main policy interactions and trade-offs. Next, still within Chapter IV, we explain our approach to energy sustainability indicators. Afterwards, we detail our modelling framework, which consists of two different but complementary models, a static optimisation one (MASTER_SO) and a dynamic simulation one (MASTER_DS). After introducing both models, we also propose a specific two-step-process for using them. Finally, we explain our approach to output representation, which makes use of Sankey diagrams and of uniform magnitudes and units, allowing comprehending the big picture of the analyzed policies and the studied energy system.

Chapter V describes MASTER_SO in detail. Given that it is an optimization model implemented in GAMS, it uses the same GAMS terminology for the sake of the reader's convenience (i.e. sets, parameters, variables, constraints and objective function). This chapter intends to provide the rationale on the mathematical modelling carried out, but in addition it has been written to be a useful reference guide for future users, also increasing transparency.

Chapter VI presents a specific study for Spain carried out with MASTER_SO. It analyses whether, from a cost minimization viewpoint, renewable support has been the best policy for reducing emissions in Spain, when compared to the promotion of energy efficiency in sectors such as transportation or buildings.

Chapter VII describes in detail the second model proposed in this PhD thesis: MASTER_DS. It is a System Dynamics-based simulation model which sets the basis for a modular model of the Spanish energy system that is able to represent realistic features of energy markets such as bounded rationality or myopia.

Chapter VIII illustrates a study case example performed with MASTER_DS: four possible evolutions of the Spanish energy system are simulated, each representing a different scenario of the evolution of the demand side.

Finally, Chapter IX presents the thesis' summary, the conclusions, the main contributions and the future research lines.

Chapter II.

CONTEXT OF THE THESIS

II.1	Outline of this Chapter	17
II.2	Sustainability	17
II.3	Energy Sustainability	29
II.4	Energy Sustainability in Spain	43
II.5	Narrowing the Focus: Sustainable Energy Policies	64
II.6	Sustainable energy policy assessment	72

II.1. OUTLINE OF THIS CHAPTER

This chapter presents the *energy and sustainability* problem, the need for certain regulation of energy markets in order to deal with it (i.e. what we will call *sustainable energy policies*), and the usefulness of computer-based mathematical models in order to analyze those policies prior to their implementation. This storyline represents the context of this PhD thesis.

The perspective of this chapter is broad at the beginning, in order to then narrow it down to our field of study. It begins (section II.2) by explaining what we understand by *sustainability* (in general) and providing a conceptual framework for its analysis based on four types of capital (i.e. natural, social, human and economic) and how equitable their distribution is. Related aspects (which are relevant for a wide understanding of our line of research) are also introduced, such as sustainability/well-being indicators, the *weak* vs. *strong sustainability* approaches, or the *Cornucopians* vs. *Neomalthusians* debate. Some relevant facts and figures are used to present some of the most relevant trends of sustainability in our planet, what will allow us to identify the key role that our use of energy plays in these trends.

This allows us to then analyze the lack of sustainability of our current global energy system, using the above-introduced *capitals* framework (section II.3). Once the global situation has been introduced, the energy and sustainability situation of Spain (and other similar countries) is reviewed in section 0. This order is followed because the situation of a single country cannot be correctly understood if the global picture is not clear beforehand. For the Spanish case, we make use of official statistics. We first present some information on the *big picture* of the Spanish energy sector using the four Sankey diagrams that we develop every year at the BP Chair on Energy and Sustainability. Then, we analyze the sustainability of the Spanish energy sector from the capitals perspective.

In section II.5, we start to narrow the focus to *sustainable energy policies*. We briefly review the liberalization process that has been carried out in most of our energy industries and how markets are not necessarily bringing sustainability to them. The need for sustainable energy policies is identified, and examples of these policies are given, reaching the conclusion that Spain lags behind most of our peers in these issues. Lastly, section II.6 discusses the need for thoroughly analyzing sustainable energy policies prior to their implementation, and identifies computer-based mathematical models as a very suitable tool for this purpose. The topic of energy modeling has then been introduced, paving the way for the review of the state of the art, which is done in the next chapter.

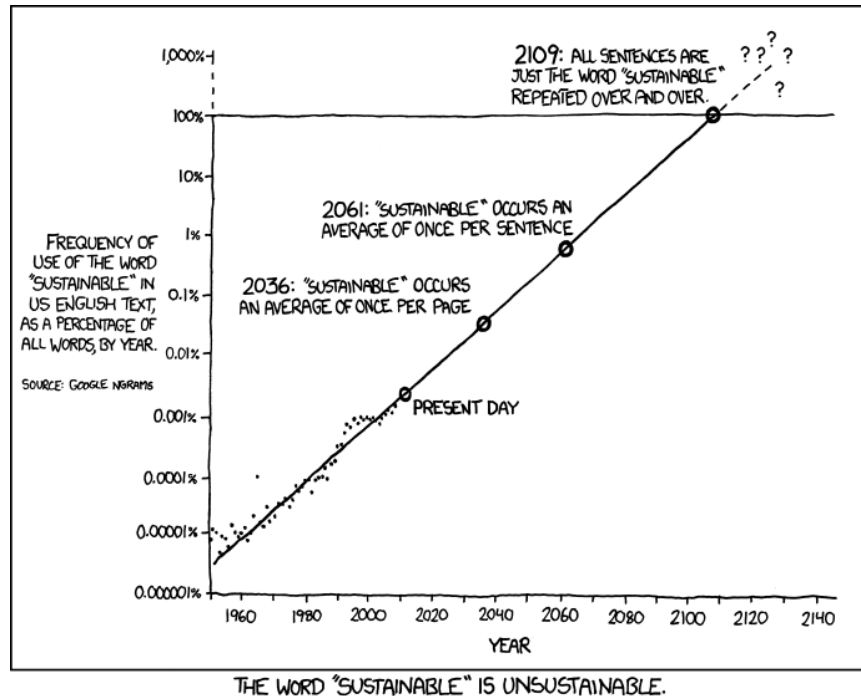
II.2. SUSTAINABILITY

Sustainability, sustainable development and similar expressions are widely used nowadays. We can see them almost daily in the mass media, in peoples' conversations and interests, in

many ads or even in the financial markets. To start discussing this issue with a pitch of humor¹⁰, the parody in Figure 1 is a good illustration of this global trend.

Figure 1: parody of the current use of the word "Sustainable"

Source: xkcd webcomic



Despite its growing use, this concept refers to a very complex and abstract issue, and it is used to express many different ideas, maybe *too* many. A first important clarification on a very common misunderstanding must be done: *sustainability* does not mean "respect for the environment", "ecology" or "nature". It is a much broader issue, which also encompasses important economic, social or political aspects, among others. Environmental issues are just a component of sustainability.

II.2.1. A conceptual approach to Sustainability

The most widely known definition of *sustainability* (or *sustainable development*), which was introduced in the *Brundtland Report* (Brundtland et al., 1987), stated that "Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Some other interesting introductory references are Daly (Daly, 1997, 2002) and Munda (Martinez-Alier et al., 1998). Based on the ideas presented by Mohan Munasinghe in the 1992 Earth Summit in Rio, resumed in (Munasinghe, 2004), the 2000 World Energy Assessment (United Nations Development Programme et al., 2000) stated that *sustainability* is constituted by three main pillars: social, economic and environmental. The basic idea behind this definition is that economic development should be done in a way that is:

¹⁰ This opening has been inspired by how one of my PhD advisors, Professor Pedro Linares, begins his *Sustainable Development* course. I think it is an excellent way of starting with such a complex and worrying issue.

- Economically viable in the long term and based on a solid and virtuous economic model which allows for the fair and adequate development of all peoples, which does not necessarily imply a growing use of material resources.
- Respectful with the environment in which human activity takes place.
- Virtuous for the basic needs and rights of all peoples, including important issues such as equity, freedom, education and health.

This conceptual definition has been widely followed in the last two decades. However, in our opinion, a more complete conceptualization can be done through the idea of *capital*, which is a measurement of value in a broad sense as will be seen. Good references on this approach are (Linares, 2012) or the first part of (Atkinson et al., 2007).

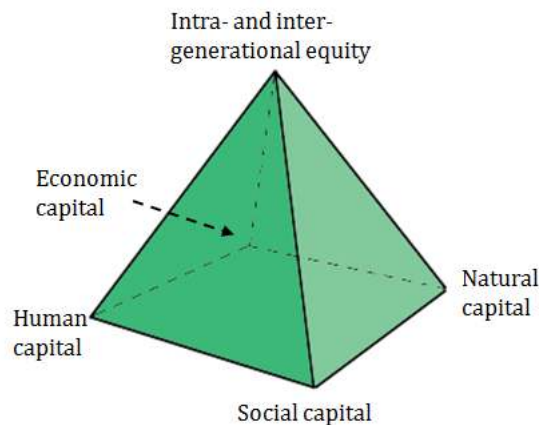
Following this definition, four main capitals can be identified. Sustainability would be achieved when two main conditions are satisfied: these capitals are preserved and all the people –present and future generations- can enjoy them in a fair way. More precisely, these four capitals are: (i.) economic capital (includes all types of economic assets, be it money, buildings, infrastructure, investment vehicles like debt or shares, etc.); (ii.) social capital (comprises all aspects regarding people’s social well being such as community relations, political participation, strong institutions, etc.); (iii.) human capital (includes the personal and intellectual development of peoples, including health, leisure, freedom, training, culture or education); and (iv.) natural capital (resources, biosphere integrity, animals and plants, etc.).

Once these *capitals* are introduced, two main approaches can be identified in defining *sustainability*. The *strong sustainability* approach implies that for a society to achieve sustainable development, all four capitals must preserve or increase their value over time independently. Meanwhile, the *weak sustainability* approach defends that the four capitals can be exchanged with one another (an interesting topic, out of our scope, are the adequate exchange rates), and therefore sustainable development implies total capital (the addition of all four) to be non-diminishing. Good discussions on both approaches are (Daly, 1997) or (Neumayer, 2004). An interesting research field, based on the strong sustainability approach and not using the *capitals* paradigm is the field of Exergy, on which a good state of the art review is (Romero Mora, 2013).

To complete this definition of sustainability, *equity* must be included. It is achieved when all citizens within a generation and in different generations can fairly enjoy the four capitals, which is respectively called *intragenerational* and *intergenerational* equity. This definition of sustainability can be imagined as a geometrical figure: a quadrangular pyramid in which the four vertexes in the basis are the four capitals and the one on top, related to the four in the basis in an equal way, is equity (both intra and intergenerational). Here becomes clear, as said above, that *sustainability* is not only *environment*. Environment is just a part of natural capital, which in turn is just a component of global sustainability.

Figure 2: graphical representation of the idea of sustainable development.

Source: own elaboration



II.2.2. Sustainability: related aspects

The question to be asked now is, can our current development be considered sustainable? During the second half of the XXth century, the Earth has contemplated how a reduced group of countries experienced large economic growth. This growth was mainly based on a *linear* economic model based on resources' extraction, conversion through the manufacturing of products, products' use and waste disposal. This model was partly due to a macroeconomic paradigm in which progress was believed to be only achieved through a continuous growth of gross domestic product (GDP), that is, of consumption. In this paradigm, only growing consumption ensures job creation and social welfare. This, combined with other sociological and political issues, has created an exacerbated consumerism in the western world.

This issue, firstly raised by Galbraith in his 1958 book "The Affluent Society", has been recognized by academics, business leaders and politicians. An example of this recognition is the rising of a new economic trend called *The Circular Economy* (as opposed to the prevailing linear economy). One of the fathers of this new paradigm was Walter R. Stahel. An architect, economist and one of the founding fathers of industrial sustainability, Stahel coined the expression "Cradle to Cradle", in contrast with "Cradle to Grave", illustrating our *resource to waste* linear economy. He created the Product Life Institute in Geneva more than 25 years ago, and has recently been appointed a Full Member of the Club of Rome. He co-authored a report on the issue for the European Commission, which later on became a book (Stahel & Reday-Mulvey, 1981). More recently, and as a good indicator of how this trend is starting to be considered by top-of-the-class companies, McKinsey&Co., a leading global strategic consulting firm has developed a report on the issue (Ellen MacArthur Foundation & McKinsey&Co., 2012).

As said, one of the main flaws of the prevailing economic model seems to be the implicit hypothesis that greater welfare or well-being is only achieved through greater consumption. Well-being is of course related to consumption (specially for some basic needs such as food, water or energy), but is also composed by many other aspects such as health, culture, education, freedom, social relations and participation, leisure time or the ability to enjoy a healthy environment.

Part of the problem seems to be the fact that one of the ultimate interests of politicians worldwide seems to be to achieve bigger and bigger GDPs, i.e. more and more consumption. In our opinion, it would be preferable if politicians aimed at improving a more comprehensive measure of well-being, which included some of the other components mentioned above. Many academics and politicians seem to agree with this statement, and this is why several attempts to develop broader measures of well-being have been carried out in the last two decades.

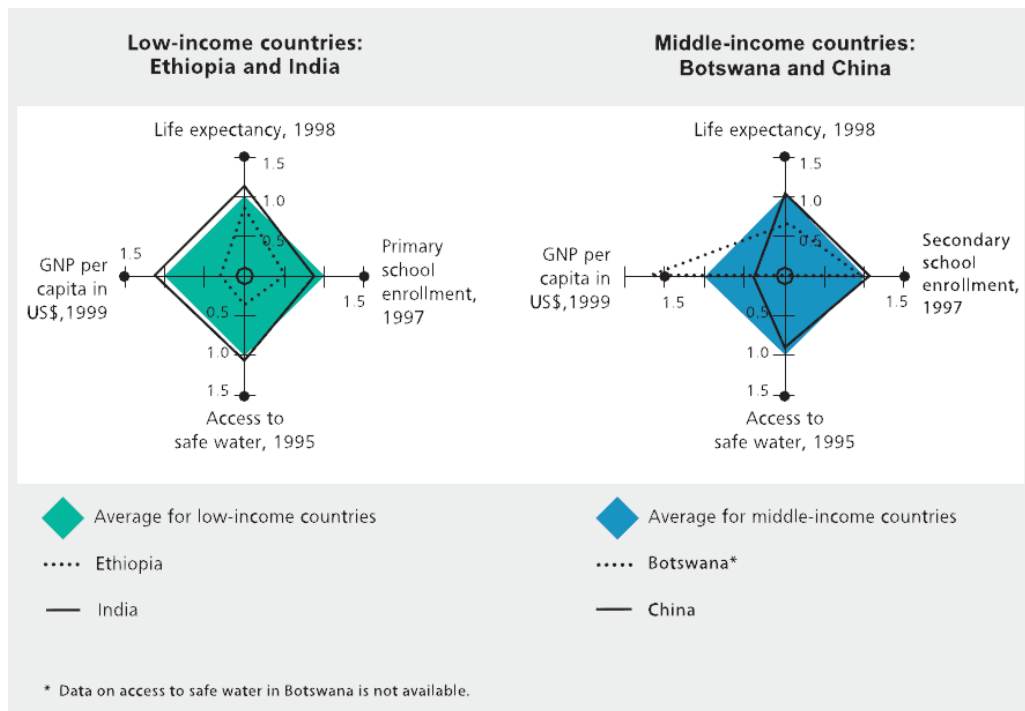
A first one was the Human Development Index, designed by economists Mahbub ul Haq and Amartya Sen in the early 1990s, and published every year by the United Nations Development Programme in its “Human Development Report” (United Nations Development Programme, 2011). It takes into account three aspects of development: income (measured as gross national income per capita), health (measured as life expectancy at birth) and education (measured as a combination of the mean years of schooling and expected years of schooling).

The United Nations Commission on Sustainable Development has also developed a set of comprehensive development indicators, which, in this case, try to be consistent with the Millennium Development Goals¹¹. An update on these indicators can be seen in a brief report published after the discussions on the issue that took place in the United Nations 2012 Earth Summit Rio + 20 (United Nations Commission on Sustainable Development, 2012).

The World Bank developed, in 2004, the Development Diamonds (Subbotina, 2004), where countries’ development measures were represented a very visual and intuitive way, as can be seen in Figure 3.

¹¹ The Millennium Development Goals are eight international development objectives that were officially set in the United Nations Millennium Declaration. All United Nations member states (193 states) and at more than 23 international organizations have agreed to achieve them by the year 2015.

Figure 3: development diamonds for selected countries.
Source: (Subbotina, 2004)



The Organization for the Economic Cooperation and Development (OECD), has also been working on this issue and one of its latest approaches is the calculation of “Your Better Life Index”. In it they aggregate aspects related to material living conditions (housing, income, jobs) and quality of life (community, education, environment, governance, health, life satisfaction, safety and work-life balance). For more information, refer to their web page (OECD, 2013).

Another interesting approach is the Happy Planet Index (Abdallah et al., 2012), in which both an objective (life expectancy) and a subjective (experienced well-being, calculated through polls) measure of well being are calculated and then divided by an ecological indicator, the Ecological Footprint¹². This is therefore an efficiency indicator, which can be interpreted of how much well-being is produced per unit of consumed resources in each country. This index is very interesting because it yields surprising results: the best-positioned countries, according to the 2012 report, were Costa Rica and Vietnam, with Norway being the first western country in position 29 and Belgium, the United States, Denmark or Luxembourg being in the last third of the ranking.

The European Commission together with other institutions such as The Club of Rome and OECD has done some work on this issue, in the framework of the Beyond GDP project (European Commission et al., 2013). The former French President M. Nicolas Sarkozy asked Joseph Stiglitz, Amartya Sen and Jean Paul Fitoussi to create a Commission to work on the issue (Stiglitz et al., 2009). More recently, Professor Carlo Carraro from Fondazione Eni Enrico Mattei is working on similar issues (Carraro et al., 2013).

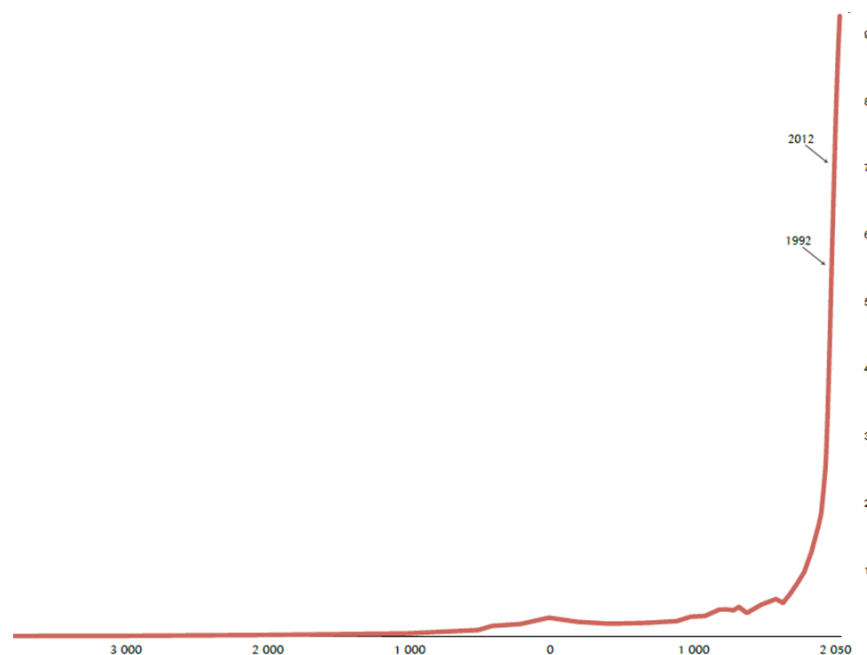
¹² Promoted by WWF as a measure of resource consumption, the Ecological Footprint is a per capita measure of the amount of land (surface) required to maintain a country’s consumption patterns.

Even if the issue that GDP is not an adequate measure of well-being is becoming clear, this capitalist linear economic paradigm seems to be the prevailing one. This is putting important pressure on our planet.

II.2.3. Facts and figures

One of the main reasons behind it is the fact that global population is growing exponentially, as can be seen in Figure 4, where it is interesting to see that in the last twenty years (1992-2012) global population has grown more than in 4000 years of human evolution. It is forecasted to reach 9 billion¹³ by the year 2050.

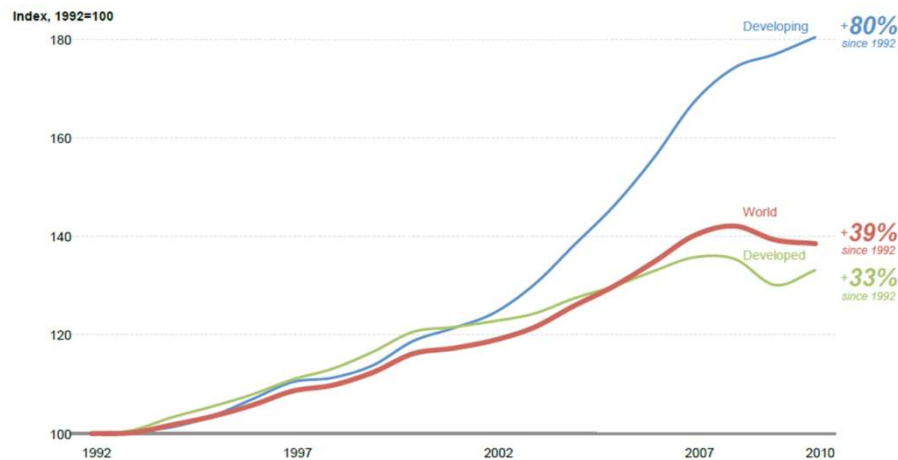
Figure 4: evolution of global population in the last 5000 years, expressed in billions
Source: adapted from the original figure in (United Nations Environment Programme, 2011)



Population is not only growing. Living standards are improving, especially in the developing world, as can be seen in Figure 5 where the evolution of GDP per capita is plotted (even if, as we said above, this indicator does not necessarily reflect improved well-being). Of course this is in principle a good thing, because it tends to reduce global inequality, but as said it is being done following the same economic model as in the OECD countries, with its inherent sustainability problems.

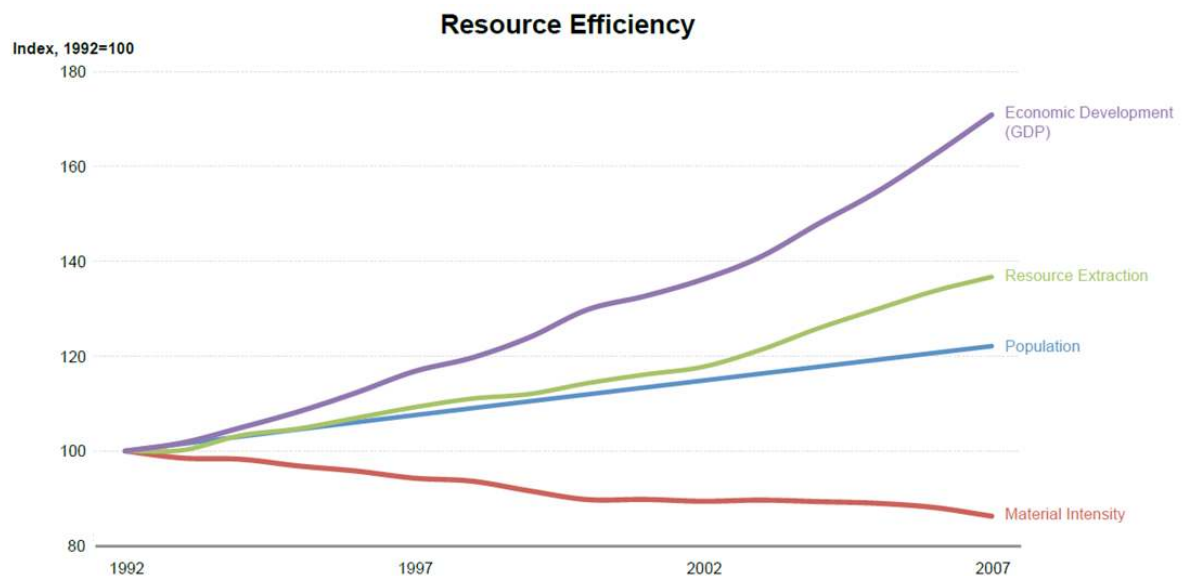
¹³ In this thesis we will consider 1 billion to be 1,000 millions (i.e. 10^9), not 10^{12} as usually defined in Spain.

Figure 5: evolution of GDP per capita in developed and developing countries, and world average
Source: adapted from the original figure in (United Nations Environment Programme, 2011)



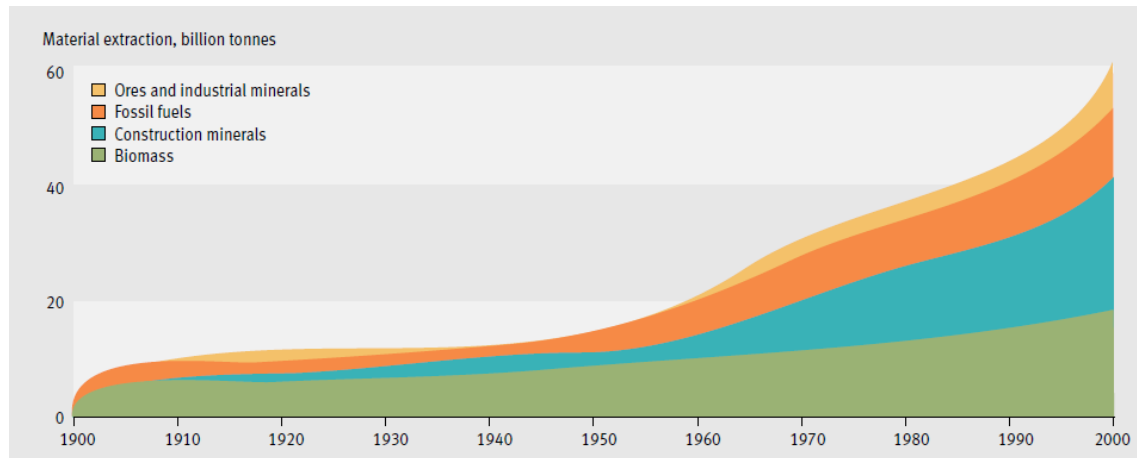
This combined growth of population and per-capita GDP implies a global growth in GDP, as seen in Figure 6. As a favorable point, this economic growth seems to have been taken place with increased material efficiency, what could be due to issues such as the greater share of tertiary sector in many advanced and developing economies, or the improved technology. However, this increased efficiency has not been enough to outpace growth, so the global resource extraction has increased as seen in Figure 6.

Figure 6: evolution of global population, GDP, material intensity and resource extraction in the last two decades. Source: adapted from the original figure in (United Nations Environment Programme, 2011)



For a greater detail level on the global use of resources, in Figure 7, the evolution of global materials extraction in the last century is plotted. Great growth can be appreciated in biomass (partly explained by the increased demand for food and wood), construction minerals (probably correlated with the increasing share of people living in cities and the rising living standards) or fossil fuels (largely due to the large increase of per-capita energy use and global mobility). A first reference to energy, the issue covered in this thesis, is done here (within the biomass and fossil fuels categories), but we will come back to it in greater detail in the next pages.

Figure 7: global material extraction in the last century, billion tonnes
Source: (United Nations Environment Programme, 2012)



Are these growing trends in population, economic activity and use of resources sustainable? This is a very complex debate that falls out of the scope of this thesis. However, it is interesting to briefly mention here the debate between two main lines of thought: Cornucopians and Neomalthusians, the former being aligned with neoclassical economics and the latter with ecological economics.

Cornucopians think that as a resource becomes scarcer, its prices will increase reflecting this scarcity, what will create incentives for technological improvement and substitution of these resources. In other words, the combination of prices and technological improvement will always solve our sustainability problems. One of the main authors in this line of thought was Julian L. Simon, with clear titles such as “Resources, Population, Environment: An Oversupply of False Bad News” (Simon, 1980) and his book “The Ultimate Resource” (Simon, 1983).

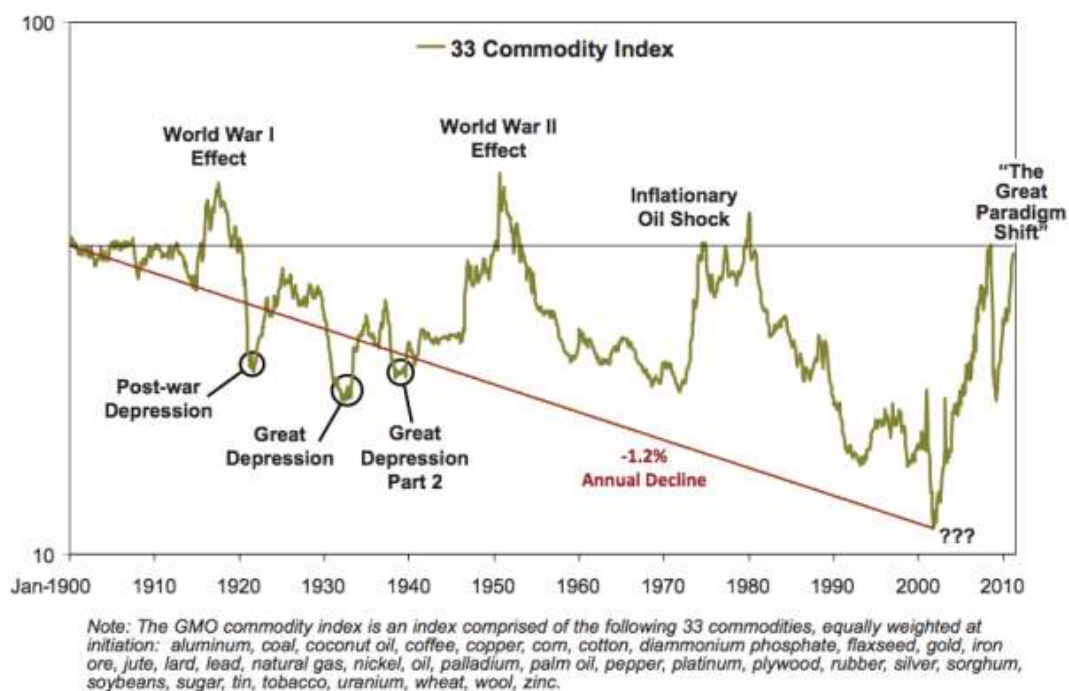
The basic argument of the Neomalthusians is that we will eventually run into the physical boundaries of our planet, because the needs and greed of humans will always grow and the prices of resources do not fully reflect scarcity (so we could *suddenly/accidentally* run out of them). One of the main exponents of this line of thought was the very commented work “The Limits to Growth”(Meadows et al., 1974), recently updated in (Meadows et al., 2004). Another important reference is Paul Ehrlich with explicit titles such as “The Population Bomb” (Ehrlich, 1995).

Both lines of thought have very solid arguments and strong supporters, and both effects are seen nowadays. On the one side, for instance, some fisheries are being exhausted due to overexploitation; on the other side, technological improvement is increasing the efficiency with which we use resources, as seen above. One of the main divergences between both schools of thought is the role of prices. Do prices adequately reflect the scarcity of resources? Neomalthusians would argue that prices do not fully reflect scarcity so we tend to overuse resources and hence prices tend to go up (although not as fast as they should); meanwhile Cornucopians would say that technological improvement would make prices go down as they are used more efficiently. Interestingly, Simon and Ehrlich did a bet on the issue (Tierney, 1990).

In Figure 8, an indicator (imperfect as all indicators) of the evolution of the prices of global resources can be seen, extracted from (Grantham, 2011). Great global events such as the World War I and II, the Great Depression in the early 1930s, the oil shocks in the 1970s or the current global economic crisis can be seen. But it seems clear that the long term trend of the prices of resources was a declining one, probably due to technological improvements as Cornucopians would defend. But since the beginning of the 21st century, this trend seems to be changing. This could point at the fact that technological improvements are not enough to deal with the very large boom in economic growth and resources use that is taking place in the last years, mainly due to the development of large developing countries such as China, India or Brazil¹⁴.

Figure 8: evolution of the prices of global resources, as measured by the GMO Commodity Index.

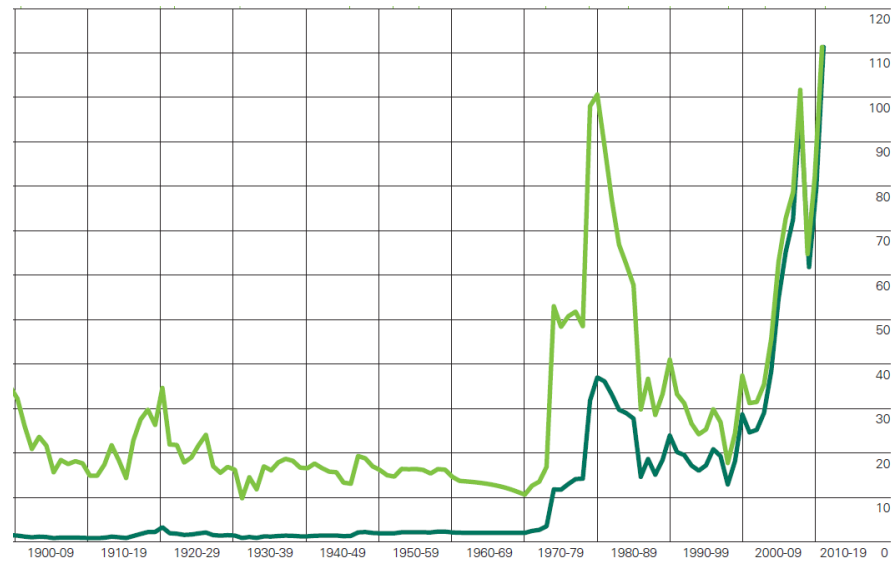
Source: adapted from the original figure in (Grantham, 2011)



In this Figure 8, as happened in Figure 7, the large influence of energy can be seen: oil shocks seem to be clearly reflected, both in the 1970s and in the early 21st century, two periods where oil prices have reached historical maximums, as can be observed in Figure 9, extracted from the "BP Statistical Review" (BP, 2012).

¹⁴ Other authors contradict this fact, saying that prices have fallen (Clayton, 2013). It all depends on how the indexes are calculated: as said, most indicators are imperfect. We do not advocate for any of the two sides in this complex debate. However, we keep the figure from (Grantham, 2011) because it clearly shows the influence of energy prices.

Figure 9: evolution of oil prices since 1900, measured in US dollars per barrel (constant 2011\$ the light green graph, current US\$ the dark one). Source: adaptation from the original figure in (BP, 2012).

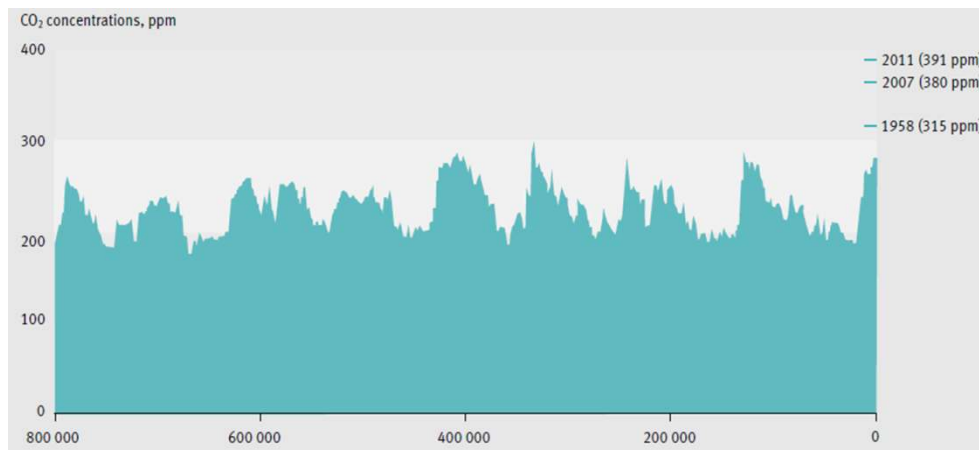


As seen, our energy needs seem to have clear implications on the use and prices of resources, the inputs for our economies. But what about the outputs from our economies, how does energy affect the impacts that we produce in our planet?

Human activity produces several important impacts, such as deforestation, losses of biodiversity, water pollution or releases of chemicals and waste (United Nations Environment Programme, 2012). Even more, it is nowadays becoming clear that one of the main long-term environmental impacts of human activity is the greenhouse effect, which creates global warming and climate change. This is mainly due to the emission of greenhouse gasses (GHG), mainly carbon dioxide (CO₂) and methane (CH₄). Climate change is already affecting us in aspects such as: (i.) more frequent & more intense abnormal atmospheric phenomena, e.g. the Hurricane Sandy in the East Cost of the United States in late 2012; (ii.) ice melting in glaciers or in the Arctic, e.g. ice surface in the Arctic reached historic minimums in summer 2012; (iii.) heat waves, e.g. "According to rankings from four top US, British and Japanese climate research centers, the ten hottest years on record have all occurred since 1998", extracted from (United Nations Environment Programme, 2011). In the future, these and other worrying aspects (e.g. severe droughts and sea level rise, which could cause massive human migrations) are likely to be continuously caused by climate change.

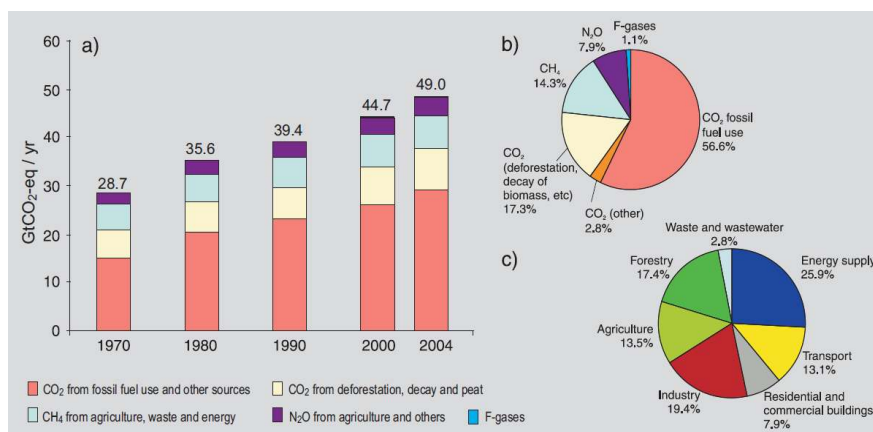
This greenhouse effect is due to the large increase in greenhouse gasses concentrations in the atmosphere that is taking place, notably CO₂. Figure 10 represents CO₂ concentrations from the last 800,000 years. The key point of this figure is in its rightmost side, where the levels of the years 1958, 2007 and 2011 are represented with three lines. What is more, June 2013 brought the announcement of the 400ppm threshold having been surpassed.

Figure 10: atmospheric CO₂ concentrations in the last 800,000 years, in parts-per-million (ppm).
 Source: adaptation from the original figure in (United Nations Environment Programme, 2012).



This large boom in concentrations is due to the increase in emissions, which has more than doubled since 1970, as can be seen in Figure 11. In this figure it can be seen how much of the increase consists on CO₂ released by fossil fuel use, mainly from energy supply, industry, transport and buildings. In other words, our use of energy is one of the main drivers of the large increment in greenhouse gas emissions, which are causing GHG concentrations to reach incredibly high levels (when compared to 800,000 years of our planet's history), what is scientifically proven to cause global warming and dangerous climate change (Intergovernmental Panel on Climate Change, 2007).

Figure 11: Global anthropogenic GHG emissions in terms of CO₂-equivalent¹⁵: a) evolution, b) share of gasses in 2004 and c) share of sectors in 2004 (forestry includes deforestation).
 Source: (Intergovernmental Panel on Climate Change, 2007).



To sum up, many sources and reports point that our current development model presents some large sustainability problems, both from the input and from the output sides of our economy, i.e. both from the resources and from the emissions/waste perspectives. The issue

¹⁵ CO₂ equivalent is used to express, in common mass terms, the masses of different gases with different greenhouse effect potentials (*radiative forcing*). It refers to the equivalent mass of CO₂ that would have created a similar greenhouse effect over 100 years, according to the values defined by the Intergovernmental Panel on Climate Change.

itself that our economy is linear and hence has an input and an output may be one of the reasons, as mentioned above. As a brief reference on how world leading institutions such as the United Nations are rising the alarm about this unsustainability, the “Summary For Policy Makers” of the recently-published “Global Environmental Outlook 5” (United Nations Environment Programme, 2012) starts with a chapter called “Critical thresholds”. This chapter starts with the following text:

The currently observed changes to the Earth System are unprecedented in human history. Efforts to slow the rate or extent of change – including enhanced resource efficiency and mitigation measures – have resulted in moderate successes but have not succeeded in reversing adverse environmental changes. Neither the scope of these nor their speed has abated in the past five years. As human pressures on the Earth System accelerate, several critical global, regional and local thresholds are close or have been exceeded. Once these have been passed, abrupt and possibly irreversible changes to the life-support functions of the planet are likely to occur, with significant adverse implications for human well-being. (...)

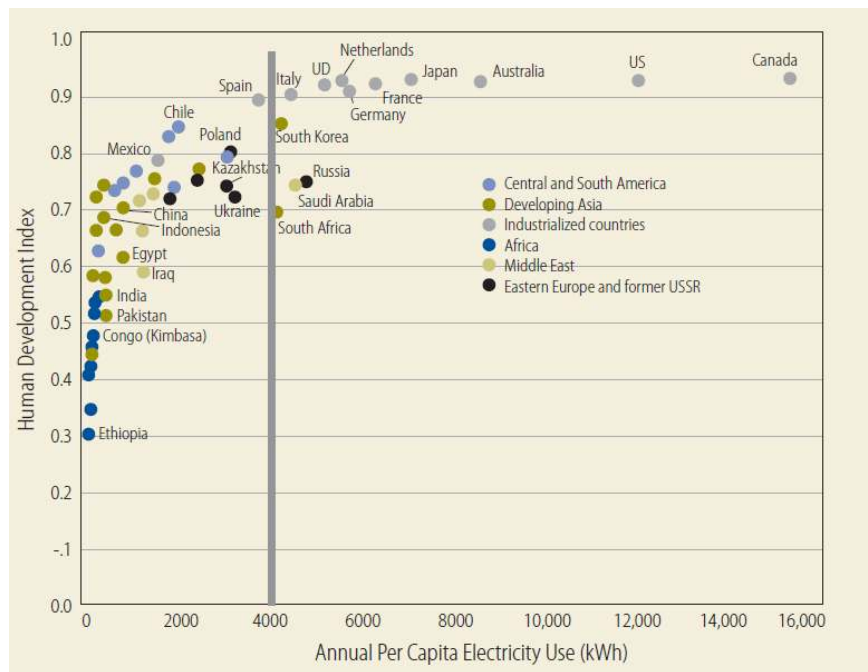
As briefly introduced, the way we use energy is a large part of the problem, being behind issues such as the large increments in resource extraction, commodity prices, or greenhouse gas concentrations. Even more, our energy model has some other important sustainability problems. In the next section, we will review some of the main aspects of the unsustainability of our current global energy model.

II.3. ENERGY SUSTAINABILITY

II.3.1. Global trends

Energy is a key input for human activity and well-being. Without the energy we consume in the food we eat, our bodies wouldn't be able to perform any physical activity; and without energy, our societies wouldn't be able to carry out any economic activity. If the energy supply for a society is not ensured in the long term and at the desired quality, the society's economic activity and development will be at stake. For a good review of energy as a key input for economic activity, refer to (D. I. Stern, 2010). In Figure 12 an insight on this issue is shown: a development indicator (the above-introduced Human Development Index, HDI) is plotted against the per capita electricity consumption for selected countries. In this graph, it can be seen that development needs some minimum energy consumption, but that at high levels greater consumptions do not ensure bigger development. A vertical line at the value of 4000 kWh/(year·person) indicates the approximate threshold where HDI starts its plateau, meaning that advanced economies need at least that level of energy use (Deutch et al., 2009). We will come back to this issue in the next pages.

Figure 12: Human Development Index vs. per capita electricity use (in kWh) for selected countries
Source: (Deutch et al., 2009)



According to The World Bank (The World Bank, 2013), in the last five decades total human population and global average gross domestic product (GDP) per capita have more than doubled: population has grown from 3.04 billion people in 1960 to 6.89 billion in 2010, and average per capita GDP has evolved from 2378 US\$ to 6009 US\$ (constant 2000 US\$). Combining both effects, total GDP is now almost six times larger, having passed from 7.23 trillion US\$ in 1960 to 41.43 trillion US\$ in 2010 (constant 2000 US\$). In other words, human economic activity is now almost six times greater than fifty years ago. Despite any improvements in energy intensity that have been achieved, the consequences of this large growth of activity upon world energy consumption can be anticipated.

The world total final energy demand has increased from 195.6 EJ¹⁶ in 1973 to 363.3 EJ in 2010, according to the International Energy Agency (International Energy Agency, 2012b). This has made total primary energy supply (TPES), which is a measure of the real amount of primary energy used in the world, to grow from 255.7 EJ in the year 1973 to 532.4 EJ in the year 2010, according to the same source. The amount of energy used by human activity has more than doubled in the last thirty-seven years. Following the same source (International Energy Agency, IEA), total CO₂ emissions from energy use have almost doubled, passing from 15.6 GtCO₂ in 1973 to 30.3 GtCO₂ in 2010.

Economic activity is now six times larger but primary energy use has “only” doubled. This is because energy efficiency in our economies has largely improved, mainly due to technological improvements that were in part explained by growing energy prices. This aspect of our energy

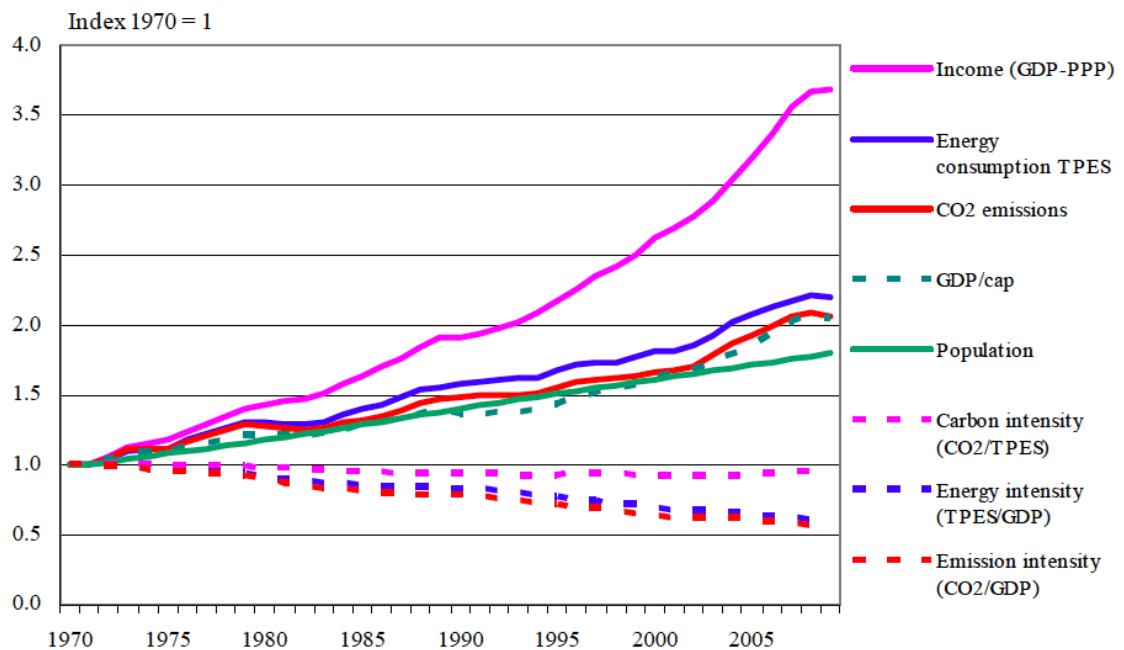
¹⁶ EJ: ExaJoules, i.e. 10¹⁸ Joules, one million TeraJoules

system seems to have followed the evolution that Cornucopians would anticipate, but of course this does not imply that the same trend will be kept in the future.

Energy use and CO₂ emissions have evolved in parallel between 1973 and 2010 (both have roughly doubled). This is because the global carbon intensity of our energy use has been almost constant: see for instance the Energy Sector Carbon Intensity Index (ESCI) developed by the IEA (International Energy Agency, 2013a), which has remained almost constant since the early 1970s. This has been due to greater shares in global energy supply of both natural gas (the least carbon-intensive fossil fuel) and coal (the most carbon-intensive one), in detriment of oil. Both effects seem to have balanced out and kept carbon intensity in energy almost equal.

These main trends can be seen in Figure 13. The values may not exactly correspond to the ones we have introduced (due to statistical differences or slight methodological changes), but the global picture and the main trends are the same.

Figure 13: global evolution of population, income (GDP in PPP¹⁷), primary energy consumption (measured as TPES), CO₂ emissions and the associated intensities.
Source: (International Energy Agency, 2009a)

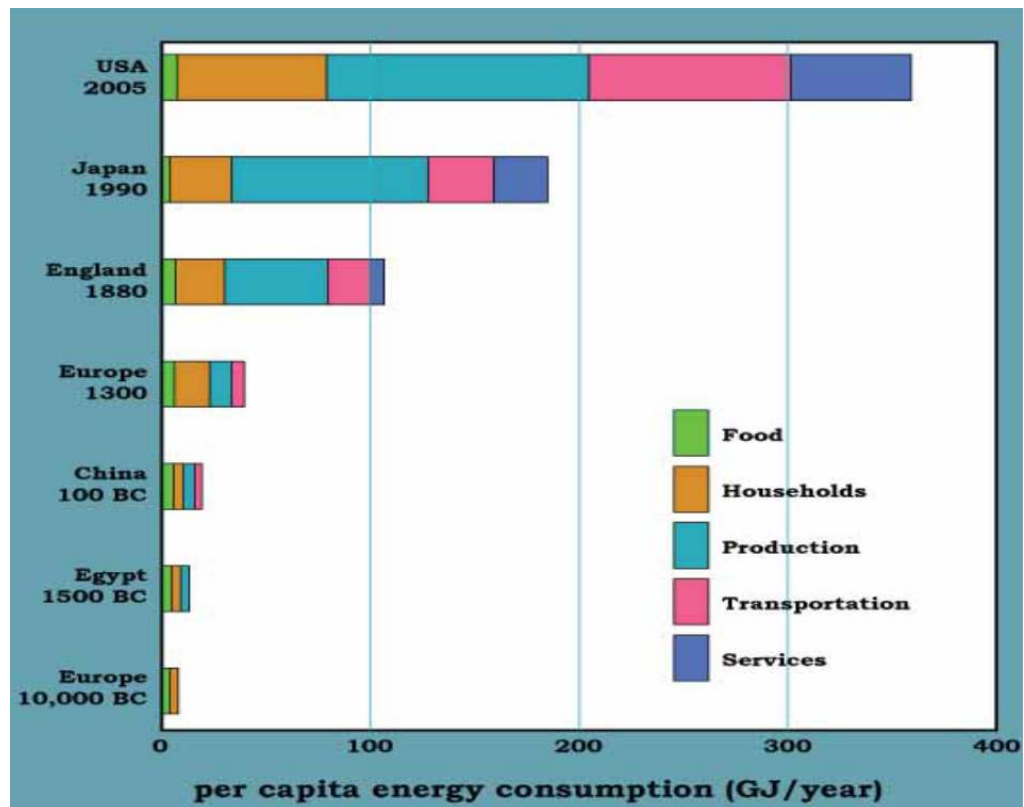


It is clear that despite the improvements in intensities, the growth in population and income have been so large that have made global energy use and emissions grow significantly. But let's look at this in greater depth, trying to get some insights about the underlying facts. Why has our energy use grown this much?

¹⁷ Purchasing Power Parity (PPP) is an improved way of measuring GDP, which normalizes for inflation and relative costs between countries, apart from exchange rates (what is normalized in usual GDP calculations). It considers how much money is needed to purchase the same goods or services in two nations, and then uses it to compute an implicit exchange rate.

As previously stated, it is related, but not only, to population or income growth. Other important issues, such as lifestyle changes (associated with economic growth), have played a key role. In Figure 14, extracted from (Smil, 2013a), the per capita energy use is represented in different historic moments and divided among main energy uses. In it, some useful insights on the history of Mankind from the energy perspective can be obtained. In the prehistoric times, energy was mainly used for basic human needs: food and shelter (i.e. for heating purposes in households). Then, other uses appeared associated with changing life conditions, such as energy used for production (manufacturing of goods) and transportation. Bigger houses and buildings in the Middle Age caused energy used in households to increase. In this first era, biomass was the main energy source. The Industrial Revolution in England during the 19th century was an important turning point in energy use, as in many other aspects of our civilisation. Industrial activity was boosted and large-distance transportation of goods and people became available, thanks to the widespread use of coal-fired steam engines. The first major *energy transition* (using Vaclav Smil's expression) had begun, where coal was increasingly used, substituting biomass. Since then, advanced economies have started a process of *tertiarisation* where the services sector played a significant role in the economy, causing consumption from this sector to grow. Another great development has been the large increase in mobility, mainly thanks to cars and planes, where intercontinental travel has become easy, fast and very common. In addition, a significant share of this mobility is carried out in very inefficient modes such as very big cars being used for a single person. The transportation sector is nowadays mainly dependent on oil, being this the reason behind the large increases in oil demand that have taken place in the last decades. Some believe that two other major energy transitions have taken place: after biomass to coal, then coal to oil and lately, oil to natural gas, which might be the *bridge fuel* to a carbon-free energy source in the future. However, official statistics, which reflect recent developments such as increased coal use in developed countries, seem to offer contradictory evidence on this issue (Smil, 2013b).

Figure 14: energy consumption per use and per capita (GJ/year-person) in different historic moments.
 Source: (Smil, 2013a)



Looking at the future, when the concern may be to ensure development and human wellbeing in the long term, the relevant question is not only *how much* energy is consumed, but *how* it is consumed. Citing (United Nations Development Programme et al., 2000):

Energy produced and used in ways that support human development over the long term, in all its social, economic, and environmental dimensions, is what is meant in this report by the term sustainable energy. In other words, this term does not refer simply to a continuing supply of energy, but to the production and use of energy resources in ways that promote—or at least are compatible with— long-term human well-being and ecological balance.

So far in this section, we have given some figures about the large growth in energy consumption, its associated emissions, and the very different levels of per-capita energy use in different countries. In the previous section, we have also introduced some issues such as how energy prices are increasing, or how a significant share of the rate of extraction of natural resources corresponds to energy. These facts and many others, which are recognised by the most reputed international organisations (e.g. the United Nations, the World Bank, the International Energy Agency or the World Energy council, just to cite a few), point out at the lack of sustainability of our current global energy model. Citing Pierre Gadonneix, Chairman of the World Energy Council, in the presentation of a 2012 report by his Institution called “World Energy Trilemma” (World Energy Council, 2012):

Our energy systems are not sustainable. All countries are experiencing growing difficulties in securing their energy supply as they engage in a cleaner growth pattern to deliver social equity (...)

A good discussion on the lack of sustainability of our current energy model from the *three pillars* perspective (introduced in section II.2.1 of the present chapter) can be seen in (Pérez-Arriaga, 2003). A brief assessment is done now from the more complete *capitals* point of view (which was also briefly introduced in section II.2.1).

II.3.2. Energy sustainability: natural capital perspective

Let's start by some insights on the natural capital perspective of energy sustainability. As introduced above, natural capital comprises all natural resources (including fossil fuels), but as well other issues such as biodiversity or the integrity of biosphere (climate change or air quality are important aspects in this issue). An intuitive approach to energy sustainability (from the strong sustainability point of view) would be to keep this natural capital growing or at least non-diminishing.

According to (International Energy Agency, 2012b) the world total primary energy supply (TPES) in 2010 depended largely on non renewable primary sources (27.3% coal, 32.4% oil, 21.4% natural gas, and 5.7% nuclear, totalising 86.8%). In addition, world total energy demand is projected to grow significantly in the future: according to the central scenario (New Policies Scenario) in the World Energy Outlook 2012 (International Energy Agency, 2012a), it will grow 35% from 2010 to 2035, when it will reach 720 EJ. And in that year, according to the same scenario, the share of renewables in the world's energy mix will be less than 18% and fossil fuels will represent 75.5% of the world's TPES. The gap between these will correspond to nuclear energy (6.6%). This fact points out to a future scenario of growing energy demand, largely dependent on finite resources that are being used without replacement, what implies a clear reduction of natural capital. These fossil fuels could even be eventually depleted (from a Neomalthusian perspective). The most paradigmatic case of energy resources depletion could be oil, where a good review can be seen in (Marzo i Carpio, 2010). For a comprehensive review on non-renewable energy resource estimates see (Michael, 2012). Even renewable resources may be limited: (Moriarty & Honnery, 2011) justify, based on a strong sustainability perspective, that there is a maximum level of renewable energy that can be extracted from nature in a sustainable way. One of the key information sources on proved energy reserves¹⁸ is the BP Statistical Review (BP, 2012). For other estimates of energy resources potential see (Mercure & Salas, 2012); for a special focus on renewables worldwide refer to (International Renewable Energy Agency, 2013), and for the potential of renewables in Spain a good reference is (Greenpeace, 2005). Another perspective that seems to point to the lack of sustainability of our current energy model from the natural capital perspective is the negative evolution of the so-called *energy return on energy*

¹⁸ It should be noted that, when talking about fossil fuels or any other minerals, *reserves* and *resources* are different concepts based on their geologic certainty and economic value. *Resources* are less certain (it is less sure that they would be technically or economically feasible to extract), whereas *reserves* are considered to be valuable and legally, economically and technically feasible to extract.

invested, EROEI, which measures how much energy is obtained per unit of energy used or invested in obtaining that same energy¹⁹ (Hall, 2011).

The natural capital is not only decreasing due to resources' depletion, but also due to the environmental impacts of energy use on the biosphere. Burning fossil fuels releases gases to the atmosphere that cause local, regional and global problems. Of these, the most worrying problem is climate change which, according to the IPCC (Intergovernmental Panel on Climate Change, 2007), is largely caused by energy-related carbon dioxide emissions. These have almost doubled between 1971 and 2010, what has made atmospheric carbon dioxide concentrations to grow from 326.3 ppm (parts-per-million) to 389.9 ppm in the same years, following data from one of the reference measuring points, the Mauna Loa observatory in Hawaii (US Department of Commerce NOAA ESRL, 2013). In June 2013, they have surpassed the 400ppm threshold. As seen in Figure 10, these values are well above the maximum levels reached in our planet in the last 800,000 years, where concentrations have never gone above 300 ppm.

What is more, global carbon emissions are projected to continue growing as fossil fuel burning is projected to continue: citing (International Energy Agency, 2012a), in the New Policies Scenario (the central scenario of the World Energy Outlook, which represents a business as usual evolution), "energy-related CO₂ emissions rise from an estimated 31.2 Gt in 2011 to 37.0 Gt in 2035, pointing to a long-term average temperature increase of 3.6°C". This is well above the 2°C value that most climate scientists agree to be the critical threshold that should not be surpassed if catastrophic climatic change is to be avoided. Hence this baseline scenario takes us towards catastrophic global warming which will severely affect our biosphere, therefore decreasing natural capital. Mainstream references on climate change are the Assessment Reports by the IPCC, either the Fourth (Intergovernmental Panel on Climate Change, 2007) or the Fifth, which will be published in late 2014.

Short-lived climate forcers (black carbon, methane or tropospheric ozone) are other important energy-related causes of climate change that have increased in the last years (United Nations Environment Programme, 2012). Black carbon is produced by the incomplete combustion of fossil fuels or biomass. Methane is released from several natural and human-related sources, some of them coming from the energy sector, such as fugitive emissions from the complete natural gas value chain, coal and oil production, biomass combustion, or from large hydro reservoirs where decomposition of accumulated organic matter takes place. Tropospheric ozone is produced in the atmosphere when ozone precursors react in the presence of sunlight; these ozone precursors, notably nitrogen oxides (NO_x), carbon monoxide (CO) or volatile organic compounds (VOCs), are produced in energy-use processes, such as combustion engines.

However, climate change (produced by the emissions of GHGs or other climate forcers) is not the only environmental impact of our energy use. Also local and regional pollution, which negatively affect air quality in certain areas, most notably in big cities and industrial areas, with

¹⁹ For example, to extract oil from an oil well, energy must be used to drill the well; to obtain energy from a hydro reservoir, energy must be used to build the dam; to use the energy contained in the wind, energy must be invested to build and install the wind turbines.

gasoline and diesel engines, coal-fired power plants, and other combustion processes being amongst the main sources. Of these, the most worrying ones are particulate matter and ozone (produced by its precursors), as will be seen next when talking about health effects.

The emissions of nitrogen and sulphur oxides (NO_x and SO_x) also affect the atmosphere, and many of them come also from the energy sector, especially from coal-fired power plants and combustion engines. SO_x gases are becoming less of a concern nowadays thanks to effective regulations on these issues, such as acid rain control measures or fuel standards, but there is still work to be done regarding NO_x .

However, not only fossil fuels create environmental impacts and decreases in natural capital. Nuclear energy has some inherent risks such as accidents or nuclear waste. Concerning the first, the Fukushima accident in Japan in 2011 being the most recent example, radioactivity represents a severe worsening of natural capital in the area, which can cause cancer to exposed populations (Ten Hoeve & Jacobson, 2012) or can negatively affect the food chain, through for example high radioactivity levels in seafood (Tabuchi, 2012). Concerning nuclear waste, it remains an unsolved issue. Long-term storage, until a significant decay in the level of radioactivity of residues is achieved, is the most common solution nowadays. A review of the quantity of radioactive waste produced and management approaches for most developed countries is summarised on a yearly basis (International Atomic Energy Agency, 2013). Of course, storing radioactive materials for many years in a natural reservoir is a way of making the natural capital in the area to decrease.

Renewable sources of energy can create environmental impacts and decreases in natural capital too. Citing just a few impacts, badly managed biomass and biofuels use can yield to deforestation and land use changes, and may require significant amounts of water. Hydropower can alter the ecosystems in rivers, can produce methane emissions due to biological decomposition processes, can significantly affect water availability, and can involve important land use changes due to the flooding of valleys needed to build these power plants. Some types of solar energy or wind power may require significant amount of land (which is also a problem with biomass or hydro) or could affect ecosystems (such as bird life in the case of wind power). A comprehensive review on the impacts of renewables can be seen in (Smil, 2003).

Last but not least, another issue associated with renewables is becoming important in the last years: rare earths. These are chemical elements that are key for producing modern electronics and renewable energy technologies. Most of their global supply comes from China, and their level of geological abundance is it still unclear. Hence the eventual supply shortages for future generations or even exhaustion may be an issue from the natural capital perspective.

As a conclusion, all types of energy use can cause some level of decrease in natural capital, be it due to resources' exhaustion or environmental impacts. Of course, some energy types are preferable to others. A more detailed discussion on this issue, beyond the brief introduction carried out here, is out of the scope of this thesis.

II.3.3. Energy sustainability: social and human capital perspective

As introduced above, social capital comprises all aspects regarding people's social well being such as community relations, political participation or strong institutions. Human capital includes the personal and intellectual development of people, including health, leisure, freedom, training, culture or education. Both approaches will be treated together in our analysis because they are related from the perspective of energy sustainability. Our energy model can have several negative impacts in these capitals. Let's start looking at health impacts²⁰. As said above, some combustion processes produce local and regional pollution that worsens air quality, which in turn can affect health. This is particularly important in cities or industrial areas, where people walk in the street very close to pollution sources such as diesel engines from old cars. The types of local and regional pollution that mostly affect human health are particulate matter (PM) and tropospheric ozone, which are estimated to cause almost 5 million premature deaths per year in the world (Anenberg et al., 2010). This is a huge quantity and should be put in the adequate context: the AIDS pandemic, in its worst years in the early 2000s, caused an estimate of 3 million deaths per year. A very recent study from the World Health Organisation for the European Commission updates the scientific evidence on the issue, confirming their adverse effects and advising the Commission to toughen the legal requisites on air quality (World Health Organisation, 2013).

Climate change also has the potential to cause large health impacts, derived from the wider presence of tropical diseases, droughts, reduced agricultural productivity, or extreme climatic events, amongst others. Radioactivity from nuclear accidents or waste could potentially cause different types of cancer. Lastly, but certainly not less importantly, inadequate use of traditional forms of energy (very related to energy poverty, of which we will speak later) causes health problems for a large share of humanity: respiratory disease from inefficient and badly-ventilated biomass combustion processes is a very common health problem in the developing world, especially for women and children, who use it for heating, cooking, lighting or productive purposes.

Energy poverty can also have important negative implications for education, which is a form of human capital. Energy access can improve access to education, which in turn increases human capital. More on this will be said in the next pages. Social institutions, democracy, political participation or peace itself are other aspects of social capital that can be negatively affected by our energy model. There is some statistical evidence of the presence of weaker democracy and institutions in fossil fuel-rich countries. This is due to the incentive that governments in these countries have to become more authoritarian in order to extract rents for private enrichment. Some authors put this as the "resource curse" (Auty, 1993; Mehlum et al., 2006; Robinson et al., 2006). For a particular case, that of a fossil energy resource (oil), refer to

²⁰ Sometimes, in the literature, health impacts are treated under the natural capital perspective. However, we will consider them as part of human capital.

(Foreign Relations Committee of the US Senate, 2008; Sala-i-Martin & Subramanian, 2003). In these countries, the administration of the enormous amounts of wealth that can be received from fossil fuel exports can become a challenge: if inadequately done, which is usually the case due to the weak institutional framework, they can create growing inequality, social unrest and political instability. Wars and incited institutional weakness, derived from interests to control energy resources, are also common problems today that negatively affect social capital. All of these issues have important geopolitical consequences for which an interesting reference, mainly dealing with the 1970s oil crisis, is (Chevalier, 1975). We believe that these problems could be mitigated if we had an energy system based on widely available energy resources, such as renewables.

II.3.4. Energy sustainability: economic capital perspective

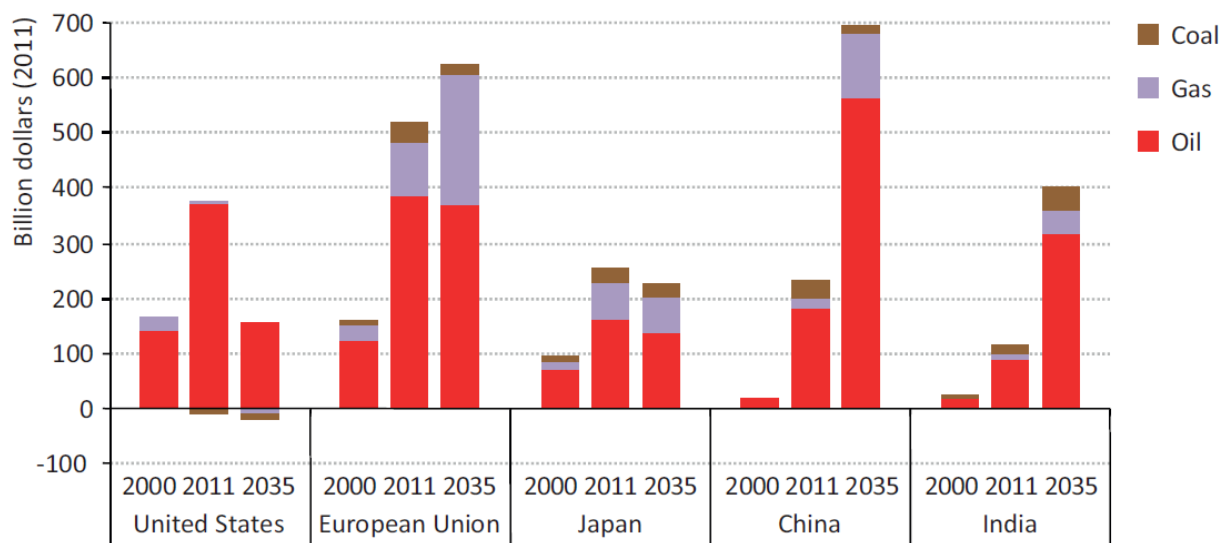
As said above, economic capital includes all types of economic assets, some of them being money, buildings, infrastructure, and investment vehicles such as debt or shares. From this economic capital perspective, on the one hand, energy is a very relevant input for our economies, allowing us to produce goods and services and to increase economic capital: we would not pay such high prices (as we do) for a good that was not as useful. On the other hand, however, the fact of our energy model being based on finite resources implies great challenges. The global demand for fossil fuels is booming, as seen above. Their global supply is becoming tight, due not only to geological, technological or environmental reasons, but also to geopolitical ones: these resources are largely concentrated on a few countries, with the ensuing geopolitical pressures (Correljé & van der Linde, 2006) and oligopoly behaviours (Adelman, 1986; Toman, 1993).

These facts have put much pressure during the last years on the prices of primary energy. According to the BP Statistical Review mentioned before (BP, 2012), crude oil prices measured as the Brent dated barrel price in constant 2011 US dollars, which since the mid eighties had been around 30\$/barrel, have been over 60\$/barrel since 2006 and over 100\$/barrel in 2008 and 2011. In nominal terms they have never in history been as high as now (refer to Figure 9 above). What is more, following the same source, something similar has happened globally with coal and natural gas (except in the US where shale gas seems to have changed this trend, for now).

This has large economic consequences for producing and consuming countries. The type of challenge that it represents for producers was mentioned before. For consuming countries, higher prices imply higher expenditures on energy (unless consumption is reduced, which in a key economic input such energy is not easy in the short term). This could represent large wealth transfers to exporting countries. According to (Petroleum Economist, 2010), the total expenditure in oil in the three years 2007, 2008 and 2009 for selected countries was: 812 billion \$ (bln\$) for the United States, 183 bln\$ for Germany, or 98bln\$ for Spain. In the case of Spain, this means almost 10% of our GDP, spent in three years. The income in the same years for selected producing countries was: 585bln\$ for Saudi Arabia, 440bln\$ for Russia or 202bln\$ for Iran.

These expenditures are forecasted to grow even more, mainly due to the foreseen increases in consumption and in prices, notably for oil. This can be seen in Figure 15, where the expenditures, for key importing regions and for the three types of fossil fuels, are plotted for their values in 2000, 2011 and 2035 (in this case as forecasted in the business-as-usual scenario, the New Policies Scenario, of the latest World Energy Outlook). The large economic impact of these expenditures for Europe, China or India can be anticipated.

*Figure 15: spending on net imports of fossil fuels in the New Policies Scenario.
 Source: (International Energy Agency, 2012a)*



As an intuitive idea of what these amounts represent, the following citation extracted from (Luft, 2008) is useful²¹

At \$100 oil, OPEC could potentially buy Bank of America in two months worth of production, Apple Computers in two weeks and GM [General Motors] in just 6 days. It would take less than three years of production for OPEC to own 20% (which essentially ensures a voting block in most corporations) of every S&P 500 company.

Focusing on energy importing countries such as most European ones, where this thesis focuses, we could ask the following question: what economic impacts do these expenditures create? How do high energy prices affect their economies? When importing countries spend growing shares of their wealth in energy, this implies a reduction in their available income for investment or consumption, and it worsens their current account balances and affects their currency. In addition, as energy is a key input in their economies, growing energy prices are passed to the rest of the economy, increasing inflation and hence reducing competitiveness. The reduced investment also implies that less economic capital is left for future generations. For a review on direct and indirect pass-through effects of energy prices to the rest of the economy,

²¹ Of course these facts may no longer hold, because of variations in the stock market or oil production levels (among other factors) that may have taken place since 2008. It is reproduced here only for illustrative purposes. We do not necessarily agree with this view, which seems to perceive OPEC as a risk.

and how wage and price flexibility or monetary policy could counteract the negative effects, refer to (Task Force of the Monetary Policy Committee of the European System of Central Banks, 2010).

For countries such as the United States or those in southern Europe, whose economies are very based on consumption, sudden price spikes have clear implications in the level of economic activity: if more has to be spent in buying foreign energy, less income is available for spending in local goods and services, reducing GDP and increasing unemployment. This happened in the 1970s oil crisis (Toman, 1993) and is believed by some authors to be one of the underlying causes of the current crisis (Hamilton, 2009).

In the near future, according to the latest issues of the World Energy Outlook, energy prices are forecasted to keep growing as seen before. In this context, (Lutz et al., 2012) forecast that the associated negative global macroeconomic effects are comparable to those of the 2008 financial crisis.

The United States Chamber of Commerce, through the Institute for 21st Century Energy, calculates an index of energy security risk for the United States and for the global economy (Institute for 21st Century Energy, 2012a, 2012b). In these, a large importance is assigned to economic consequences of energy dependence. Interestingly, the economic risks are not only derived from absolute price levels and expenditures, but also to volatility, which implies greater uncertainty for many economic agents in their costs and in valuing their investments, which increases risk premiums and financing costs.

Energy dependence is an issue for importing countries not just due to these expenditures, but as well from the perspective of physical supply interruptions, given that supply shortages can significantly damage the possibility of a country to sustain its economic activity. Good references on this are (Labandeira & Manzano, 2012; Le Coq & Paltseva, 2009; Löschel et al., 2010; Scheepers et al., 2007; Winzer, 2012).

Also important economic costs of our energy model are those derived from climate change which, as said, is being largely caused by the way we use energy. The well known Stern Review on The Economics of Climate Change estimated that, in a business as usual scenario (where average global temperatures reach around 5-6°C over pre-industrial values), the costs of climate change could imply a yearly global welfare loss equivalent to a 5% to 20% reduction in global GDP during the next two centuries (N. Stern, 2006).

II.3.5. Energy sustainability: equity perspective

Finally, looking at the top vertex of the sustainability pyramid, the current world energy model is unsustainable from the equity perspective because, according to the last World Energy Outlook 2012 (International Energy Agency, 2012a), almost 2.6 billion people in the world rely on traditional biomass for cooking, and almost 1.3 billion do not have access to electricity, the most versatile modern form of energy. And in 2030, according to the same source, unless adequate additional policies are put in place (i.e. according to their reference case *New Policies Scenario*), 2.6 billion will still be without advanced cooking facilities and 1 billion will still lack access to electricity. It should be noted that universal access does not necessarily guarantee

equity in access to energy, which refers to a *fair* access to modern energy sources to all humans, both in current and in future generations. It is of course a necessary condition, but not a sufficient one.

The lack of access to modern energy for a large share of human population has important consequences for the wellbeing and economic development of these people. As we saw, energy consumption is inextricably linked with economic growth (D. I. Stern, 2010), even if this may not hold for countries in advanced stages of economic development, where growth is driven by high added-value activities such as services: refer to (D. I. Stern & Kander, 2012) for a case study on Sweden.

A clear example of the relation between access to modern energy sources and development was seen above, in Figure 12. Ironically, these energy access problems exist even in countries with large energy reserves, with huge differences in energy use and access between rich people in large cities and poor people in rural areas. Access to energy presents the same inequality patterns as does access to other forms of wealth, what is a great obstacle for the development of many people worldwide.

Energy poverty can also have important negative implications for education (hence this could also be addressed under the perspective of human capital). For instance, many NGOs and International Organisations are nowadays working in improving energy access in rural areas in developing countries²². One of the top priorities in these actions are schools, because in many cases children have to be working in the familiar activity (e.g. agriculture) during the day so they can only attend classes when it is dark. Energy access guarantees electricity, which is useful for lighting, computers or Internet connection, all of them important for educative purposes.

Since 2004, the International Energy Agency publishes (in its annual World Energy Outlook) an Energy Development Index which tries to measure the transition to modern use of energy in different countries in a better way than just simplified indicators such as the electricity use per capita. A general improvement is observed, although much work remains to be done. According to the same source, in order to achieve universal access to electricity and clean cooking facilities, an annual global investment of around 50 billion \$ would be needed until 2030, being most of it for electricity access. Interestingly, these figures are very small compared to the total annual investment in energy infrastructure that will be required: it will represent around 3% of overall investment needs. Even though, this requires an additional policy effort over business-as-usual: according to (International Energy Agency, 2011) only 9 billion \$ were invested globally in 2009 and their central scenario forecasts a value of around 14 billion \$ until 2030, clearly under the needed investments.

The important relation between modern energy and development was made clear by Ban Ki-moon, the Secretary General of the United Nations, when he declared 2012 as the International Year of Sustainable Energy for All (United Nations, 2013). Other interesting

²² Energía Sin Fronteras is one of the key NGOs in Spain working in this field. The author of this thesis has been very involved in this NGO during his PhD. His advisors are also very implicated in these issues.

references on the issue are (International Energy Agency, 2010a; Practical Action, 2013; World Energy Council, 2012).

The great asymmetry between countries in the access to modern energy, and in per capita energy consumption allows us to state that intragenerational equity is not achieved by our current energy model, hence this is another aspect of its current lack of sustainability. What is more, we think that intergenerational equity could not be being respected either: we could be depleting energy resources (e.g. declining EROEIs), implying that future generations will not be able to enjoy them as we do now (although of course this may not be true as new resources could be found or used, and as technology improves). In addition, many other aspects of our energy model create impacts that will be born by future generations, being climate change the first concern.

In conclusion, we could say that our current energy model is not equitable neither from the intragenerational nor the intergenerational perspective, what is another element of unsustainability, according to the conceptual definition of sustainability that we are using.

II.3.6. Energy sustainability: conclusion and outlook

As has been seen, our global energy model seems to be unsustainable from the natural capital, social capital, human capital and equity perspectives. From the economic capital perspective, energy allows us to produce economic capital (which is a positive aspect), but it also has negative implications. A very detailed and clear discussion on the complex situation of the current world energy model can be found in (Smil, 2003), book whose title “Energy at the Crossroads”, is a good anticipation of its contents. Another interesting and more recent reference on the social, economic and institutional challenges of our current energy model, from a more theoretical perspective, is (Peura, 2013).

Looking at the future, the International Energy Agency foresees an energy system that, unless modified by ambitious policy action, will see strongly-growing demand (mainly from developing countries, while industrialized countries stabilize), largely relying on fossil fuels, with similar levels of inequality in access to modern energy, and which will clearly surpass the emissions limits that the scientific community has established in order to keep climate change in manageable magnitudes (International Energy Agency, 2012a). Strong policy action is needed because our energy system is clearly unsustainable and, in the business as usual scenario, it will remain to be so. This represents a major threat for economic activity and human wellbeing in the long term. The Spanish case is not an exception, as we will see in the next section.

II.4. ENERGY SUSTAINABILITY IN SPAIN

II.4.1. Main trends of energy supply and demand in Spain

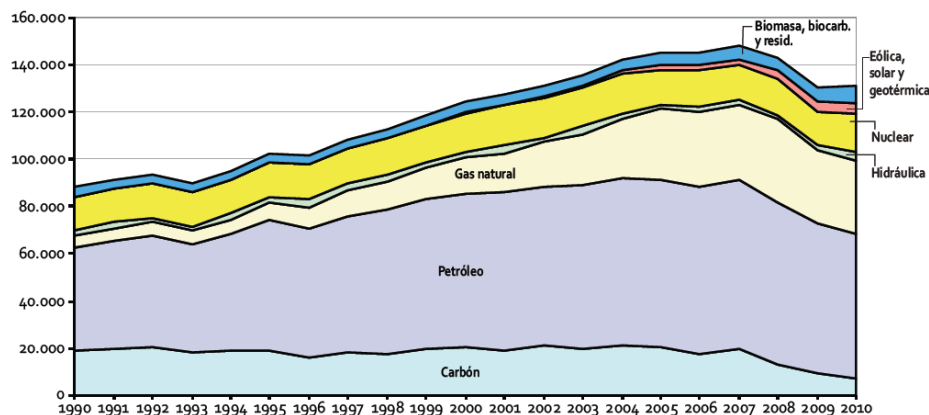
We will now narrow our focus to the energy unsustainability characteristics in Spain and similar countries (most western European countries and the United States). In these countries, modern sources of energy are widely accessible, hence energy poverty is less critical, and it is limited to low-income people who may have trouble in warming their households in cold winter months. In (Moore, 2012) a description of the United Kingdom case is provided. Social issues caused by energy, such as political or institutional unrest, are not as important as in large exporting countries (although the problems in exporting countries could be considered to be partly due to the energy consumption of importers). Human capital aspects (e.g. lack of education due to lack of modern energy) are neither a big issue in these countries as they are in developing ones. Hence in these countries the main concerns are from the economic and natural capitals perspective, as well the intergenerational inequity. This is derived from the large energy consumption of these countries and their major dependence on fossil fuels.

This thesis focuses on the Spanish case (even if its methodology is applicable to similar countries). The Spanish energy model closely follows the same lines of unsustainability as the ones just described. Taking this into account, this thesis' emphasis is placed on the economic and natural perspectives of energy sustainability.

Focusing on the Spanish case, some macro figures are given first²³. According to (Ministerio de Industria, Energía y Turismo, 2012), the final energy demand in Spain grew from 1.68 EJ in 1973 to 3.93 EJ in 2008, more than doubled. This made total primary energy use grow from 2.26 EJ to 6.38 EJ in the same years. The current economic crisis has made energy consumption descend significantly, to 3.49 EJ of final energy demand and 5.85 EJ of primary use (-11% and -8% respectively). The temporal evolution over the last twenty years in terms of primary energy use can be seen in Figure 16.

²³ Much of this analysis is based on the yearly "Observatory on Energy and Sustainability in Spain" that we publish from the BP Chair on Energy and Sustainability (López-Peña, Linares, Pérez-Arriaga, et al., 2013). Although the following analysis can be also seen in this reference, we have decided to include some of it here for two reasons: (i.) it provides an smooth reasoning line to introduce how energy sustainability problems apply to the Spanish case, outlining its main characteristics, which are needed for the rest of the thesis (without the need for the reader to go and read the full Observatory); (ii.) the Observatory and this PhD thesis are very strongly connected in their methodology and development; indeed, the author of this thesis has contributed in a significant amount to the work of the Observatory.

Figure 16: evolution of primary energy use in Spain²⁴ (ktoe).
 Source: (Ministerio de Industria, Energía y Turismo, 2012)



As can be seen, most of Spanish energy consumption relies on fossil fuels. In 2011 this reliance was 79%: 49% oil, 21% natural gas, and 9% coal. The effects of the economic crisis can also be seen here, since the use of fossil fuels has descended more than the other energy sources. In 2008, the reliance on fossil fuels was almost 86%: 50% oil, 25% natural gas and 11% coal. Nuclear energy has remained constant around 11%. This has made energy-related greenhouse gasses emissions grow from 212 Mton CO₂-eq. in 1990 to 317 Mton CO₂-eq. in 2008 and 306 Mton CO₂-eq. in 2011 (Ministerio de Agricultura, Alimentación y Medio Ambiente, 2013), which has made Spain to rely on buying emissions permits from eastern European countries in order to comply with the Kyoto Protocol (Zafrilla et al., 2012).

This implies that the Spanish energy dependence²⁵ was 88% in 2008 and 84% in 2011, well above European levels, which was around 53% for the EU-27 in 2010 according to (European Commission, 2012). This energy dependence had a consequence: in both years, around 55 billion € were spent by the Spanish economy in importing energy (not only fossil fuels), what was above 5.5% of its nominal GDP in each year (López-Peña, Linares, Pérez-Arriaga, et al., 2013).

The forecasts for the future of the Spanish energy system are in line with the rest of the world: unless an ambitious action plan is adopted, the Spanish energy system is expected to continue largely depending on fossil fuels, with the above-mentioned consequences upon economic and natural capitals. The latest comprehensive model-based energy forecast for Spain (Ministerio de Industria, Turismo y Comercio, 2007), done before the current crisis, estimated a continuous growth of energy demand in Spain. The total primary energy use in the year 2030 in the reference case was estimated to be around 8.4 EJ (41% increase from 2008), with an energy dependence on imports of around 85%. The associated emissions would be around 450 Mton CO₂-eq, a 41% increase from 2008. No recent comprehensive model-based energy forecasts for

²⁴ Translations: “carbón” stands for coal; “petróleo” stands for oil products; “hidráulica” for hydro power; “eólica, solar y geotérmica” for wind, solar and geothermal; and “biomasa, biocarb. y resid.” for biomass, biofuels and waste.

²⁵ In the BP Chair on Energy and Sustainability, we consider Spanish nuclear energy as imported, given that neither mining nor uranium pre-treatment are done domestically.

Spain, which take into account the crisis, have been identified during the development of this thesis. On a shorter time horizon, a commission in the Spanish Parliament forecasted energy demand to remain stable in the current (post-crisis) levels until 2020, thanks to a strong improvement in energy efficiency (Congreso de los Diputados, 2010). These forecasts have been adopted by the Government (Ministerio de Industria, Turismo y Comercio, 2011a, 2011b). In them, fossil fuels still play an important role (71% of primary energy in 2020, in the central scenario).

A preliminary conclusion can be reached: the Spanish energy system presents the same unsustainable, fossil-fuel dependant, characteristics of most countries in Western Europe or North America. What is more, unless decided policy action is taken, it is forecasted to remain so by official projections. In the next paragraphs, we explain in further detail the reasons behind this.

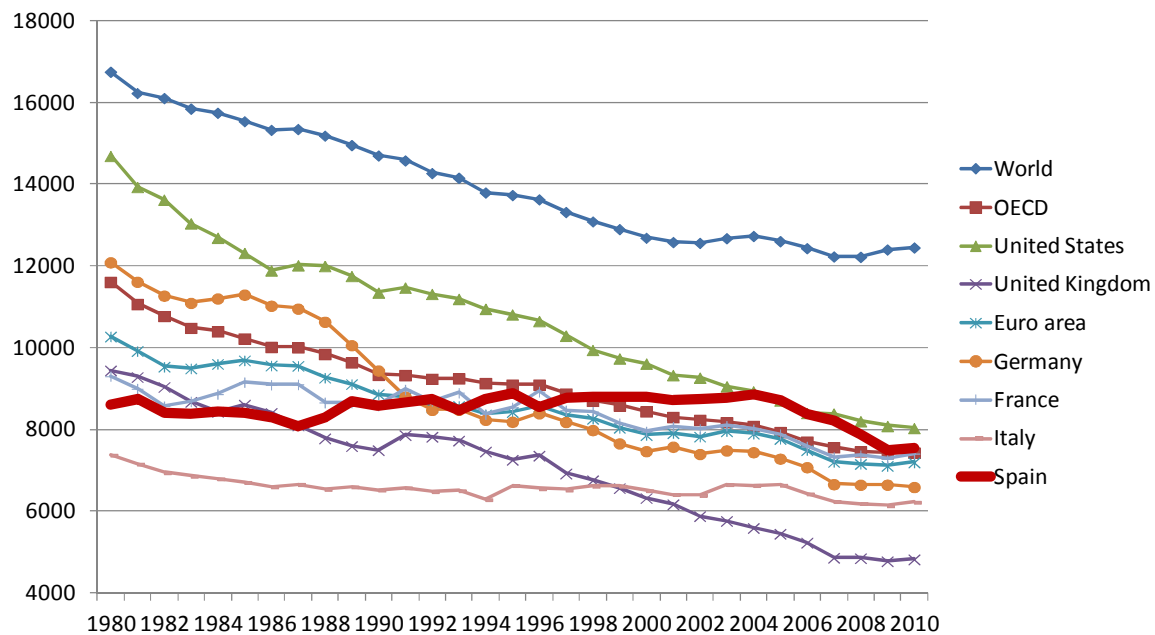
Spain has experienced a significant economic growth in the last decades, and only the current economic crisis has changed that tendency. Much of this growth has been based on low added-value, energy intensive sectors such as construction, especially since the late 1990s. According to (Mendiluce, 2009; Mendiluce et al., 2010), this means that Spain, when compared to similar countries, consumes a high amount of energy per unit of produced GDP, Spain has high *energy intensity*. In other words Spain is, from the perspective of this macro (and imperfect²⁶) indicator, less energy efficient than similar countries. In Figure 17, the evolution of the primary energy intensity (primary energy consumption/GDP) in selected regions is plotted. It can be seen how energy intensity has improved globally, probably due to: (i.) structural changes in the economy, such as a larger share of services, although some studies question whether *terciarization* implies reduced energy use (Fourcroy et al., 2012; Mendiluce, 2009); or (ii.) improvements in the energy efficiency of productive processes (what can be a consequence of security of supply fears after the 1970s oil crisis or rising energy prices). Three interesting issues to note on the graph: (i.) the Euro area seems to be more energy efficient than the United States; (ii.) Germany has improved significantly; (iii.) the high energy efficiency of the UK (what can be caused by a large share of high- added value²⁷, low- energy consumption sectors, such as financial services, in their GDP). It can also be seen that Spain did not improve its energy efficiency (as measured through this indicator) while most similar countries were doing so. (Mendiluce, 2009; Mendiluce et al., 2010) carry out an in-depth decomposition analysis on the issue, and conclude that the causes are, as anticipated: (i.) the structure of the Spanish economy (large importance of low- added value, high- energy consuming activities such as construction, which brings along a large demand for energy consuming transportation of goods); and (ii.) the smaller energy efficiency of key sectors such as transportation or residential. Only the recent economic crisis seems to have changed this trend in Spain, by considerably reducing the activity

²⁶ An interesting discussion on the adequacy of *energy intensity* as an indicator for energy efficiency is done in (Mendiluce, 2009)

²⁷ It is arguable whether some type of speculative financial operations produce added value if a broad, social perspective is considered

in economic sectors such as construction and its associated services (e.g. transportation of goods). Energy efficiency policies implemented in Spain in the last years can have also helped, although we believe that the structural effect is the predominant one²⁸. The fact of Spanish energy intensity having worsened in 2010 (when economic situation progressed slightly) and improved again in 2011 (when economy went back to its negative trend) seems to support our hypothesis (López-Peña, Linares, Pérez-Arriaga, et al., 2013).

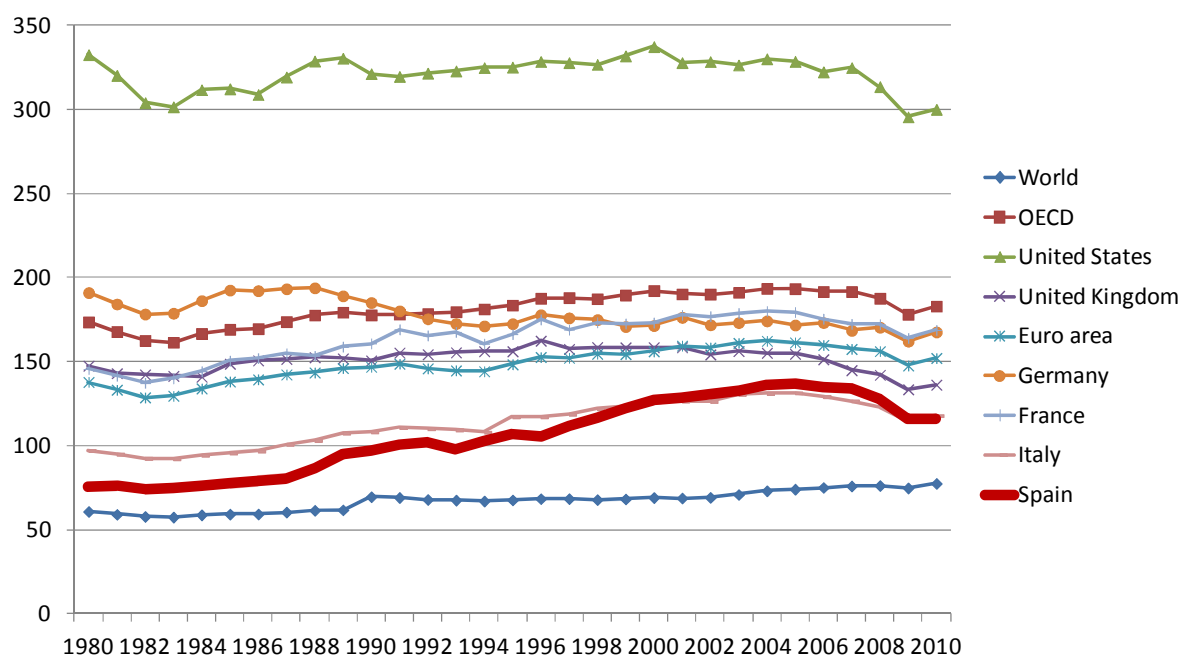
Figure 17: evolution of primary energy intensity (GJ/million constant 2000 US\$) in selected regions.
Source: own elaboration with data from (The World Bank, 2013)



If the energy consumption per capita is analysed, similar conclusions regarding the bad evolution of energy efficiency in Spain can be reached. The evolution of per capita energy use for the same regions is plotted in Figure 18. The world average level has been increasing, as a result of economic development (especially in large developing countries), but it remains well below the average in industrialised countries. Within these, the per capita energy consumption in the United States is much higher than in Europe, what can be due to factors such as the low density of population in some areas or the intensive use of large cars. Within Europe, Italy and Spain are clearly in the lower part, probably due to a more favourable weather with milder winters. But in most European countries, per capita energy use has remained almost constant in the last decades, while in Spain this indicator has worsened (i.e. increasing). This is largely due to the increased living standards in our country, where people have adopted more and more appliances in their houses (e.g. air conditioning), or where more and larger cars circulate in our roads (Mendiluce, 2009). Once again, only the current crisis has changed this trend.

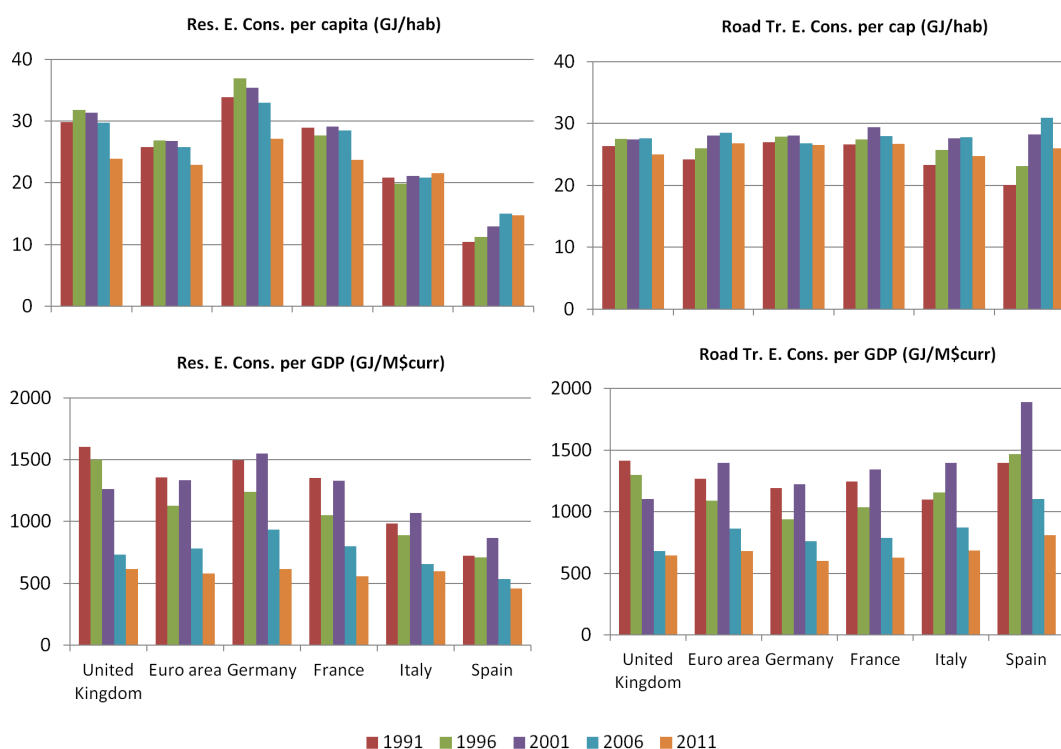
²⁸ This can be due to the longer lead times that energy efficiency policies take to produce their effects, when compared to the fast adjustments in the economic structure in periods of deep crisis such as nowadays. But it can also mean that efficiency policies are not being effective or aggressive enough.

*Figure 18: evolution of per capita primary energy consumption (GJ/cap) in selected regions.
 Source: own elaboration with data from (The World Bank, 2013)*



To better understand the evolution of energy consumption in Spain in the residential and road transportation sectors, Figure 19 is useful. In it, final energy use per capita (top) and per unit of GDP (bottom), in the residential (left side) and road transportation (right side) sectors, in Spain and other selected countries, are plotted. The large increase in energy consumption in these sectors can be seen.

*Figure 19: evolution of selected indicators of sectoral final energy use
 Source: own elaboration based on data from (Eurostat, 2013) and (The International Monetary Fund, 2013)*



For a more disaggregated approach to calculate energy efficiency indicators for Spain refer to (Observatorio de Energía de la Fundación Repsol, 2012), which reaches similar conclusions regarding the low energy efficiency in Spain compared to the EU15, and affirms that the only sector with a higher energy efficiency than the EU15 average is the services sector. For a focus on households refer to (Gas Natural Fenosa, 2013), which affirms that almost 9% of residential energy use could be saved in Spain with small behavioural changes. Focusing on the potential savings in households, (WWF Spain, 2010) and (Cuchí & Sweatman, 2012) are interesting references, which once more point at the large potential. For a recent review on energy efficiency in residential and tertiary sector at the European level refer to (Bertoldi et al., 2012). Lastly, (Economics for Energy, 2011) carries out an in-depth analysis of the economic potential for energy savings in Spain in the 2030 horizon, and concludes that, indeed, large potentials exist in the transportation and residential sectors. Given the large importance of energy efficiency in these sectors, more work is being currently done at the BP Chair on Energy and Sustainability²⁹.

The bad evolution of energy efficiency in Spain (in comparison with our peers) have made Spanish emissions follow a similar negative path, as said above (Kreisler & López-Peña, 2011; Zafrilla et al., 2012). Refer to (López-Peña, Linares, Pérez-Arriaga, et al., 2013) for further detail on the emissions in per capita and per unit of GDP terms.

II.4.2. The *big picture* of the Spanish energy system: Sankey diagrams

In addition to the low energy efficiency of Spain, it is interesting to analyze the composition of the consumed final energy, and through it, understand the energy flows throughout the complete sector. With these, it will be useful to also understand the flows of energy-related CO₂ in Spain, the economic flows in the Spanish energy sector, and these monetary flows once environmental externalities³⁰ are discounted. For this, the Sankey diagrams that we publish every year in the “BP Observatory on Energy and Sustainability in Spain” will be used (López-Peña, Linares, Pérez-Arriaga, et al., 2013). We build them each year using public and official data sources such as Eurostat, the International Energy Agency, the World Bank, The International Monetary Fund, the Spanish Energy Ministry, the Spanish Environment Ministry, the Spanish Statistics Institute (INE), the Spanish Energy Regulatory Commission (CNE), Spanish trade statistics, the Spanish Network Operators for gas, electricity and oil products (REE, ENAGAS, CLH), the Oil and Gas Products Strategic Reserves Corporation (CORES), or the Institute for Energy Diversification and Savings (IDAE), among others. The following Sankey diagrams will allow us to better understand the *big picture* of the Spanish energy system. Then (in the next sections), we will analyze the sustainability of the Spanish energy sector from the capitals perspective, as done above for the global energy system.

²⁹ A M.Sc. thesis is being developed which analyzes energy saving potentials in the complete Spanish energy sector with the models developed in this thesis. In addition, there is an ongoing Ph.D. thesis focusing on transportation.

³⁰ *Externality* (or *external cost/benefit*): in an economic transaction, cost or benefit born by third parts which is not reflected on the transaction's agreed price

Figure 20, presents the Sankey diagram of the energy flows in Spain in 2011 and their change with respect to 2010 (the data for 2012 was not available when this PhD thesis was being written). In it, the width of each flow represents the actual amount of energy in the year (in ExaJoules, EJ), and the dashed black line represents the Spanish border. Each type of energy is represented with a different colour³¹. From left to right, it is possible to see:

- The energy imports entering the system³², representing a sort of *first column of energy boxes*. From top to bottom: nuclear energy³³, imported coal, pipeline natural gas, liquefied natural gas (LNG), oil products, and finally crude oil.
- The total primary energy used in Spain, already being inside the border³⁴ and representing a second *column*. Note the (small) magnitude of renewables (in the top part, above nuclear in yellow) or the domestic coal production (which produces an increment in the magnitude of the black flow).
- The energy conversions (third *column*, composed of only three *boxes*), which transform primary energy into final energy³⁵.
- The final³⁶ energy transportation processes³⁷, representing a fourth *column*. Note that much of the gas from the gas network is used in electricity and heat production (it goes into that conversion process).
- The net exports of electricity and gasoline can be seen (coming out of the Spanish border, represented as the dashed line³⁸).
- The rightmost (i.e. fifth) column³⁹ represents: (i.) on top, in red, the total losses in the complete energy system (most of them being thermal losses from power generation);

³¹ Colors used: (i.) black for coal; (ii.) grey for natural gas and liquefied natural gas (LNG); (iii.) brown for crude oil and oil products; (iv.) yellow for nuclear energy; (v.) light beige for electricity; (vi.) green for biomass, biofuels and waste; (vii.) dark blue for hydro; (viii.) light blue for wind; and (ix.) orange for solar (all types).

³² Labeled on top with the word "Importaciones", i.e. "Imports".

³³ As said above, in the BP Chair on Energy and Sustainability, we consider Spanish nuclear energy as imported.

³⁴ Labeled on top with the words "Energía Primaria", i.e. "Primary Energy".

³⁵ Power and heat production on top are labeled "Generación Eléctrica y Cogeneración"; LNG regasification in the middle is labeled "Regasificadoras"; oil refining and other energy transformations in the bottom are labeled "Refinerías y otras transformaciones energéticas"

³⁶ Natural gas can be considered both primary and final energy. In this thesis, in order to be consistent with the modeling framework, which will be presented later, we consider natural gas to be final energy. It can be imported / exported through gas pipelines. LNG, however, is considered to be primary energy, and before being transported through the gas network, it must pass through a conversion process: regasification. LNG can be traded as well, in this case, through LNG vessels.

³⁷ Power network is labeled "Red eléctrica", natural gas network is labeled "Red de gas" and fuels distribution is labeled "Redes distribución combustibles".

³⁸ Electricity on top labeled "Exportaciones de electricidad", and gasoline in the bottom, labeled "Derivados del petróleo exportados".

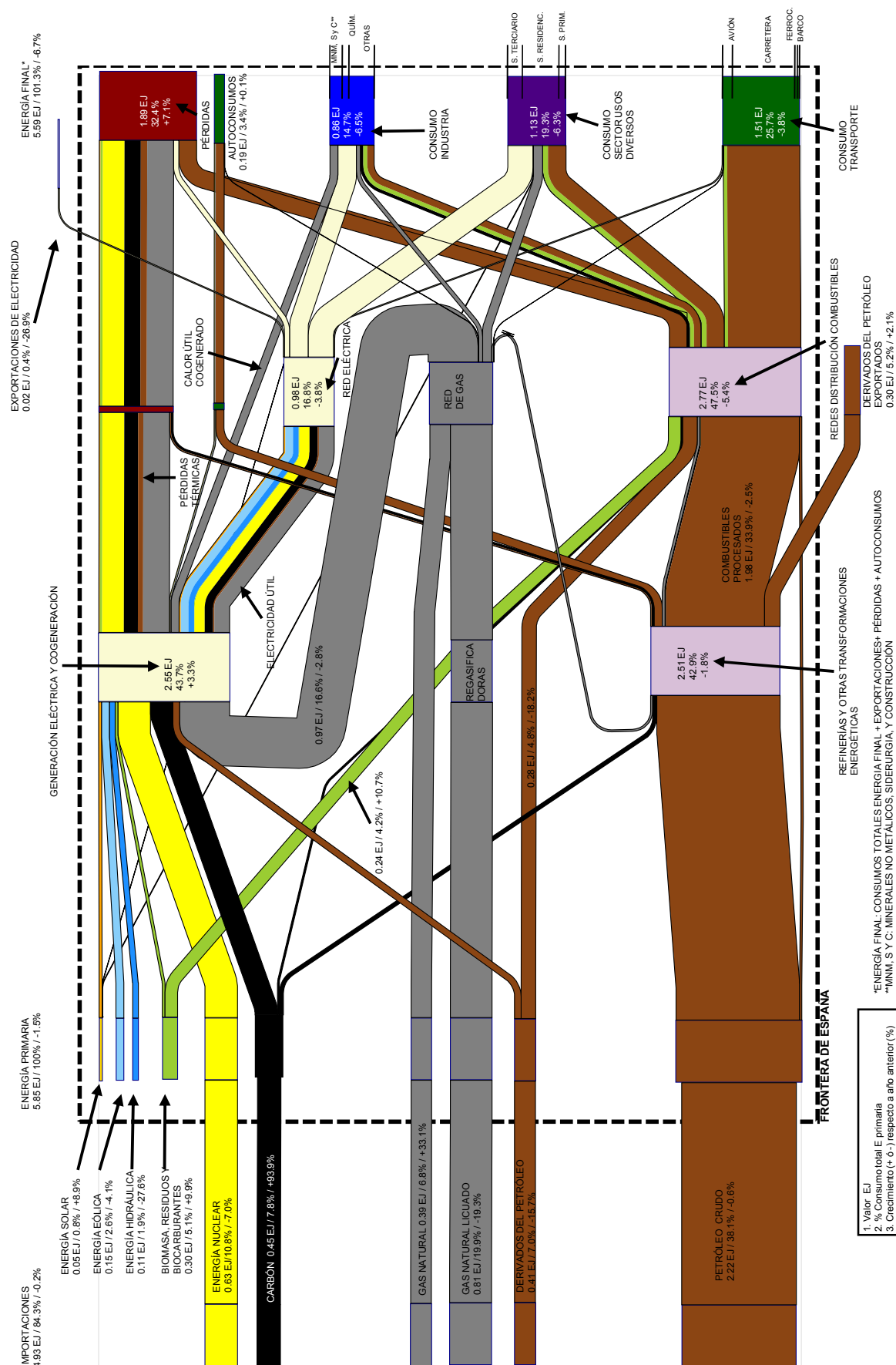
(ii.) in dark green the self consumptions in processes throughout the energy system (most of them from oil refining); (iii.) in blue the final energy consumption in industry; (iv.) in purple the final energy consumption in other uses sector (primary, tertiary and residential); (v.) in light green the final energy consumption in transportation sector. These last three have horizontal black lines to divide amongst the subsectors⁴⁰. It is notable the substantial weight of road transport and residential sectors, as was expected.

³⁹ Labeled “Energía Final” on top

⁴⁰ These divisions affect the complete mix of final energies in each *box*, not meaning that each subsector consumes the types of energy that enters to each box in the left at the same horizontal level. “MNM, S y C” stands for non-metallic minerals, iron and steel, and construction; “QUÍM” means chemical industry; “OTRAS” stands for other industries; “S. TERCARIO” means tertiary sector; “S. RESIDENCIAL” is residential sector; “S. PRIM” is primary sector; “AVIÓN” stands for plane transportation; “CARRETERA” means road transportation, “FERROC” means railways, and “BARCO” stands for shipping.

Figure 20: Sankey diagram of the Spanish energy sector in 2011.

Source: own elaboration, originally published in (López-Peña, Linares, Pérez-Arriaga, et al., 2013).



This Sankey diagram is very useful to understand the *big picture* of the energy sector in Spain, to see the total primary energy used both from domestic and imported sources, how this energy passes through the different conversion and transportation processes to reach final consumption sectors, indicating for each of them the different energy types used. It provides as well their numeric quantities⁴¹. Furthermore, it provides an innovation compared with classic Sankey diagrams: the aggregate width of the different energy flows in each phase (primary energy, energy conversions, energy distribution and final energy) remains constant along the diagram, with a total width equalling the total primary energy. This allows easily visualizing the relative importance of each process and how the energy progresses through the various transformations, easily evaluating the energy lost in the processes as a measure of the overall efficiency of the system.

Note that electricity production⁴² and the thermal losses in power generation⁴³, even if they are homogeneous types of energy (i.e. electricity or heat) have been assigned colours to represent, for illustrative purposes, the proportional participation of each primary energy type.

In this energy Sankey diagram, some interesting aspects to be seen are:

- The large share of fossil fuels in final energy (54% oil products, 12% natural gas, 2% coal).
- The large overall importance of oil products, especially due to road transportation.
- The significant amount of losses and self consumption (37% of primary energy).
- The small value of renewable energies when analyzed under the point of view of the complete energy sector, which however become important in electricity, especially due to the null generation losses they produce⁴⁴.
- The great importance of natural gas, which is largely imported as LNG and mainly used for power generation and cogeneration.
- Coal is almost only used for power generation and large industries.
- The significant share of biofuels in transportation and of biomass and waste in industry and other uses.
- The important energy dependence of Spain: 84.3% of our primary energy is imported.

⁴¹ In each numeric label, the first figure is the value of the flow in EJ, the second shows how much it is relative to the total consumed primary energy, and the third is the increment or decrement (+ or -) with respect to 2010.

⁴² Labeled “Electricidad Útil”

⁴³ Labeled “Perdidas Térmicas”

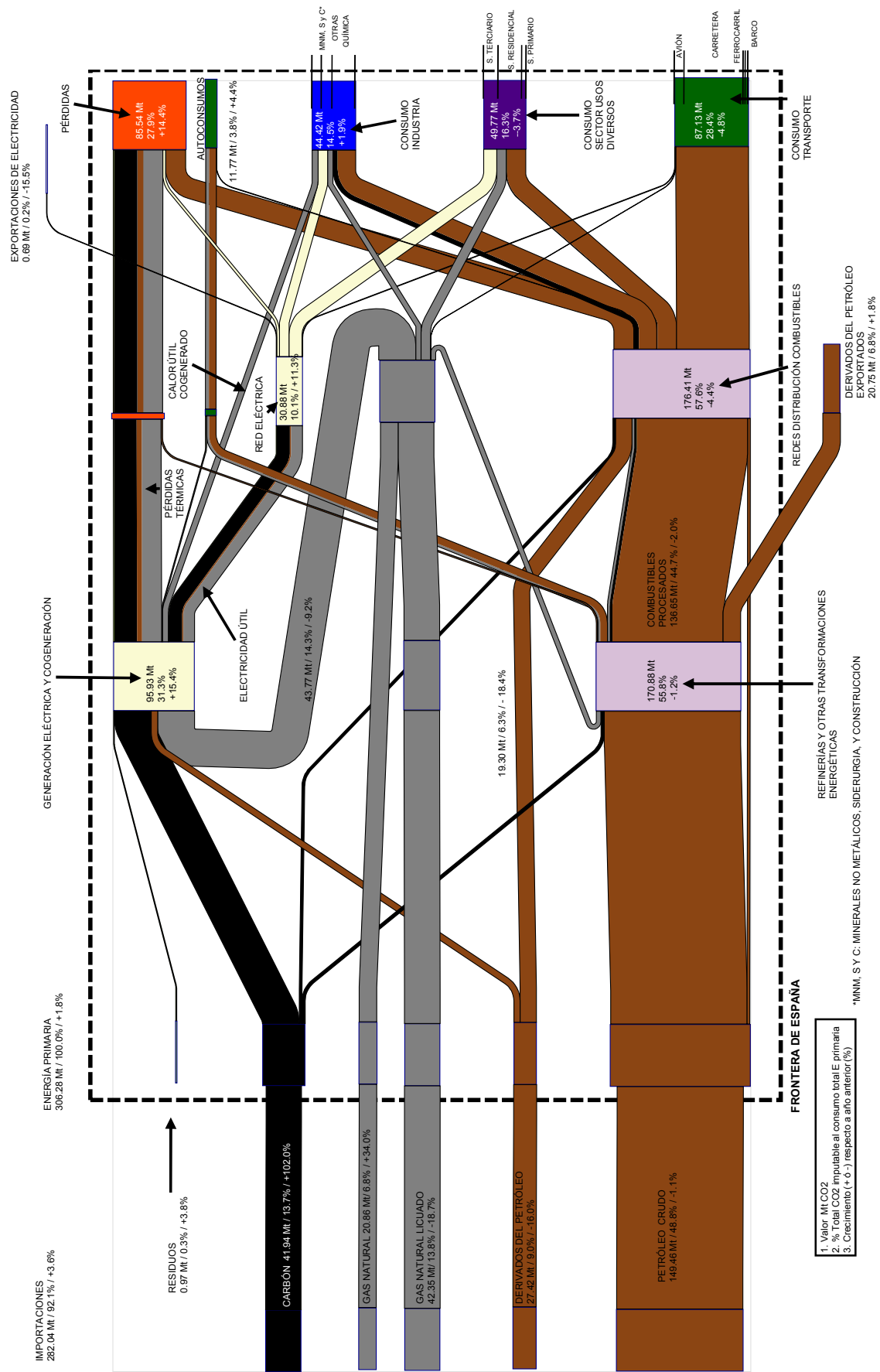
⁴⁴ We have used the following convention for generation losses, inspired in the guidelines from the International Energy Agency. For combustion processes (using both fossil and renewable fuels): their thermal efficiency; for nuclear: 33% efficiency; for wind, hydro, solar PV and solar thermoelectric: 100% efficiency.

This Sankey diagram can be almost immediately translated into a Sankey diagram of energy-related⁴⁵ CO₂ emissions in Spain. It is presented in Figure 21, and it graphically identifies the fuel types and energy uses (also including losses, self consumptions and indirect vectors such as electricity) responsible for energy CO₂ emissions⁴⁶.

⁴⁵ There are other sources of CO₂ emissions that do not come from the energy sector and are therefore left out of this diagram. Examples are industrial processes, land use change or waste disposal. However, these other sectors are small in comparison: energy represents around 93% of CO₂ emissions in Spain (Ministerio de Agricultura, Alimentación y Medio Ambiente, 2013).

⁴⁶ In the elaboration process of the 2012 BP Observatory, we replicated this diagram to consider the carbon emissions throughout the complete life cycle of the conversion technologies. Some CO₂ appears as associated to nuclear and renewable electricity, but it is small in comparison with fossil fuels, so it does not add much relevant information and we did not add it to the final publication. The main data sources we used were the databases from Ecoinvent (Swiss Centre for Life Cycle Inventories).

Figure 21: Sankey diagram of the Spanish energy-related CO₂ in 2011.
Source: own elaboration, originally published in (López-Peña, Linares, Pérez-Arriaga, et al., 2013).



In this CO₂ diagram it is easy to identify that the transportation sector emitted around 87 million tonnes of CO₂ (Mt CO₂) in 2011, the other uses sector accounted for almost 50 Mt CO₂, and that industry emitted around 44 MtCO₂. The large importance of oil products in CO₂ emissions in Spain is clear. It can also be seen that electricity and heat production in Spain emitted around 95 Mt. CO₂ in 2011, how much of it corresponded to gas, oil products and coal, or how these emissions can be assigned to thermal energy losses or electricity demand in final use sectors.

The next Sankey diagram, in order to analyze the sustainability of the Spanish energy sector, is the one that adds the economic component to the energy and environmental aspects which are expressed in the previous diagrams. Every year, in the BP Chain on Energy and Sustainability, we build a monetary Sankey in which we represent the economic flows along the complete Spanish energy sector. For this, we use data from the Spanish National Accounts (Contabilidad Nacional, published by INE) and the flows from the energy Sankey, as explained in (López-Peña, Linares, Pérez-Arriaga, et al., 2013).

The economic Sankey diagram is shown⁴⁷ in Figure 22. It is important to remember that, despite following a similar representation as the Sankey diagrams shown before, the total economic value in each stage does not remain constant: it is increased as the energy advances through the supply chain. This is because each processing sector creates economic added value, resulting from the capital and labour employed in that sector, which is assigned to the energy vectors it produces, increasing its economic value. This diagram easily identifies the sectors and energy sources which are responsible for: (i.) the generation of added value; (ii.) the energy dependence of Spain in economic terms; (iii.) the net taxes raised in the energy sector; (iv.) the economic losses (due to energy losses and self consumption) associated with the energy production and transformation processes⁴⁸.

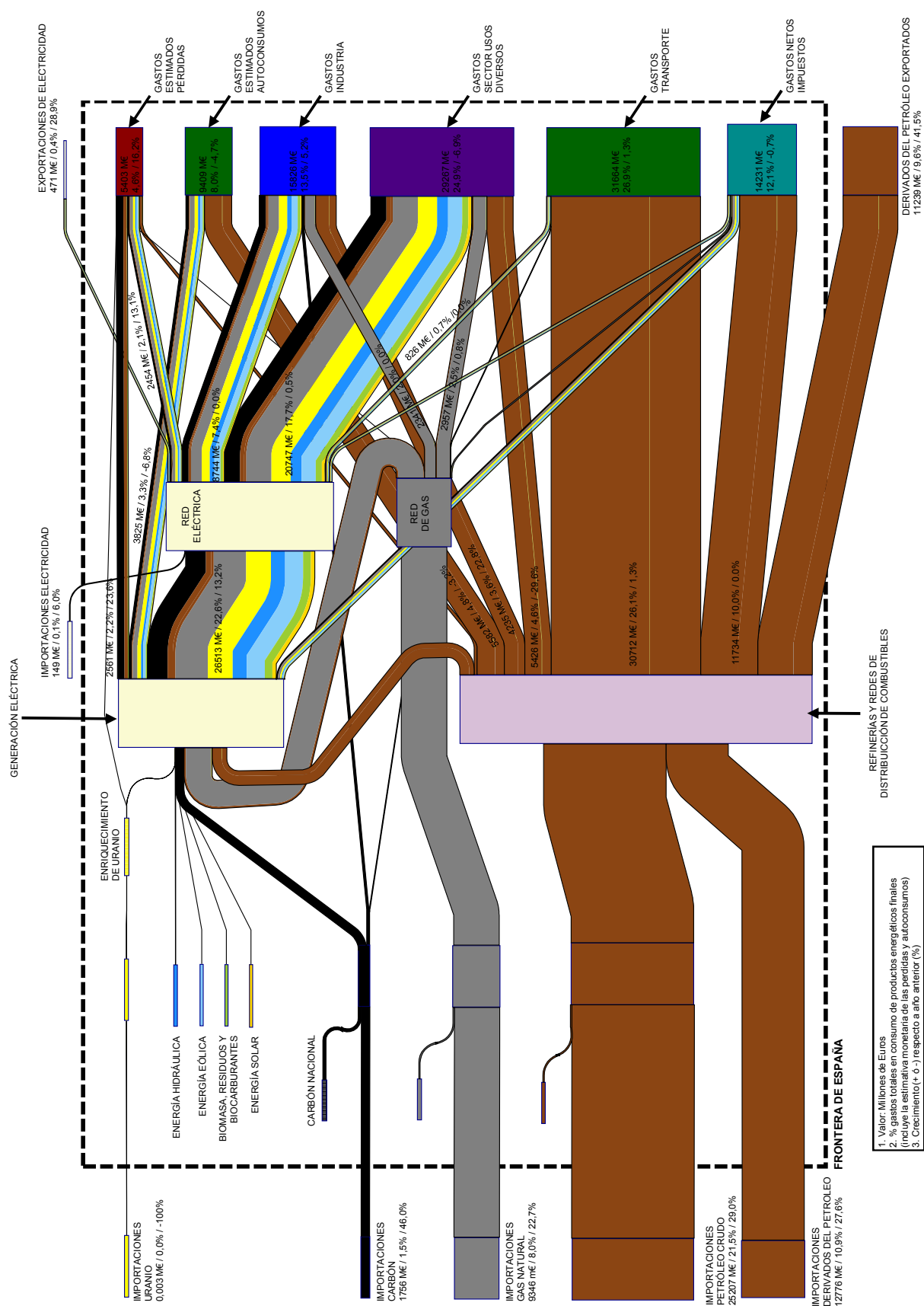
The leftmost column represents the direct expenditures in importing each type primary energy, which in 2011 accounted for around 63,billion €, after growing more than 50% since 2009 values (when oil and gas prices were low due to the international crisis) and even surpassing 2008 values (the historical peak). This value is almost a 6% of Spanish GDP. The rightmost column represents the total economic cost of final energy to consumers, including the price of added value throughout the system and comprising taxes (which are represented in a separate box, as said). This value represented around 77 billion € in 2011, after decreasing a 1.2% in 2011 compared to 2010 due to the lower energy consumption caused by the crisis. The total added value in the energy conversion processes was around 20billion € in the power

⁴⁷ The topology and color codes of the energy diagram have been respected as possible. Oil refineries and fuel distribution have been merged into a single *box*, because data availability forced us to. A new box in the final use column has been created, which corresponds to net taxes paid by the energy sector (in blue, labeled “Gastos Impuestos Netos”). Another one for uranium enrichment has been also added.

⁴⁸ It is important to note that the data availability for this figure is much lower than for the previous energy and CO₂ ones. For example, non-energy uses of energy products (i.e. feedstocks such as oil products for petrochemical industry) are not separated in the National Accounts. Hence these economic values must be considered as estimates.

sector, around 17 billion € in oil refining, and around 1.6 billion € in gas processing, totalizing around 38.6 billion €.

Figure 22: Sankey diagram of the monetary flows in the Spanish energy sector in 2011.
Source: own elaboration, originally published in (López-Peña, Linares, Pérez-Arriaga, et al., 2013).



Interesting issues to see in the economic Sankey diagram:

- Even if Spain has low taxation on oil products when compared to European standards (European Commission, 2012), most of the net taxes levied on the energy sector come from oil products.
- The low relative economic value of thermal losses and the high value of self consumption, when compared with the physical amount of energy they represent (as seen in the energy diagram in Figure 20). This is due to the low quality of lost energy (from the thermodynamic perspective, given that they are thermal losses with high entropy) compared to the high quality of self consumption. This is the reason why losses are, indeed, losses: their low quality makes them unworthy to recuperate and reuse. Self consumptions, on the contrary, are ready-to-use energy, whose self-use represents an opportunity cost for energy industries.
- The high relative costs of electricity in the “other uses” sector when compared to industry, taking into account the actual amounts of energy consumed in each sector. This is due to the fact that domestic consumers are charged with higher electricity tariffs than industry, what could represent a cross-subsidy from consumers to industry, in order to preserve industrial competitiveness (electricity can be a very important cost for some industries), or a sort of Ramsey pricing⁴⁹. This is common in some industrialized countries. In some developing countries (e.g. in some Latin American ones) it is the opposite, with industry subsidizing domestic consumers.
- The large value of electricity and oil products consumption when compared to their respective magnitudes in physical (energy) terms. This is because electricity and some oil products are very versatile, high quality and valuable energy vectors, which are priced accordingly by energy markets.
- The income that the exportation of oil products (mainly gasoline) represents for Spain, in the bottom right of the figure.
- Concerning renewables, the diagram only includes those used for electricity production, since the cash flows associated with its use for thermal uses (e.g. biofuels, biomass, solar thermal) are negligible in comparison. A special feature of renewables is that, except for biomass, there is no economic value assigned to the primary resource used (e.g. wind, solar radiation, water in rivers). Hence, if we compare the economic flows into and out of the power generation sector, we can see how it was necessary to spend only 1€ in primary energy purchase for 3.4€ value of electricity (discounting losses, own consumption and taxes). The equivalent figure for the refining sector is 1.8€ per euro spent on primary energy. In other words, the use of renewable energy sources (except

⁴⁹ In economics, Ramsey pricing is a method to assign an economic cost to a heterogeneous group, when a clear assignation method (i.e. cost causality) is lacking, and trying to minimize the inevitable economic distortion (i.e. welfare loss) caused by it. It consists on charging higher taxes (or, in our case, tariffs) to consumers with lower price elasticity of demand, in order to minimize their response to those high taxes and, consequently, the economic distortions produced by them.

biomass, as said) causes the *relative* creation of added value to be greater in the power generation sector. The added value from renewable power production entirely corresponds to non-energy related production factors (e.g. labour and capital), and therefore constitutes a net creation of economic value added.

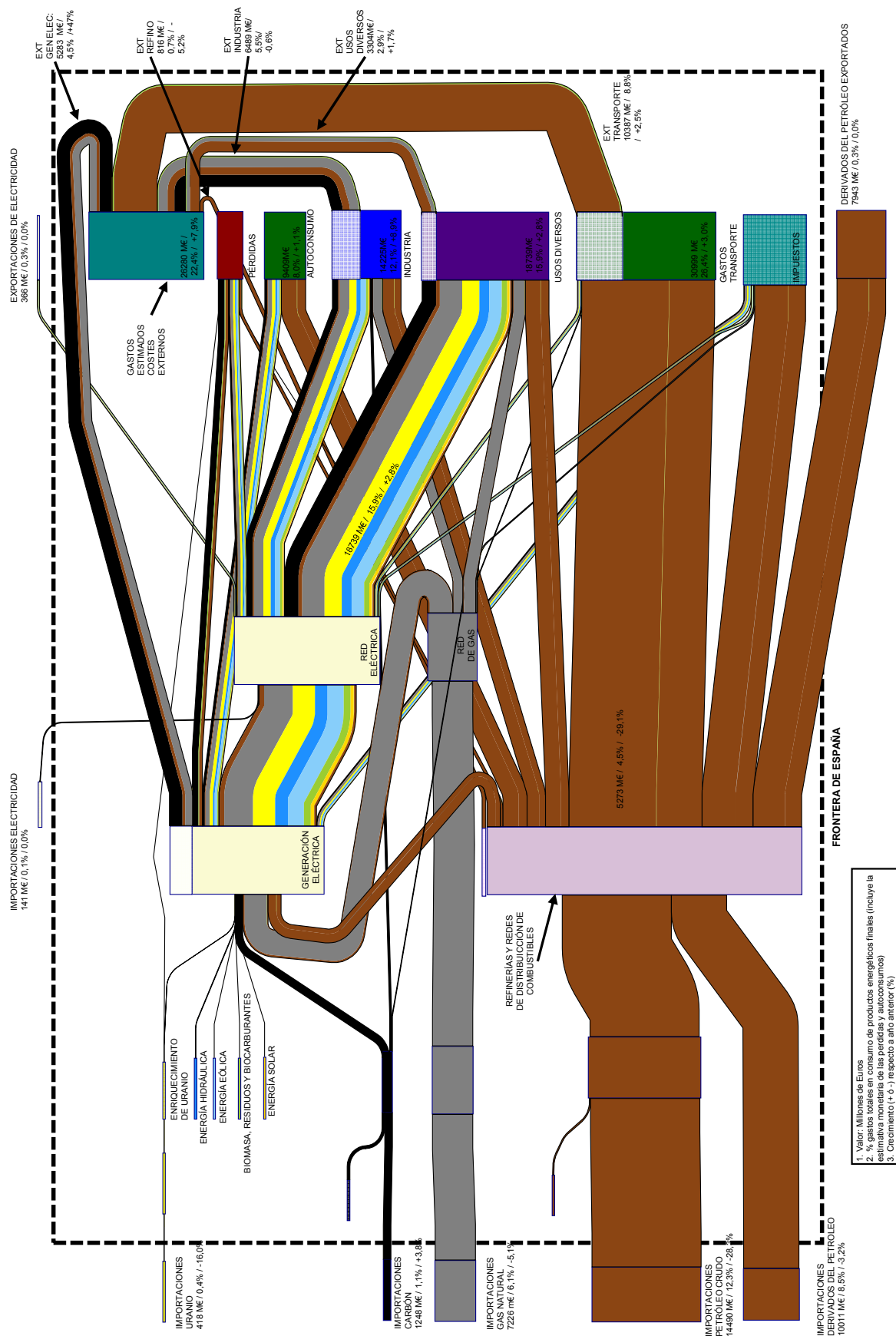
- Another interesting interpretation of this issue in the diagram refers to energy security, another component of energy sustainability, as said. Indeed, one of the major energy security risks for Spain is the price risk, due to the volatility of energy imports' expenditures and its impact on the economy (due to our high energy intensity). In this sense, a larger difference between the width of the primary energy expenditure (left side of the Sankey diagram) and expenditures on final energy carriers (right side of the diagram), would indicate a smaller influence of the prices of primary energy in the final expenditure. This would be equivalent to an increased resilience to increases in primary energy prices, and therefore less price risk. Briefly: it could be argued that the greater the difference in the width of the initial and final flows, the greater the energy security in terms of price risk (López-Peña, Linares, Pérez-Arriaga, et al., 2013).

The fourth and last Sankey diagram is shown in Figure 23. It represents the same monetary flows in the Spanish energy sector in 2011, but discounting the external costs to society that emissions from CO₂, SO₂, NO_x and particle matter create. Indeed, emissions create externalities due to issues such as climate change and local or regional pollution, which for example creates respiratory disease, as was seen above. It would be complicated to consider all externalities of the energy sector, so we only consider the more relevant ones to the Spanish case, according to one of the most comprehensive studies for the quantification of externalities of energy available in the literature: the *ExternE* project (European Commission, 2011a).

The quantification of these external costs is somehow controversial, as it is being addressed by several research groups. For CO₂, a value of 40\$/tCO₂ (expressed in €) has been used, which has been obtained from the review of integrated assessment models ⁵⁰ done in (Tol, 2009). For the other pollutants, the values from (ExternE Project, 2005) have been used: for SO₂: 8000 €/t; for NO_x: 10,500€/t; for particulate matter PM₁₀: 8,000€/t. Multiplying these values by the total emissions of each pollutant in each subsector, as contained in the National Emissions Inventory (Ministerio de Agricultura, Alimentación y Medio Ambiente, 2013), we obtain the economic values that are then subtracted from the previous economic Sankey (López-Peña, Linares, Pérez-Arriaga, et al., 2013). These economic values are represented as flows that go into a newly created light green box in the top right part of the diagram, which represents a *sink* of economic value to society. They are depicted as a subtraction of economic value added from each subsector, which goes into this sink.

⁵⁰ Integrated Assessment Models are models of the complete Earth, the oceans, the biosphere, the atmosphere, the land, etc. and how these interact with the global economy and human life. They are able to model the long-term impacts of global carbon emissions and their economic costs. More detail on these models will be given in Chapter 3.

Figure 23: Sankey diagram of the monetary flows in the Spanish energy sector in 2011, discounting the external costs to society that emissions from CO₂, SO₂, NO_x and particles create.
 Source: own elaboration, originally published in (López-Peña, Linares, Pérez-Arriaga, et al., 2013).



From this last graph (economic once external environmental costs to society are subtracted), the following interesting insights can be obtained:

- The total economic value created by the energy sector is largely decreased by external costs, by more than two thirds, from the previous value of nearly 39,000M€ to around 11,400M€.
- These external costs are mainly caused by NO_x (39%), CO₂ (30%) and SO₂ (28%). PM₁₀ account only for 2%.
- The reduction of value added in the electricity sector is around 5,200M€, most of it caused by emissions from coal power plants.
- The reduction of added value caused by oil products is even greater, around 15,300M€, most of it being caused in the transportation sector where, apart from CO₂, pollutants from cars in cities cause respiratory diseases and other local problems.
- Emissions from industry create significant external costs to society, almost 6,500M€, most of them being caused by coal and gas combustion.
- If externalities are considered, renewables are even more favourable from a social perspective, because the important added value they create (sawn above) is entirely preserved due to their lack of emissions.

Once introduced the big picture of the Spanish energy system (through the initial discussion on our energy inefficiency and through these four Sankey diagrams), we analyze now its sustainability, from the capitals and equity perspective presented above.

II.4.3. Energy sustainability in Spain: natural capital perspective.

As seen before, the Spanish energy system is largely dependent on fossil fuels. Even if it is small in comparison with other international players, Spain plays its part in this global problem. We contribute to energy resources depletion, climate change, or local/regional pollution, which create large external costs for society as seen above (for instance, the large dieselization of our car fleet is one of the reasons for the important levels of local pollution problems in our cities).

Spain being a Mediterranean country will be severely affected by climate change (even if this climate change was completely produced by other countries). Some of its effects, according to (European Environment Agency, 2012), will be increased temperatures, decrease in river flows (affecting agriculture or hydropower, among others), greater frequency and intensity of droughts, reduced yield of some crops due to heat waves and droughts, increased water demand for irrigation or even less attractiveness for tourism due to a more extreme weather or sea level rises. For more information on impacts of climate change that are already being noticed in Spain refer to (Abanades et al., 2007; Greenpeace, 2009; Ministerio de Medio Ambiente & Moreno, 2005). For projections of how these could be in the future, refer to (Brunet et al., 2009). For a

reference on current evidence and how to adapt to climate change, see (Castro Acuña et al., 2011).

On a final note, it is relevant to mention Spanish policies to support national coal production, which produce large environmental impacts and externalities (e.g. climate change, local/regional pollution), as reported in (López-Peña, Linares, Pérez-Arriaga, et al., 2013).

II.4.4. Energy sustainability in Spain: social and human capital perspective.

From this perspective, the first issue to be acknowledged is that energy poverty in Spain is not such an important issue as could be in other countries, either developing or developed which suffer from very cold winters. The energy poverty issue in Spain will be treated in more detail in the next pages (in the “equity perspective” section), but from the social and human capital perspective we can already affirm that some of its related problems such as difficulties for education or development are not too important.

What is indeed an important problem in energy sustainability in Spain from the social capital perspective are the effects on health. Our transportation sector (mainly due to cars and trucks) creates important pollution in big cities such as Madrid or Barcelona, which has made the European Commission to carry out inquiries on these cities’ policies for air quality. One of the main reasons is the large dieselization of our car fleet (i.e. diesel cars release more particulate matter than their gasoline equivalents, even if they are better from the NO_x perspective) which, in addition, is getting older due to the current crisis causing new and cleaner cars are to not be adopted as fast as would be needed. This is one of the reasons behind the large external costs created by local/regional pollutants that we saw above in the fourth Sankey diagram.

Another issue relates to social institutions, democracy, political participation or peace itself, as stated before. Spain, being an important consumer of fossil fuels, can be amongst the contributors to the important problems that are globally present regarding these issues. More precisely, we import large quantities of oil and gas from several North African, Sub-Saharan African, Middle Eastern or Latin American countries according to official statistics such as (CORES, 2011; ENAGAS, 2012; Ministerio de Industria, Energía y Turismo, 2012).

Another issue related to human capital and the energy sector is that, according to some studies, Spaniards are amongst the least informed Europeans on energy issues (Díaz & Rodríguez, 2008; Eurobarometer, 2007).

II.4.5. Energy sustainability in Spain: economic capital perspective.

From the economic capital perspective, it must be first said (as done above) that energy is a very positive input for our economy, allowing us to produce goods and services, increasing our economic capital. On the other hand, however, it is also clear that Spain consumes a large

quantity of fossil fuels, contributing to the global problems presented above (resources exhaustion, declining EROEIs, rising energy prices, etc.).

Security of physical energy supply can be considered to be another aspect of sustainability from the economic capital perspective, as seen above. In Spain this risk is largely mitigated by the fact that we have well-developed energy conversion and distribution infrastructures, and that our energy importing assets allow us to have a well diversified and flexible supply chain, as pointed by the Spanish National Energy Regulatory Commission (Yunta, 2013). This is true especially for natural gas: while some important European countries largely depend on gas flowing in through pipelines from exporting countries such as Russia, Spain has built significant regasification capacity, which allows us to import most of our gas in LNG vessels which can come from any exporting country in the world (ENAGAS, 2012).

In any case, Spain spends almost 5% of its GDP in importing fossil fuels, mainly oil. Upwards variation in global energy prices results in a wealth transfer to exporting countries, which reduces our available income for investment or consumption, what can affect GDP growth and increase unemployment. Expenditures in energy imports also worsen our current account balance: in 2011, 87% of Spanish trade deficit was explained by energy products (Ministerio de Economía y Competitividad, 2011). This trade deficit must be financed, what worsens our financial position with respect to other countries. Furthermore, being energy a key input in our economy, growing volatility in energy prices are passed to the rest of the economy, increasing inflation (Banco de España, 2011; Task Force of the Monetary Policy Committee of the European System of Central Banks, 2010). This inflation can be amongst the underlying causes of the reduction in competitiveness that the Spanish economy experienced before the current crisis. This is because wages were indexed to inflation, so they (i.e. labour costs) rose with inflation and not with productivity. For more on this issue refer to (Álvarez et al., 2009; de Miguel et al., 2012; Hernandez, 2009). See (Manzano & Rey, 2012) for a study on the impacts of energy insecurity on the Spanish welfare. In addition, increased exposure to volatile energy prices also creates uncertainty for economic agents, increasing risk premiums and financing costs.

Other interesting aspect of the economic impacts of energy are those on employment. Globally, and in Spain, there is much discussion about *green jobs* and how a more sustainable energy system can foster employment. In Spain, the renewable energy sector has created important employment in the last years, but recent policy developments seem to be impacting the sector and, hence, its employment (Asociación de Productores de Energías Renovables, 2012; Sustainlabour et al., 2012). However, care must be put when looking at these studies on economic impacts of the promotion of certain energy technologies. It is not clear that they are methodologically sound: e.g. it is unclear how they consider the direct/indirect/induced and gross/net job creation (Breitschopf et al., 2011; International Energy Agency, 2012c), and they do not always take into account the opportunity cost of the capital used (Böhringer et al., 2013; Ragwitz et al., 2009).

Something similar happened with the coal sector (a less sustainable type of energy according to our conceptual definition): Spanish coal needs subsidies in order to be competitive,

so Spanish government provides them in order to keep employment in the sector (even if security of supply reasons are often argued).

II.4.6. Energy sustainability in Spain: equity perspective.

In Spain, thanks to extensive efforts in rural electrification carried out in the last decades, access to electricity can be considered to be universal. The same happens with other modern energy carriers. In any case, energy poverty can be an issue in Spain: there are low income segments of the population which, during the winter, may not be able to afford a correct level of heating in their households. Recently, with the economic crisis, this may be becoming more of an issue in Spain, mainly in rural areas (Observatorio de la Sostenibilidad en España, 2012; Tirado, 2012; Tirado et al., 2012). Significant attention to this issue is also paid in other European countries, for instance, in the United Kingdom.

Lastly, but definitely not less importantly, another element of equity unsustainability of the Spanish energy system (which could also be considered under the economic capital section) is the so-called *tariff deficit*. In Spain, electricity consumers pay an *access tariff*, a part of their electricity bill which does not correspond to energy itself, and many residential consumers are under inclusive regulated tariffs. These access tariffs are established by the Government. In the last decade, the costs of the electric power sector have grown significantly, due to issues such as increases in primary energy prices (gas being the key one here, with power utilities having gas supply contracts usually indexed to oil prices), new grid investments or renewables support, among others. But the Governments in the same period have not risen regulated tariffs accordingly, afraid of the political consequences. As a result, tariffs did not comply with the basic *additionality* principle of tariff design (i.e. they did not cover the costs), so a significant *tariff deficit* has been accumulated, which at the end of 2011 accounted for almost 26 billion €, mainly titularised and held by financial institutions and power utilities (Comisión Nacional de Energía, 2013). This debt will have to be paid by future generations, so it can be considered an issue of intergenerational inequity.

II.4.7. Energy sustainability in Spain: conclusion and outlook.

As it has been anticipated, the Spanish energy system is clearly unsustainable. For more details on this, a useful reference is our “BP Observatory on Energy and Sustainability in Spain” (López-Peña, Linares, Pérez-Arriaga, et al., 2013). Even more, as seen above, no official and comprehensive projections for the future of the Spanish energy system exist beyond 2020. Those of 2020 project a future energy system largely reliant on fossil fuels, hence unsustainable.

II.5. NARROWING THE FOCUS: SUSTAINABLE ENERGY POLICIES

In this section, we start to narrow the focus to *sustainable energy policies*. From the previous sections, it can be clear that our energy systems are not evolving towards

sustainability. From another perspective, it is a fact that in many western countries, energy industries have been liberalized, and markets have been introduced. We will now briefly review these liberalization processes, to conclude that markets are not necessarily bringing sustainability to them. This is due to the important market failures that occur in the energy sector, which should be corrected with policies and regulations to *complement* the markets (we do not disagree with the idea of markets *per se*). The need for sustainable energy policies is then identified, and examples of how these policies could be are given. Finally, we reach the conclusion that Spain lags behind most of our peers in these issues.

In developed countries, a general liberalization trend started in the early eighties with the ideas of influential economists such as Milton Friedman or Alfred Kahn. Some conservative politician leaders like Margaret Thatcher in the United Kingdom and Ronald Reagan in the United States followed these liberal ideas and carried out deregulation processes in several sectors.

As a result, energy industries in the developed world have been mostly deregulated in the last three decades. Focusing on Europe and following with the British example, natural gas market liberalization started with the privatization of British Gas with the British Gas Act in 1986. In the petroleum industry, the main milestone was the privatization of British Petroleum between 1979 and 1987. In Spain, Repsol was privatized in 1989 and Gas Natural in 1991. The electricity industry deregulation has been similar: even if it started in the early 1980s in Chile, to be followed by Argentina and many other Latin-American countries, the first European country in liberalizing the electricity industry was the United Kingdom, in 1990, whereas the Spanish electricity industry was liberalized in 1998. At the European level, the Directive 96/92/EC established the first requirements on electricity sector liberalization in the year 1996.

Liberalization and privatization have been mainly supported as a means for introducing, through competition, greater efficiency in the liberalized industries. It is indeed generally agreed that markets and competition are good for promoting efficiency. A very good didactic explanation of how perfect markets work can be seen in (Harford, 2007).

However, perfect markets do not exist in reality, and this is very true in the energy industries. In these, important market failures exist, some of the most important being imperfect competition, information asymmetries and the presence of important externalities.

Imperfect competition is mainly caused by the fact that energy is a technologically advanced and capital-intensive industry; with presence of natural monopolistic activities (energy transport and distribution networks); the existence of large incumbent companies (most of them as a result of privatized monopolies in liberalization processes); the need to establish targets and standards to limit the environmental impact of the energy supply activities (which limits the technological choice and hence, possible competition); and the barriers of entry that could be created by these factors and that would prevent new possible competitors to enter the market. These facts also have an important repercussion concerning information imperfections. In addition, numerous externalities are also present: almost every kind of the above-mentioned impacts on equity, natural, social, human or even economic capitals are not correctly priced in current energy markets.

This allows us to reach an important preliminary conclusion: even if the introduction of markets in the energy sector may have improved efficiency, there are important market failures that seem to be preventing markets from taking into account all the above-described energy sustainability aspects. In other words, markets alone seem to not be taking our energy systems along the road to sustainability. This could be attributed to the fact that imperfect markets are not able to fully account for long-term concerns, being sustainability the most important of them.

This raises the necessity of some sort of policy/regulation in the energy sector in order to *complement* (not to substitute) markets and to make them work in the best possible way towards society as a whole, towards sustainability. This allows us to introduce a key concept in this thesis: *sustainable energy policy*. Sustainable energy policies, in the context of this PhD thesis, are those policies that are applied to energy markets with the aim of making the energy system evolve towards greater sustainability. In this thesis we will put ourselves in the position of an independent regulator (be it a regulatory authority or a government) whose final aim is the public good, being energy sustainability a necessary condition for it⁵¹.

These policies should be determined through an exercise of *energy indicative planning*. This exercise, which has already been done in other European countries, is specially needed in Spain, as has been advocated by this PhD's advisors in a paper whose name is very indicative: "Markets Vs. Regulation: A Role for Indicative Energy Planning" (Pérez-Arriaga & Linares, 2008). Citing literally from this paper:

Indicative energy planning should provide the integral vision for all stakeholders, plus the constraints to be respected, the targets to be met and the incentives to achieve both. We must insist that this indicative planning should not curtail the freedom of (...) utilities, which would continue operating in a free market environment. But indicative planning should provide the framing conditions that should be known by all agents that may be affected, and should set up goals and well- determined resources for everything that is regulated: (...) Indicative planning is more than just prospective energy analysis. Rather than estimating what might happen we should envision the basic traits of what should happen to achieve a sustainable energy model.

This PhD thesis is inspired by this idea, and proposes a methodology that could be used for this purpose: carrying out an indicative energy planning exercise in order to identify the needed sustainable energy policies.

Energy policies are nowadays defined from several governance scales: global, regional, national and, in certain countries like Spain, sub national. Following with the Spanish example, its energy system is subject to a large portfolio of regulations: some examples could be the Kyoto Protocol (global scale), the European Directive 2009/28/EC that establishes the well-known 20/20/20 objectives (regional scale), Spanish energy laws (national scale) and, in some cases, specific regulations at sub national level (Comunidades Autónomas).

⁵¹ Although the methodology developed here could be used by any other stakeholder of the energy sector, e.g. companies, consumers, lobbyists, consultants, academics, etc.

Of all these levels, this thesis will concentrate on the national one. Given that the policies that must be specifically put in place very much depend on the physical, economical and social characteristics of the country to which they are applied, this thesis will be focused on Spain or countries with similar characteristics. That is, industrialised and market-oriented countries from the OECD with well-developed energy systems and infrastructures but facing serious problems of economic and environmental lack of sustainability, such as high use of fossil fuels and energy dependence. Social, human and equity aspects of sustainability will not be treated in this research, because they are considered to be secondary in the specific case of Spain.

To sum up, this thesis will address sustainable energy policies focusing on the economical and environmental aspects of sustainability and applied at a national level to Spain or similar countries.

Sustainable energy policy, as defined above, can be a rather broad term, and these policies could be very diverse. A brief enumeration (which does not intend to be exhaustive but indicative) of some of these policies is done next, including some current international examples.

- Demand-side policies, aiming at changing the way energy is used by demanding sectors, be it either:
 - a) promoting certain type of energy demand instead of others (energy switching): for example when electric cars are supported, this can be assumed to be an energy switching policy, from fossil fuels to electricity.
 - b) changing the way the energy is consumed, for example moving a demand from one moment to another, which is very typical in the power sector with for example special (cheaper) night tariffs for electricity which intend to make people move certain loads from day to night, even if the total amount of energy demanded is the same.
 - c) improving energy efficiency and achieving energy savings, that is, reducing the amount of energy consumed to meet the same demand for energy services⁵². This can be achieved using:
 - i. standards (e.g. energy efficiency standards for domestic appliances or for cars such as the CAFE ones in the United States),
 - ii. certifications (such as the Energy Star ones in the US or the European energy labeling),
 - iii. economic incentives (e.g. reduced taxes for more energy-efficient cars or markets for white certificates),
 - iv. or supporting innovative business models to support energy efficiency (e.g. the energy services companies)

⁵² The term *Energy Service*, as considered in this PhD thesis, was defined in the previous chapter.

- d) actually reducing the amount of demanded energy services, for instance, reducing the amount of space heating demanded in residential building by improving their thermal insulation, or reducing the amount of mobility demanded by professionals and business people by promoting videoconferences.
- Supply-side policies, aiming at changing the way energy is supplied to demanding sectors. This is normally done by supporting certain technologies such as renewables, nuclear power, coal (as done in Spain to support the domestic coal industry) or fossil fuels in general (as done in several countries to foster economic development and fight poverty⁵³). For the example of promoting renewables, this can be done in several ways:
 - a) Economic incentives: providing promoters with regulated incomes (e.g. feed-in-tariffs), with extra incomes (e.g. feed-in-premiums), or with reduced expenditures (e.g. tax credits for renewable power promoters but as well for biofuels' consumers), among others. This has been largely successful in many European countries such as Denmark, Germany or Spain.
 - b) Quantity-based mechanisms: for instance establishing renewable energy quotas (e.g. the Renewable Portfolio Standards in the US, the biofuels mixture quotas for liquid fuels in Europe or the markets for green certificates⁵⁴ used in the United Kingdom), or establishing renewable power auctions (e.g. as implemented in Brazil)
 - c) Information and knowledge: improving the knowledge and information about renewables such as creating resources maps, providing technical assistance to developers, organizing courses and trainings, or compiling documents with all the existing knowledge on the issue (IRENA, the International Renewables Energy Agency is carrying out significant work on this line).
 - d) Supporting technological advance in these technologies, for example through directed research and development programs.
 - e) Other support, such as financial (for instance through creating special financial mechanisms to lower the risks, and financial costs of investors) or infrastructure-based (e.g. the Government investing in power lines needed to evacuate large amount of power from a large offshore wind farm).
- Policies aiming at reducing emissions, be it either:
 - a) a limit on quantity: either a standard (such as the ones set in the Montreal Protocol for phasing out CFCs, or the EURO standards for automobiles in Europe), or a cap

⁵³ According to recent studies by reputed institutions (e.g. the International Energy Agency and the International Monetary Fund), subsidies to fossil fuels represent a very large volume of resources, much higher than subsidies to renewables, and accounting for around 2.5% of global GDP. However, they do not necessarily achieve their main objectives (fighting poverty) as they tend to benefit wealthy classes. Even more, they have other negative effects some of them being on energy use (reduced incentives for efficiency), emissions, or macroeconomic stability,

⁵⁴ Green certificates can be considered as a sort of quota.

and trade program (such as the European Emissions Trading Scheme for carbon dioxide).

- b) a price on emissions: for example through a carbon tax (as done in Australia or British Columbia in Canada).

Some interesting reviews of different types of energy policies are (Linares & Labandeira, 2010) and (Gillingham et al., 2006) for demand-side measures, (Batlle et al., 2012; International Renewable Energy Agency, 2012) for renewable support policies, or (Ellerman et al., 2010) for a review on the European Emissions Trading Scheme.

Some of the countries in our same social, economic and political context are already implementing sustainable energy policies. In the United Kingdom, the 2009 *UK Low Carbon Transition Plan* (UK Department of Energy and Climate Change, 2009a), outlined the proposals and measures that will be adopted to decarbonise the UK economy, achieving a 18% reduction on 2008 levels (34% on 1990 levels) in carbon emissions by 2020 and an 80% reduction on 1990 levels by 2050. The Plan includes, among its measures, objectives like 30% electricity from renewable sources by 2020, four CCS⁵⁵ demonstration projects, or new nuclear power plants. In addition, it clarifies Ofgem's mission (the energy regulator) in tackling climate change and ensuring security of supply. It also sets a plan for greener houses through energy efficiency and low carbon heat and electricity generation, establishes a strategy for tackling emissions from the transportation sector, supports green industries' R&D and sets the obligation of producing a longer term load map and a vision for smart grids. Some of these measures (like the CCS incentive and clarifying Ofgem's mission) were already implemented in the 2010 *Energy Act* (UK Department of Energy and Climate Change, 2010a). The 2011 *Energy Bill* (UK Department of Energy and Climate Change, 2010b), sets a households energy efficiency investment framework in what is called the *Green Deal*, provides new energy security measures and establishes a new plan for electricity smart metering, among other measures. More recently, the UK is carrying out a reform of the electricity market, which includes the next main changes: (i.) sets a floor for carbon prices, (ii.) creates a capacity mechanism to ensure investment in power generation capacity, (iii.) establishes a feed-in tariff based on contract for differences (FiT CfD) to promote renewable generation, and (iv.) imposes an emissions performance standard to limit specific carbon emissions from new power plants. For a good review on this and other aspects recent UK energy policy, refer to (International Energy Agency, 2012d). Another interesting issue in recent UK policy is the recent creation of the Green Investment Bank, which is doing much of its initial activity in the energy sector.

In France, the 2005 *Loi-Programme d'Orientation de la Politique Énergétique* (Ministère de l'Économie, des Finances et de l'Industrie. République Française, 2005) set an ambitious target to cut France's CO₂ emissions by 75% (from 1990 levels) in 2050. In addition, it established a high reduction in final energy intensity, and short-term specific objectives (for the year 2010): 21% renewable electricity production, 10% renewable share in total primary energy, 50%

⁵⁵ CCS: Carbon Capture and Sequestration

increase in the heat produced with renewables and achieving a biofuels 7% share in transportation. R&D in energy was as well appointed as a national objective. Later, in 2007, the environmental programme *Grenelle de l'Environnement* (Ministère de l'Ecologie, du Développement Durable, des Transports et du Logement, 2011) was created. It contains ambitious targets concerning emissions from buildings and transportation (transport sector emissions in 2020 must equal the 1990 levels) and support for renewables. In addition, the French government has carried out an energy indicative planning process with the 2020-2050 time horizon (Centre d'Analyse Stratégique, République Française, 2008). For a review on French energy policy, refer to (International Energy Agency, 2009b).

In Germany, the most recent and important development is the *Energiewende*, a plan to completely transform their energy system, progressively phasing out fossil and nuclear energies, towards renewables. It was first adopted in September 2010 (Federal Ministry of Economics and Technology, 2010), but in 2011, after the Fukushima nuclear accident, an accelerated phase-out of nuclear was established (Germany should be nuclear-free by 2022). Of course, these plans are supported by model-based, long-term energy prospective scenarios, such as the ones in (DLR et al., 2012).

Italy has, according to (International Energy Agency 2010b), implemented a system of green certificates and white certificates, reorganised the gas and electricity sectors, diversified and reinforced gas supply, invested in CCS research, and removed the nuclear moratorium (which was reintroduced in 2011 after a referendum), among other measures. Lately, Italy is also performing a long-term energy prospective exercise (Ministero dello Sviluppo Economico, 2012). Ireland is also developing extensive research and outlooks of their energy system up to 2050, the so-called SEAI 2050 Energy Roadmaps (Sustainable Energy Authority of Ireland, 2013). Also Denmark has done a similar exercise, proposing a 100% renewable energy system by 2050 (The Danish Ministry of Climate, Energy and Buildings, 2011).

On a supranational level, the European Commission has done a very interesting energy prospective with the 2050 time horizon (the “Energy Roadmap 2050”), which establishes four possible decarbonisation scenarios where Europe would comply with the required emissions reduction in 2050 from developed countries in order to keep climate change manageable (global temperature rise not bigger than 2°C compared to preindustrial levels). According to the IPCC, this implies a reduction of at least 80% compared to 1990 levels. This Energy Roadmap 2050 has been one of the major milestones in European energy policy discussions in the last years, because it confirms the serious commitments of European authorities with decarbonisation (European Commission, 2011b). And very recently, the European Commission has also started the process for defining the 2030 energy and climate policy framework (European Commission, 2013).

Outside of Europe, the Government of the United States also performs periodic long term energy forecasts (up to 2035), the Annual Energy Outlook (EIA U.S. Department of Energy, 2010a). Recently, the Obama administration seems to be giving much importance to energy policy, being its main objectives increasing energy efficiency (as seen, the U.S. is well above the OCDE average in terms of energy consumption per capita), fostering domestic energy production, and pursuing collateral avenues to reduce emissions (toughening standards on

emissions from vehicles or power generation plants), since a comprehensive climate change policy is subject to great political uncertainty (although Mr. Obama has taken some recent action).

Even Australia, a country rich in fossil fuel resources, gives importance to sustainable energy policy. Australia is the world's ninth biggest energy producer and one of the only three net energy exporters of the OCDE. This has a great influence in its economy, especially thanks to the growth of energy demand in Asia. In this context, Australia is pursuing a large deployment of clean energy and a reduction of carbon emissions thanks to a recently-introduced carbon price. This can be due to political and economic objectives such as using their resources mostly for exports, to fight climate change, or to become a clean technology leader in the region. For more information refer to (International Energy Agency, 2012e).

Large developing countries such as China, India, Mexico or Brazil are also starting to change their energy policies towards sustainability, introducing measures such as renewables support and starting to think about instruments for emissions reductions. Even if we consider these countries as hugely important for global energy sustainability, we will not study them in greater detail because, as said, this PhD thesis focuses on Spain and similar OCDE countries.

This country-by-country review could continue, but the conclusion would be the same: countries are increasingly realising the lack of sustainability of our current energy model, are performing long-term energy prospective scenarios, and are adopting sustainable energy policies. Spain is clearly an exception on this issue amongst industrialised countries. Some regulations have been or are in place, such as the support for renewables for power production, public financial incentives for purchasing more energy efficient equipment, or solar thermal incentives (Pablo-Romero et al., 2013). But a comprehensive and long-term policy framework is missing in Spain. For a recent review on Spanish energy policy refer to (Kreisler & López-Peña, 2011). For a good international energy policy database see (International Energy Agency, 2013b).

II.6. SUSTAINABLE ENERGY POLICY ASSESSMENT

This section briefly mentions the need for thoroughly analyzing sustainable energy policies prior to their implementation, and identifies computer-based mathematical models as a very suitable tool for this purpose. The topic of energy modeling has then been introduced, paving the way for the review of the state of the art, which is done in the next chapter.

With the previous discussion, the need for implementing sustainable energy policies has been expressed. However, it is important to note that sustainable energy policymaking is a very complex issue. Energy systems are very intricate, integrated by a large set of economic agents with different interests, technologically complicated infrastructures, and strong international interrelations. Added to this, the outputs of energy systems (modern forms of energy ready for final use) are vital inputs for economic activity. Therefore, relations between the energy sector and the rest of the economy are very important and of great complexity. This becomes even more entangled if the environment is included. In a simplistic way, economic activity drives energy use, which creates environmental impacts, which in turn can affect the economy and energy sectors.

Sustainable energy policies should be carefully analysed and assessed prior to implementation. Just to cite a reason, different policies can be counterproductive or synergic: for example, climate change, security of supply and local pollution control policies can be very synergic (McCollum et al., 2011), whereas renewable support can counteract climate policy by reducing emissions price.

Policy analysis in the context of this thesis refers to the quantitative and qualitative assessment of different policies in order to decide which of them best fulfils the desired objectives, and therefore allow policy-makers to make correctly informed decisions about the expected outcomes of their regulations.

Luckily, modern computation technologies make complex mathematical calculations largely accessible at affordable prices. This brings the possibility of representing intricate energy-economic-environmental systems with computer-based numerical models that make it possible to simulate these systems' evolution under different assumptions. Hence computer-based mathematical models are a very valuable tool for energy policy analysis.

For instance, in order to be able to consider all policies at the same time, the effects they produce and how they interact with each other, most of the previous energy roadmaps and predictions are supported in models such as NEMS, PRIMES or MARKAL/TIMES, just to cite a few (these and others will be carefully described and analysed in the next chapter).

This thesis will focus on sustainable energy policy evaluation and design for Spain, and for the evaluation, computer-based energy models will be used. In the following section, a review on the relevant literature on this topic is presented.

Chapter III.

ENERGY MODELLING STATE OF THE ART

III.1	Outline of this chapter	75
III.2	Key concepts and techniques	75
III.3	Mainstream energy models	86
III.4	Other energy models	119
III.5	Conclusions of the State of the Art: the Gap to be Covered by this Thesis.	123

III.1. OUTLINE OF THIS CHAPTER

In the first section of the chapter after this outline (III.2), the key concepts and techniques of energy modeling are described, where we comment on issues such as top-down versus bottom-up modelling, partial equilibrium versus general equilibrium, optimization versus simulation, the representation of uncertainties about the future, or how technological evolution is modelled.

Then (III.3), we present some of the mainstream energy models in the literature, such as MARKAL/TIMES, PRIMES, POLES, or EPPA, we describe their modelling rationale according to the key techniques reviewed before, we punctuate them according to our judgement of what a good tool for sustainable energy policy analysis should be (and we summarise it in a clear table), and we provide examples of which studies have been carried out with each model.

Later, in section III.4, we review some other models, not as mainstream as the above but which also allow us to gain useful insights about how the energy modelling literature is evolving in the last years.

This allows us to obtain some conclusions (III.5) of the state of the art of energy modelling, and to clearly identify the gap where this thesis tries to add its value.

III.2. KEY CONCEPTS AND TECHNIQUES

As indicated before, computer-based mathematical models are useful in the analysis of the behaviour and evolution of complex systems under changing and uncertain circumstances. They have been widely applied to policy analysis for sustainable development, because of the high complexities involved, such as long term uncertainties and human-nature interaction (Boulanger & Bréchet, 2005). However, modeling can also be a problem itself if done badly. For instance, (Bankes, 1993) states that much attention should be paid to not confusing *consolidative* modeling and *explorative* modeling. According to this reference, consolidative modeling consists of building a model of a system whose internal dynamics are known, and then use that model to replicate the system's behaviour under different circumstances. Explorative modeling consists on making assumptions about the unknown internal dynamics of the system and then modeling the system's behaviour under different values of these assumptions (in this case the resulting model can't be considered as a reliable image of the system under study). Energy modeling (where this thesis focuses) may be either in the first or second category, depending on issues such as the analyzed time horizon or the available data, and the modeller should know what she is dealing with.

The above distinction between *consolidative* and *explorative* modeling is just an example to clarify our point: modeling can be very useful, but also can be a problem if not done with care. This chapter intends to present a review of the state of the art of energy modeling which will allow us to justify our methodology (in Chapter 4) and which is useful for future researchers

aiming to work in this field. We will present a classification of energy modeling techniques, we will discuss how some of the main models in the literature fit within our classification and later (in Chapter 4, where we present our proposed methodology), we will place our models within this classification. An important point should be made clear here. In the energy modeling literature there are many different classifications of techniques. In our opinion, some of them are more useful than others, each one may have its fair purpose, and the separation line between classifications is often unclear. The classification we propose here is largely based on our literature review, experience and best judgment within the framework of this thesis. Of course, we do not claim ours being the only or best possible classification.

Modeling for policy making in the energy field started with the oil crisis in the seventies. The first models were technologically-accurate, representing energy systems from an engineering perspective, but without considering their very important reciprocal relation with the rest of the economy. Later, the oil crises in the seventies and early eighties, which clearly showed the interrelation between energy and economy, made them evolve towards energy-economy models, which specifically represented the energy-economy relation. A very representative example is PIES, the Project Independence Evaluation System (Hogan, 1975). More recently, when environmental concerns started, these models were extended to take into account relations with the environment: both the effects of energy and the economy on the environment and, as well, the effects that environmental protection and/or degradation could cause on the economy.

Focusing on the energy-economy relation, the economy's influence upon the energy sector is mainly through energy demands (which of course, affect energy prices): in principle, the stronger the economic activity, the greater the energy demand will be, and the economic structure (i.e. the relative weights of different economic sectors) will influence which energy forms are demanded (e.g. if transportation sector has a large weight, oil products will be highly demanded). Other influences of the economy in the energy sector, such as interest rates, which condition debt costs, and financial markets, which condition equity costs (both of them influencing the rates of return required by investors in energy assets), are out of the scope of this PhD thesis.

III.2.1. Economic representation and environmental feedbacks

From the perspective of the energy sector's economic representation, the first kind of model that can be considered estimates the energy demand from economic, demographic and other activity data. In these models the economy-energy relation can be considered to be unidirectional. Once energy demands are obtained, the next step consists on modeling how these demands are met by energy supply technologies, that is, how demand and supply curves intersect obtaining the energy market equilibrium. If these models only consider energy markets, they are called *partial equilibrium* models, and the economy-energy relation is also unidirectional. If this relation wants to be modelled in a bidirectional way, i.e. to consider as well the energy sector's influence on the complete economy (normally through its prices, which are costs for energy-consuming processes, but also through quantities since energy sectors are also

a part of the economy and therefore of GDP), the equilibrium in all the economy's markets must be modelled, giving result to what is called *general equilibrium* models. General equilibrium models are needed to analyze policies which affect to different economic sectors or which only affect one sector but whose output is an important input to other sectors, and hence these policies affect the entire economy. The energy sector is one of these sectors (its output, energy, is a key input in many other sectors), so general equilibrium models are very useful for energy policy analyses. However some authors think otherwise: in the energy modeling literature there has been a debate about how important the energy sector is within the economy, this debate being commonly referred to as "the fable of the elephant and the rabbit stew" (Hogan & Manne, 1977), where another interesting reference is a special issue of *The Energy Journal* (Hourcade et al., 2006). The problem with general equilibrium models, as will be seen, is that it is mathematically difficult to model technological detail in them, which is very important to analyze energy policies (Rodrigues, 2009).

Partial equilibrium models, on the contrary, allow a much higher technical precision, at the expense of economic detail. They can be represented with price-inelastic or price-elastic demand. The first one implies that the amount of demanded energy is constant no matter its prices, whereas the second implies that when prices tend to go up, the economy adjusts and energy demand tends to diminish. Partial equilibrium models with elastic-demand representation can be seen as a step ahead towards general equilibrium, somehow representing middle ground between partial equilibrium (with inelastic demand) and general equilibrium.

This PhD thesis focuses on partial equilibrium models which account for energy issues, economic aspects and environmental impacts, because from a sustainability perspective we need to be able to account for them all.

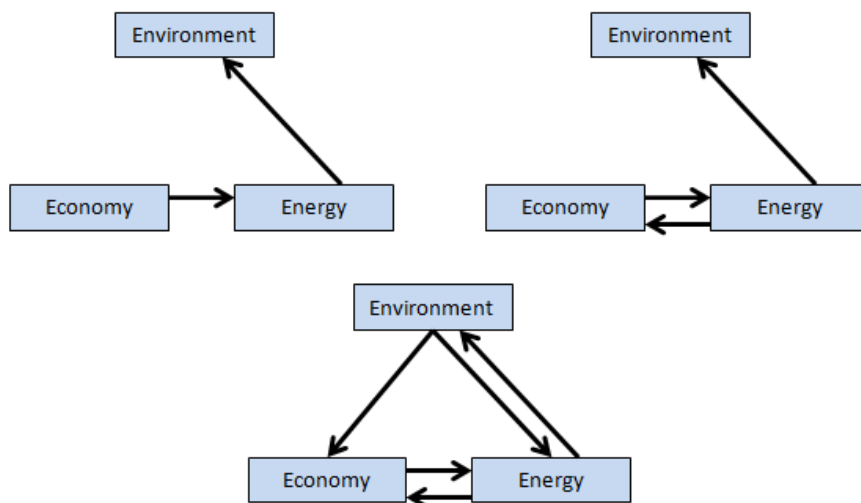
In order to better understand these important issues, it is useful to graphically represent the above-introduced concepts of partial and general equilibrium. It is done in Figure 15. Partial equilibrium models normally obtain energy demand from input data on the economic activity, and they calculate how this demand is met by the energy sector while taking into account the environmental impacts of the energy sector⁵⁶. General equilibrium models represent how the economy demands energy and how the energy sector meets it, yielding some energy prices, which in turn can affect the economy and hence again energy demand and energy prices, and so on. This reciprocal influence reaches equilibrium between the energy sector and the rest of economic sectors, which is what general equilibrium models represent. Then, the environmental impacts of energy use are calculated. The most complex models (called *integrated assessment models*) include in the equilibrium the impacts that a damaged environment can cause on the energy sector and in the complete economy (for instance, due to health damages, reduced water availability, worse land productivity or natural disasters). This is what we will call *environmental feedbacks* in the context of this thesis. These models are mainly used to assess climate change and climate policy.

⁵⁶ The order of these calculations does not need to be so in the actual computation of the models, it is used here only for illustrative purposes.

Figure 15 represents these relations through arrows which indicate the directions of the main effects/influences in three types of models: partial equilibrium, general equilibrium and integrated assessment models. In partial equilibrium models, the economy determines the demand for energy (first arrow), which is supplied by the energy sector, in turn creating some environmental impacts (second arrow). In general equilibrium models, the energy sector also affects the economy (hence the new arrow), and when both reach an equilibrium, the environmental impacts of the energy sector are obtained. Lastly, in integrated assessment models, two new logical relations are considered (two new arrows): the effects that the environment has in the economy (e.g. diminished GDP due to health impacts of regional pollution) and in the energy sector (e.g. increased costs of thermal power plants caused by reduced refrigeration water availability due to climate change impacts). Of course, an arrow should go in reality from the economy to the environment, representing environmental impacts of non-energy activities within the economy (e.g. water pollution, residues generation, land use changes due to agriculture, etc.). This does exist in some integrated assessment models, but we will not consider it within this PhD thesis. Lastly, it should be reminded that these figures and arrows are just for illustrating the internal logic of the models, it does not imply that the actual computation is done in this order.

Figure 24: conceptual illustration of relations in models: partial equilibrium (top left), general equilibrium (top right) and integrated assessment models (bottom).

Source: own elaboration.



III.2.2. Modeling techniques: optimization vs. simulation

Energy modeling techniques are normally classified into two main categories: *optimization* or *simulation*. According to some authors, optimal situations represent the ideal outcome for a system given the available information. Simulation on the contrary tries to represent real trends, which are observed in reality even if they may not lead to optimal situations (in reality, indeed, ideal situations are very scarce). Citing (Bahn et al., 2004), “simulations and trend analysis models focus more on the most likely outcomes whereas optimization models look for ‘ideal’ outcomes (e.g., best technologies and energy forms satisfying exogenous constraints)”. According to (Stermann, 1991), “the output of an optimization model is a statement of the best

way to accomplish some goal” and “optimization models are prescriptive, but simulation models are descriptive”. Simulation has more of a *descriptive* approach (what *will probably* happen), whereas optimization is a *normative* approach (what *should* happen), simulation tends to describe realistic (imperfect) rationality of the agents making decisions, while optimization (normally) assumes perfect information and full rationality. Depending of what the modeller wants to obtain from the model (a *descriptive* or a *normative* answer), she should choose to use one or the other of these techniques. However, we think that all the above is not as clear, it is not as *black or white*: many shades of grey can exist. For example, optimization techniques can be used with the purpose of simulating the imperfect reality, and simulation can be used to try and obtain optimal outcomes. Also, it should be reminded again that our classification of modeling techniques is not perfect, that the border lines are often unclear and counter examples can be found. Our classification is only intended to be useful for a first general understanding of the main energy modeling philosophies, and other researchers may very well not agree with it.

Within these two main families (i.e. optimization and simulation), other usual techniques fit. *Equilibrium problems*, used to represent the interactions of companies within energy markets, can be included within the optimization family because agents are modelled as maximizing their profits or utilities, and the equilibrium is the situation where no agent can improve its situation without worsening other agents’ situation, that is, equilibrium represents a global optimum in the market (in the case of perfect markets). *Econometrics*, on the contrary, belongs to the simulation family. This technique is normally used for forecasting values of an independent variable from other explanatory variables’ values, by means of econometric relations that have been previously adjusted through statistical techniques over historical data. This can be seen as a way of simulating past relations over the future, relations that may have been suboptimal and are assumed to remain being so. Econometrics is useful for relating variables whose relation is difficult/not interesting to explicitly model but which is believed to remain true during the study horizon. For example, econometrics can be used for estimating energy demands from economic and demographic macro aggregates. This philosophy, empirically/statistically modeling variables’ relations (instead of through more “physical” relations), makes econometrics one of the key techniques in top-down approaches (see below).

These two main families of techniques are non-exclusive: there are a number of models, to be reviewed later, which within a simulation framework include optimization formulations (aiming at representing a system of agents that individually optimize their decisions but who interact in a non-optimal global system). And there are optimization models that can incorporate simulation methods, e.g. using econometrics for estimating some input parameters for the optimization model.

The optimization vs. simulation discussion is a traditional one in the modeling literature. Some interesting references are mentioned next: the first two stand more in the optimization side, the third one in the simulation side, and the last two are interesting because they approach both with constructive criticism. (Barquín, 2006), performs a comprehensive review of

electricity market⁵⁷ models, including the discussion between models for regulatory use vs. those for companies' use, some information on models' temporary scope, and a discussion of both main modeling techniques (optimization or simulation). (Ventosa et al., 2005), reviews the state of the art in electricity market models, classifying them in three main groups: optimization problems for one firm, market equilibrium considering all firms, and simulation models. (Dyner & Larsen, 2001) is an interesting reference about how liberalization processes have changed the models used for decision-making within electric utilities, and it includes a good review of some simulation techniques such as *Agent-Based Modeling* and *System Dynamics*. (Boulanger & Bréchet, 2005) carry out a survey of models used for sustainable development policy-making, but with the aim of developing a methodology for evaluating the strengths and weaknesses of each modeling approach and for helping policy makers in choosing the right one. (Stermann, 1991) is a very recommendable reference for anyone willing to understand computer modeling (its title, "A Skeptic's Guide to Computer Models", is descriptive enough). It performs a good critical review of optimization vs. simulation approaches.

III.2.3. Technological detail: bottom-up vs. top-down

From the technological detail point of view, the models identified above can have two approaches: *bottom-up* or *top-down*. The first approach is engineering-based and consists in obtaining general data (e.g. total gasoline demand in a country) through aggregation of low level, technically-detailed values (consumption of each type of cars, depending on their fuel efficiencies and usage level, for example). The second approach is economy-based and aims at obtaining the same general data but starting from other general upper level data, without caring about low-level technical details (estimating the demand of gasoline through gross domestic product and population for instance). To better understand this differentiation, we will review three energy demand estimation models, one with a bottom-up and two with a top-down approach. (Fletcher & Marshall, 1995) presents a bottom-up model for the estimation of industrial energy demand. Using as main inputs the demand for industrial products (e.g. tons of steel, aluminium, etc.) and industrial energy prices, for each simulation year it estimates the installed capacities of each production technology (taking into account new investments, retrofits, decommissioning, etc.). Then, it calculates the usage level of each production technology (in order to meet the demand for industrial products) and, according to this, the energy demanded. For instance, in the aluminium sector it considers energy demand from pumps, fans, motors, air compressors, air refrigerators, furnaces or space heating devices. It is clearly an engineering-based bottom-up model. On the contrary, (Adeyemi & Hunt, 2007) present a top-down model for estimating industrial energy demand in the OECD. They start with panel data from fifteen countries, and use several econometric approaches to estimate industrial energy demand through three main explanatory variables: industrial output, industrial energy prices and some index of energy efficiency. Lastly, (Pock, 2010) estimates, using an econometric approach (i.e. a top-down one), the demand of gasoline from cars in some European countries

⁵⁷ Much of the discussion for electricity markets can be extrapolated to other energy markets

using as explanatory variables the real income per capita, the prices of gasoline, and the stock of gasoline and diesel cars per driver.

Of course, it is to be expected that results from bottom-up and top-down models will not be perfectly coincident: none of the approaches is *better* than the others, each has its application field and its purpose. Sometimes, applying both approaches and comparing results could be a useful exercise. In this sense, the following references are good examples, where climate policy implications from bottom-up and top-down climate policy evaluation models are compared (Fortes et al., 2013; van Vuuren et al., 2009).

Once a brief discussion about technological detail in energy demand estimation models has been done (with the purpose of making clear the difference between top-down and bottom-up approaches), the focus will be put now into how partial equilibrium and general equilibrium models consider technological detail. Partial equilibrium models normally sacrifice an exhaustive representation of the energy-economy relation to achieve a greater technological detail. Therefore, they generally use a bottom-up approach. The most paradigmatic example of partial equilibrium bottom-up approach is the MARKAL/TIMES family, which started with the MARKAL model (Fishbone & Abilock, 1981) and then evolved to TIMES (Loulou et al., 2005). These models use an optimization philosophy. On the other hand, bottom-up partial equilibrium models can also be solved with simulation techniques, such as the World Energy Model (International Energy Agency, 2012f) and POLES (Criqui, 1996). All of these models will be reviewed in great detail in the next section.

General equilibrium models represent economy-wide interactions in a more accurate way, but the level of technological detail in the energy sector is usually lower. Their approach is normally top-down, where sectors or even the whole economy are represented through aggregated production functions as explained in (Huntington & Weyant, 2002). The energy sector, given its central role in these models, can be represented in different ways: the simplest is as another production function whose output is the commodity *energy*, used by other production functions representing other economy sectors. This is what is done in some general equilibrium models like the Walrasian CGE⁵⁸ model, explained in (Rodrigues, 2009). A higher level of detail is attained through the integration of technologically-rich representations of the energy sector within general equilibrium models, what can be seen as a mixture of bottom-up modeling for the energy sector and top-down for the rest of the economy. This can be done through hybrid optimization-based CGE approaches like those explained in (Rodrigues, 2009), through bottom-up simulation models coupled with macroeconomic modules as done in NEMS (EIA U.S. Department of Energy, 2009), or through other techniques that fall out of our scope.

Other representative general equilibrium models are the WITCH model (Bosetti et al., 2006), which is a top-down model with a good representation of technology and its evolution in time, and the Emissions Prediction and Policy Analysis (EPPA) model (Paltsev et al., 2005), the module representing human and economic activity within the Integrated Global System Model

⁵⁸ CGE stands for Computable General Equilibrium

(IGSM), which is the climate change integrated assessment model (Sokolov et al., 2005) created at the Massachusetts Institute of Technology (MIT)⁵⁹.

III.2.4. Geographic perspective

From the geographic perspective, models can be national, regional or global. Some examples of national models are the TIMES-based model developed by CIEMAT, a Spanish energy research centre, called *TIMES-Spain* (Caldés et al., 2008; Labriet et al., 2010), or the *National Energy Modelling System* (NEMS) from the U.S. Department of Energy (EIA U.S. Department of Energy, 2009). Examples of regional models are the already mentioned PRIMES (Capros et al., 1998) and PET (Pan-European TIMES model), a Europe-based model used for analyzing energy externalities in the frame of the NEEDS project, whose related information can be seen in the International Energy Agency's ETSAP program web page (International Energy Agency, 2013c). Finally, on the global perspective, some representative models are MIT's EPPA (Paltsev et al., 2005), the IEA's World Energy Model (International Energy Agency, 2012f), POLES (Criqui, 1996), and three interesting TIMES-based global models: TIAM (an Integrated Assessment Model⁶⁰ using the MARKAL/TIMES methodology), ETP (Energy Technology Perspectives, the model used for the IEA's homonymous publication) and SAGE (System for the Analysis of Global Energy Markets which tries to replicate some features of real imperfect energy markets as will be seen below). See (International Energy Agency, 2013c) for more information on these last models.

III.2.5. Time representation

Concerning time, each kind of model has its characteristic time representation and horizon: while some models such as top-down integrated assessment models are designed to represent energy system's evolutions for decades, general equilibrium models are less suited for that because their underlying methodology (based in social accounting matrixes as will be seen later) may not allow them to correctly represent economy's structural changes (Rodrigues, 2009), making them more suitable for short term analysis (although the foreseeable use of dynamic stochastic general equilibrium models, DSGE, for energy modeling may change this). Bottom-up optimization problems are situated somewhere in the middle between these two. The models that consider the evolution of a system over several states of time (e.g. years) are called *dynamic*, whereas the models representing only one state of time (which can be useful as well, as will be seen later) are called *static*. We will come back to this in detail in Chapter 4, where we present our methodology, which consists of two models, a static one and a dynamic one.

⁵⁹ More precisely, at the MIT Joint Program on the Science and Policy of Global Change, where the PhD candidate did a research visit during 2012. <http://globalchange.mit.edu/>

⁶⁰ It should be noted that TIAM is not a complete IAM in the sense described in this PhD thesis, because although it does represent climate change and temperature increases, it does not represent how these environmental damages feed back into the economic activity.

III.2.6. Uncertainties and future foresight

Other interesting aspect of energy models is their hypotheses concerning uncertainties and future foresight. Energy systems are subject to great uncertainties about many aspects of the future, like technological advances, the evolution of energy prices or policy developments, just to cite a few. The first main decision that a modeller needs to make before using/developing a model is if she wants to account for these uncertainties *externally* or *internally* to the model. In the first case, she would for instance execute the same model with different scenarios and then assess the uncertainties externally looking at those executions. In the second case, she would model these uncertainties endogenously, for instance modifying the degree of information about the future (i.e. future foresight) that is available to the agents making decisions within the model. More precisely, some models consider *perfect foresight* (i.e. perfect information about the future) while other models, trying to be more realistic about the information that agents have about the future, do take *myopia*⁶¹ into account. Some examples about this (i.e. internal treatment of uncertainties through different levels of myopia/foresight perfection) are given next for better understanding.

The mainstream TIMES model can be considered to represent perfect foresight, because it is solved by minimizing the total discounted energy supply cost over the complete study horizon simultaneously, which implies that information about the future is perfectly available for all the deciding agents. This can be interpreted as a sort of “optimal evolution path” for an energy system, but it is also a hard hypothesis. On the contrary, the TIMES-based SAGE model (International Energy Agency, 2013c) addresses this issue, introducing some myopic forecasting elements within the optimization. Other optimization models can also consider myopia in other ways, such as through dynamic or stochastic programming.

Recursive dynamic models such as POLES or EPPA, treat this issue in a more realistic (i.e. myopic) way: by being recursive, they represent agents making their decisions based on available information each year (in each recursive execution of the model), what represents *adaptive expectations* (i.e. expectations about the future are dynamically formed and adapted with time based on current and past information).

In reality, none of these extremes (i.e. myopia or perfect foresight) are real: certain myopia and uncertainty about the future exist, but decisions are not purely myopic as agents learn from past experience.

It is also interesting to mention policy anticipation: perfect foresight implies policy anticipation from agents, that is, they *know* that a policy will be implemented in the future and prepare for it in an optimal way. In the other hand, if myopia is considered, agents suddenly

⁶¹ Actual agents in actual energy markets have different degrees of *myopia*. One could argue that this is *per se* a *negative* feature: energy markets would be closer to the notion of perfect markets if agents were not myopic. However, from the modeling perspective, myopia is treated as a *positive* feature, because it is closer to the actual behavior of agents, what is in principle desirable in any model. In other words, myopia is a positive feature in a model because it is more realistic in the representation of a negative, but real, feature of agents.

receive the effects of the policy, adapting to it in the best possible way but with less time for preparation. In an ideal world, policy anticipation would normally yield smaller costs and better results from policies, but it may not be realistic. Even more, policy anticipation can also reduce the effectiveness of policies or/and increase their costs if the agents hedge against the policy, which may actually happen in reality according to the “theory of rational expectations”, within which lies the conveniently-termed “policy-ineffectiveness proposition” proposed in 1975 by Thomas J. Sargent and Neil Wallace⁶².

Both extremes regarding policy anticipation by agents are present in reality, and both are interesting to study. Refer to (Babiker et al., 2009) for a comparison of both approaches in the framework of a top-down general equilibrium model applied to climate policy, where one of the main conclusions is, indeed, that global macroeconomic costs of policies for reducing carbon emissions are substantially smaller in the case with perfect foresight. See (Keppo & Strubegger, 2010) for a comparison in the framework of a bottom-up partial equilibrium model also applied to climate policy, where similar conclusions are reached: with myopic foresight, there is a higher reliance on fossil fuels and larger carbon emissions.

To sum up, the modeller should be aware of the different possibilities for treating uncertainty inside or outside the model, and how to deal with it if inside treatment is decided. Also here, the borders within our classification can be unclear. There may be, for instance, a model with perfect foresight executed in several scenarios to externally account for uncertainty, or a recursive model with myopic foresight/adaptative expectations solved only for one set of exogenous data, or any other possible combination.

III.2.7. Technological change

Another crucial aspect of energy modeling is technological change. The costs of technologies evolve with time, mainly due to two factors: (i.) research and development, and (ii.) accumulated experience; being the first one known as *learning-by-research* and the second one as *learning-by-doing*. The way these processes are represented within energy models is very relevant, because they determine future costs of energy assets, and hence technological mixes in the future. Some models consider technological change as purely exogenous (e.g. giving as input data the costs of each technology and how they evolve with time), while others make this evolution endogenous and hence the model may be more realistic. Good references on this subject are the following. (Herzog et al., 1997) is an interesting introductory reference on energy modeling and how technology improvement is represented in them; (Kouvaritakis et al., 2000) reviews how to include these issues in adaptative expectations models, describing the specific case of the POLES model; (Barreto, 2001) describes how to include technological learning in optimization energy models such as TIMES; (Huntington & Weyant, 2002) describe key concepts such as *induced technological change* and *autonomous energy efficiency improvement*; (Löschel, 2002) performs a comprehensive review on how technological change is introduced in

⁶² It was originally proposed for monetary policy, but it could be similarly applied to other types of policies.

E3 models⁶³; (Nordhaus, 2002) describes how to do this in climate policy assessment models; (Berglund & Söderholm, 2006) analyses how learning-by-doing is generally introduced in bottom-up models in the literature; and finally (Jacoby et al., 2006) explains the case of the EPPA model. A very representative model regarding the representation of technological change is WITCH (Bosetti et al., 2006).

III.2.8. International energy markets

Important as well is the representation of the international energy markets that each model considers. The availability and prices of energy sources is a critical aspect for energy systems. National-oriented energy models, like TIMES, consider international energy prices and availability as exogenous data; even if, when representing large countries or regions, the exogenous prices hypothesis does not necessarily hold (i.e. energy decisions in a large country can affect global prices). The same happens with some regional models like the Pan European TIMES model and PRIMES, which consider primary energy prices as exogenous parameters. Global models like EPPA, WITCH or POLES, on the contrary, tend to represent primary energy prices in an endogenous way through devoted international energy market characterizations. Some exceptions are present in the literature: NEMS, although a national model, endogenously considers the evolution of international energy markets (due to the fact that it represents the United States, which is one of the main players); and the World Energy Model, despite being a global model, considers primary energy prices as exogenous.

III.2.9. Summary

The above-introduced concepts are key to understand the remainder of this review of the state of the art, where specific mainstream models and methodologies will be examined in greater detail. However, before doing so, other interesting introductory references to energy modeling are mentioned next, which could be useful to the reader. (Bhattacharyya & Timilsina, 2010) provide a review on energy systems models but with a special focus on developing countries. (Jebaraj & Inian, 2006) provide a wide review of the different types of models with more than 250 references, including (among others, and following their terminology) energy planning models, forecasting models, specific models for analyzing renewable energy or emission reductions, and also including other techniques such as neural networks and fuzzy theory. (David Connolly et al., 2010) analyze almost 40 tools for assessing the integration of renewable energy, although many of them are energy systems models so they are also relevant from our perspective. It includes an estimation of the number of users of each methodology worldwide and some very useful classificatory tables. (Rodrigues, 2009) carries out an in-depth analysis of the state of the art of CGE models applied to energy policy analysis, describing their basic theory, assumptions and criticism, making it a very appropriate starter reference into the

⁶³ E3 is a term normally used in the literature to refer to Energy-Economy-Environmental models, which take into account all the relations in all senses (i.e. also the feedback effects of the environment on the economy and energy sector, or the environmental impacts of other non-energy sectors in the economy).

CGE world. (Van Beeck, 1999) is also a very good review on energy models, although slightly older and with a special focus on local energy planning.

III.3. MAINSTREAM ENERGY MODELS

In this section, some of the most representative families of models in the literature will be reviewed, which cover many of the techniques described above. A brief introductory table will be included at the beginning of each section, where the model is classified according to its main characteristics as described above. It must be noted that within each family, there may be some variants of the model which can present some different features than those described in the introductory table. However, we think it is interesting to include the table, which in each case will represent the characteristics of the mainstream model in each family⁶⁴. For each model/family, there will be three sections:

- First, a description of the main modeling rationale and methods will be done. For this, an introductory table for each model will situate it from the perspective of the techniques/modelling approaches reviewed above (in Section III.2. “Key concepts and techniques”).
- Second, the strong and weak points of each model will be discussed according to our judgment and considering some of the main modelling features that we deem necessary in a sustainable energy policy making tool as explained in chapter 1. These are: (i.) modeling flexibility; (ii.) technological detail; (iii.) economic representation (i.e. how accurately is the energy-economy relation modelled); (iv.) real energy markets (i.e. how detailed is the representation of real, non-perfect, markets); (v.) transparency/ease of utilization; (vi.) direct policy effect modelling (i.e. for transparency, instead of modelling internal agents’ decisions, directly modelling the policy effect, which allows us to have less internal parameters); and (vii.) synergies/trade-off analysis (i.e. our model should allow to well understand interactions between policies, for which dual variables may be very useful). We have left out other features which we believe are not necessarily linked to the modelling itself, such as data acquisition, and presentation of results/magnitudes/units. We have also left out some features which every model includes (i.e. the comprehensive representation of the complete energy sector, because they are all energy models) and also those which none of the models include (i.e. a comprehensive measurement of energy sustainability). Finally decision support techniques, although very important, fall out of the scope of this thesis, so they have not been included either. This discussion, based on seven features, will allow us to better determine the gap to be covered by this thesis (in the conclusion of this chapter) and to justify our methodological proposal in chapter 4.

⁶⁴ For example, MARKAL/TIMES models normally consider perfect future foresight. However, within the MARKAL/TIMES family, there is SAGE, which can represent myopic foresight. In this case, given that SAGE is an exception within the family, the introductory table will say that MARKAL/TIMES considers perfect foresight.

- Third, we will describe some characteristic applications of each model.

III.3.1. Bottom-up partial equilibrium optimization modeling: the MARKAL/TIMES family⁶⁵

III.3.1.a. Description

*Figure 25: introductory table containing the main features of the MARKAL/TIMES family of models.
Source: own elaboration.*

	MARKAL/TIMES
Economic representation	Partial Equilibrium
Env. Feedbacks	No
Modelling technique	Optimization
Technological detail	Bottom-up
Geographic perspective	Customizable
Time representation	Dynamic
Future foresight	Perfect
Technological change	Exogenous
Internat. energy mkts.	Exogenous

The MARKAL/TIMES family of models is one of the flagships of modern energy modeling. MARKAL and TIMES are two different models, but with a very similar rationale (indeed, TIMES is an evolution of MARKAL), hence the literature normally puts them together. According to our research, they have been developed based on ideas from three different, although (maybe/probably) related, sources.

The first one of its precursors was a model used in a study published in the Energy Policy journal in 1975, where the authors use a linear programming model to analyze possible worldwide energy transitions away from fossil fuels by using nuclear energy (Häfele & Manne, 1975). A key contribution of this model⁶⁶ was the use of *processes*⁶⁷ for energy modeling, which is the essence of the subsequently developed MARKAL/TIMES models (and of those developed in this PhD thesis).

Second, and also in the seventies, the EFOM model was developed in Europe, more precisely in France, by Dr. Dominique Finon. It was first used by Dr. Finon for energy policy analysis in France (Finon, 1974) and then adapted by the European Commission to be used for European-wide studies (Van der Voort, 1982). One of the main contributions of EFOM was its

⁶⁵ Special detail will be put into this family of models, given that has inspired much of the methodology in this PhD thesis and since the author of the PhD has done significant modeling work using TIMES.

⁶⁶ For which we have not found a name

⁶⁷ A *process* is, simply, a technology that converts some inputs into some outputs, and for doing so, it has some technical constraints and creates some costs in the studied system. Some examples could be an oil refinery, a nuclear power plant, an electric car or a coal mine. This will be seen later in greater detail.

topological representation as a network of energy transformation processes with energy flows connecting them and flowing between them. Citing from (Van der Voort, 1982), “(...) The energy system used is an oriented network carrying the primary energy over intermediate stages till finally meeting consumers' demand. (...)”.

Third, in the United States, MARKAL itself was being developed during those years (Fishbone & Abilock, 1981; Marcuse, 1974). MARKAL is an acronym for “market allocation”. One of the main contributions of MARKAL was, in our opinion, the concept of *reference energy system*, which is still used nowadays in TIMES (see below). Just like the above-mentioned two models, MARKAL represented in great technological detail (i.e. with a bottom-up approach, using *processes*) an energy system, and optimized (through linear programming) the discounted cost of supplying energy demand (i.e. partial equilibrium) over a period of time. Copying literally the abstract from this reference:

As part of a project to assess the value of new energy technologies, an international group of researchers created a linear-programming model of national energy systems. This model, MARKAL, is driven by useful energy demands, optimizes over several time periods collectively, (...).

The TIMES model (in its many versions) is the latest exponent of this modeling tradition, and tries to capture the advantages of both EFOM and MARKAL without having their main drawbacks. Indeed, TIMES is an acronym for “The Integrated MARKAL-EFOM System”. It was developed under the auspices of the International Energy Agency under the Energy Technology Systems Analysis Programme (ETSAP). Its main references are all contained in the ETSAP web page (International Energy Agency, 2013c; Loulou et al., 2005). The following description is mainly based on them.

As advanced in the table above, TIMES is a partial-equilibrium bottom-up model with an optimization approach. It is *demand-driven* in the sense that the demands for energy are the main input data and the model supplies them while maximising the discounted welfare for society during the complete study horizon. In order to supply these demands, it calculates all the upstream energy flows (final energy distribution networks, energy transformations, energy imports/exports, energy extraction, use of stored energy, etc.), the needed capacities in all processes, the required investments in new capacities (an initial stock of installed capacities can also be introduced), the associated costs or the emissions produced, among others. It is based on the *reference energy system* concept, which is a topological representation of the studied energy system, with processes and commodities flowing among them.

The next thing to be noted about TIMES is that it is not a *model*, but a *model generator*: it is a flexible tool for studying any energy system or subsystem that is completely specified by data, without the need to modify any equation (hence TIMES has sometimes been called *data driven*). The entire energy system, all its processes, commodities, possible flows between them, costs, capacities, efficiencies, etc. are fully specified by data, having the TIMES model itself always the same fundamental and mathematical structure, the same equations, etc. The only aspects that vary among different TIMES-generated models are the number of elements in the different

sets⁶⁸, and the associated input parameters, which are fully specified through data. The first are used for the qualitative description of the model (the topology in the reference energy system, the processes, the commodities, the possible flows, etc.), and the latter are used for the quantitative description. Thanks to its important modeling flexibility and full data-specification, TIMES can be used for studying any local, national or regional energy systems, and for studying only parts of the energy system (e.g. the gas sector, district heating networks, isolated power systems in rural areas, etc.). Multiregional models can also be modeled linking them through trade of commodities (representing for instance energy vectors or emissions). However a large number of regions can make computation too complex.

TIMES optimizes the total social welfare over the complete time horizon (several years), so it is a dynamic model (because it represents several years) with perfect foresight (because it optimizes all periods simultaneously). Actually, it minimizes the total discounted costs of energy supply plus the costs of unsupplied energy, what is equivalent to welfare maximization if perfect energy markets with perfect competition are assumed. All the supply costs are included: investment, decommissioning costs (or revenues), residual values over the study horizon, all fixed and variable costs of energy processes, energy extraction/production costs, energy import/export costs/revenues, and importantly, social costs of unsupplied energy. It also allows for the introduction of costs for all non-energy related commodities, such as used water or materials. This also allows to model environmental externalities: for example it can be modelled that emissions-producing processes have, as one of their outputs, an *emissions* commodity, which then is assigned a cost (e.g. for the case of CO₂ this could be the price of the European emissions market, or the estimated social cost of carbon). MARKAL/TIMES does not include environmental feedbacks on the economy in detail (mainly because they are partial equilibrium models so they do not model the economy). However, TIMES can represent the external costs of some energy commodities as just said and MARKAL can include damage functions in the objective functions.

The demands can be given either in terms of final energy (e.g. electricity, gasoline, etc.) or in terms of energy services (e.g. heating, illumination, mobility, etc.), and they can be price inelastic, price elastic or even specified as a demand curve. Any energy-demanding economic sector can be represented, and the demand can be introduced directly or through expressions which depend on energy demand drivers such as population, GDP, added value per sector, etc. Elasticity makes the problem more complicated, because the objective function is no longer linear. In order to solve it, TIMES performs the linearization through piece-wise linear functions.

Energy policies can be implemented through constraints called *user constraints* (for example maximum emissions, minimum installed capacities of some technologies, minimum efficiency standards, etc.) or through costs/subsidies that can be added to processes or commodities. Both micro (e.g. targeted subsidies) or macro policies (e.g. global carbon tax) are possible. All technologies are completely specified through data, so their costs (and therefore

⁶⁸ Refer to some basic linear programming or GAMS reference to understand these concepts. For instance (Rosenthal, 2010)

technological learning) are in principle exogenous to the model. What is more, some technologies can be considered to be too old or too novel and this can be modeled limiting their availability in some years of the study horizon. In any case, some extensions of TIMES allow making technological representation more realistic: endogenous technological learning (through experience, i.e. learning by doing) or discrete investments (i.e. for example nuclear power plants may only be built in discrete capacity steps of 1GW each) can be implemented, although adding complexity to the model's computation. Citing from (Loulou et al., 2005) "The quality of a TIMES model rests on a rich, well developed set of technologies, both current and future, for the model to choose from."

Primary energy and materials supply can be given by fixed values or by supply curves, which can be stepped functions. This, together with interregional trade, can allow endogenously representing international energy markets in the model. However in most national or regional cases this may not be correct (modeler's judgment should determine it) if the regions do not represent a large-enough share of global markets that would allow them to modify international prices. This is why many of the reviewed TIMES applications have exogenous energy prices.

The time horizon can be divided into periods of variable length, normally n-years (to allow for example for a greater resolution in the shorter term than in the long term), and inside each period time-slices (seasons, months, weekday/weekend, day/night, load levels, etc.). Time slices are specially important when the cost of producing an energy carrier in different times of the year are different, if storage is expensive or impossible, or if there is the need for an infrastructure whose capacity should be able to cope with the yearly's peak demand, such as with electricity. Peaking equations can be also modelled in order to account for power system's *adequacy* and *reserves* requirements, as described in (Batlle et al., 2007).

In this paragraph a brief comparison between MARKAL and TIMES is done, based on the information from (Loulou et al., 2005). Both are technology detailed (bottom-up), partial equilibrium optimization models of the energy sector (in a region or in several), and solved by linear programming. Both maximize total discounted welfare of society while supplying demands for final energy or for energy services; hence they are dynamic models with perfect foresight (as justified above). However there are some features of TIMES not present in MARKAL (mostly much more flexibility and realistic representation of processes, commodities, time representation, data, investment processes, etc.); and some MARKAL features not in TIMES (the possibility of stochastic executions, possible representation of myopic energy markets (MARKAL-SAGE being a clear example), introducing damage costs in the objective function (i.e. MARKAL-MACRO)).

Lastly, and in this case from the economic perspective, the MARKAL-MACRO model is specially interesting: it represents an attempt to link a bottom-up partial equilibrium model (i.e. MARKAL) with a macroeconomic model (i.e. MACRO) in order to be able to account for economic feedbacks and hence advance towards a general equilibrium approach (Manne & Wene, 1992). For a good revision on how to link bottom-up and top-down models refer to (Rodrigues, 2009). Similarly, work is being done in TIMES-Macro, attempting to hard-link TIMES with a top-down representation of the economy using GAMS (Kypreos & Lehtila, 2013).

III.3.1.b. Strong and weak points

As said, punctuation from 1 to 5 (1 being the lowest) will be given for each feature.

- Modeling flexibility: almost any relation between processes and commodities in the studied energy system can be modelled through data and through the convenient user interfaces available (e.g. VEDA⁶⁹). Punctuation: 5.
- Technological detail: a very large level of technological detail can be achieved: the limiting factor in this aspect will hardly be the model itself but data availability. Punctuation: 5.
- Economic representation: it is not accurate if inelastic demand is used, but gets better if elastic demand or even demand curves are used. However, this is a common drawback in partial equilibrium models, which can be somehow overcome by linking them with economic top-down models, such as done in MARKAL-MACRO (reviewed above). Punctuation: 2.
- Real energy markets: the hypotheses of perfect foresight, perfect competition and fully rational agents, which are behind the minimization of the discounted energy supply costs (i.e. minimization of costs is equivalent to welfare maximization if perfect markets are assumed, and intertemporal optimization implies perfect foresight), are far from reality. Energy markets are largely imperfect. These hypotheses may be useful for some studies, but the modeller must know that a real energy system will probably evolve in quite different paths. In addition, one of the most common issues with MARKAL/TIMES is the following: being a linear programming (LP) model, it sometimes yields unrealistic results where, for instance, certain technology (the most convenient from the optimization perspective) is used well over what would be realistic. Some authors call this behaviour of LP optimization models “all-or-nothing” or “knife-edge” solutions (Kydes & Goldstein, 2002). Citing from this reference “Knife-edge solutions/decision-making is a common problem encountered by LP models. It refers to the tendency for a model to invest and/or operate only one type of technology over all others due to its relative cost-competitiveness. However, such model behaviour is not truly representative of actual behaviour in energy markets. Therefore, market sharing/market-penetration adjustments often need to be incorporated in order to make the model respond more realistically”. We experienced this in an undergraduate engineering thesis that we directed from the BP Chair (Pérez et al., 2012)⁷⁰. Punctuation: 1.

⁶⁹ <http://www.kanors.com/Index.asp>

⁷⁰ In this thesis, where TIMES was used to assess energy policies for Spain, the best way to provide urban mobility for passengers (from the optimization perspective) was to use bikes, and the model used it for 100% of the urban movements. This is unrealistic, since many other psychological, comfort or sociological issues, which are not considered in the purely-economical optimization problem, play an important role in users’ decision to use a bike versus other modes such as motorbikes, cars, or public transport. In reality, bike use is much lower. To make LP

- Transparency/ease of utilization: from our perspective, TIMES is not a transparent and easy to use model. The large databases that are needed to run a comprehensive TIMES model, the output information (large spreadsheets full of numbers), the complex parameters (some of them of hard physical interpretation) and the need for a graphical interface such as VEDA make its execution quite complex. In addition, the fact that several years are optimized simultaneously sometimes yields results that can be difficult to understand. Punctuation: 2.
- Direct policy effect modelling: the large political intervention in the energy sector (as explained in chapter 1) can be well represented in TIMES because it is an optimization model. It can be done with the so-called *user constraints* (mentioned above), even if it can be sometimes hard to model (the formulation of user constraints is not always straightforward). But with some practice from the modeller this can be done, so we consider it a positive issue. Punctuation: 3.
- Synergies and trade-off analysis: this can be conveniently done (e.g. shadow prices of user constraints can be extracted from TIMES⁷¹), because there is a clear objective function, but their interpretation can be hard given the mathematical structure of the constraints and the obtained units and data formats. In any case, an expert modeller will be able to do it and extract important information from it. Punctuation: 3.

III.3.1.c. Interesting application examples

Some examples of current uses of the MARKAL/TIMES methodology are given next. In (Labriet et al., 2005), a 15-region World MARKAL model is presented and used to study world GHG emissions and policies for controlling them. SAGE (EIA U.S. Department of Energy, 2003; Kydes & Goldstein, 2002) is an interesting MARKAL model of the world, which intends to better represent some features of real (i.e. imperfect) energy markets, such as: (i.) liberalized energy markets imply that used technologies are not necessarily chosen based on a global cost minimization for the complete system, hence a set of technologies (and not only one, as happens in *knife-edge* solutions) play a role, what is modelled using a *technology penetration algorithm*; (ii.) perfect foresight does not take place, some degree of myopia is always present, which is represented through a recursive optimization for different time steps, instead of a simultaneous/intertemporal optimization of the discounted costs through the complete time horizon. Another global use of the TIMES methodology is ETP-TIMES, used for the analytical calculations in the elaboration of the widely known IEA report *Energy Technology Perspectives* (International Energy Agency, 2012g). It only covers the energy conversion sector of the global

models such as TIMES more realistic, hypotheses about the utilization of certain technologies should be used, and these constraints must be included in the model.

⁷¹ In our opinion, the most convenient way of understanding policy effects in optimization models is to include them as user constraints and, through the shadow prices of these constraints, understand how the policy is affecting the objective function. Policy trade-offs and synergies can be understood by doing it orderly for different constraints (i.e. policies) and, in each step, seeing the variations in the objective function and in the shadow prices of the other constraints.

energy system, not the final energy use sectors. This is because for final energy use sectors, simulation approaches are adopted. This is to correctly consider some of the aspects of the real (i.e. imperfect) energy markets mentioned above, which play an especially important role in final uses, where individuals (instead of firms or governments, which could be considered to be more rational) are making the decisions. ETP-TIMES endogenously represents learning-by-doing technological improvements, through learning curves based on cumulative installed capacities for each technology. Other global TIMES-based model are TIMES-World, used for instance in (Vaillancourt et al., 2008) to assess the future participation of nuclear power for climate change mitigation, or ETM (the EFDA TIMES Model), developed to analyze the role of fusion energy in the future (Cabal et al., 2010; McEvoy et al., 2012).

Another global TIMES-based model is TIAM, TIMES Integrated Assessment Model (Loulou & Labriet, 2008). It contains a climate module able to compute, from the level of greenhouse gas emissions yielded by TIMES and using the equations of the RICE model (Nordhaus & Boyer, 1999), the atmospheric concentrations, the changes in radioactive forcing and the temperature changes. However, it should be noted that TIAM is not a complete IAM in the sense described in this PhD thesis, because although it does represent climate change and temperature increases, it does not model how these environmental damages feed back into the economic activity. (Kesicki & Anandarajah, 2011) uses an improved version of TIAM (e.g. elastic demands, greater desegregation of the Western Europe region) to understand how the reduction in demand for energy services can help in climate change mitigation. Other applications of TIAM, where it is used for the analysis of climate change mitigation policies, are (Ekholm et al., 2010; Loulou et al., 2009; Syri et al., 2008).

At a regional level, it is relevant to mention is TIMES PanEU (or “PET”), the Pan European TIMES model (Blesl et al., 2010; Kypreos et al., 2008; Lavagno & Auer, 2009; RES2020 Project, 2009a), which was for instance used in (RES2020 Project, 2009b) to study European renewable energy objectives in 2020. This model is composed of 29 TIMES-based models of individual countries (EU-25 plus Iceland, Norway, Romania and Switzerland) integrated in a single European model. This leads our discussion to mention some national-level MARKAL/TIMES models.

Some examples of national MARKAL/TIMES models are cited next. TIMES_PT for Portugal, which in (Cleto et al., 2008) is used to analyze the implications of climate change in the Portuguese energy system (more precisely, the impacts of reduced availability of hydro resources). MARKAL UK for the United Kingdom (Kannan et al., 2007), which has been linked to a macroeconomic model (in a similar approach as MARKAL-MACRO) in (Strachan et al., 2009), and is used in (McDowall et al., 2012) to study the implications in the UK of bioenergy sustainability constraints, in (Anandarajah et al., 2009) to analyse pathways for a low-carbon economy in the UK and even by the UK Government to analytically assess their “UK Low Carbon Transition Plan” (UK Department of Energy and Climate Change, 2009b). In (Blesl et al., 2007), a TIMES-based model of the German energy sector is used for the assessment of the role of energy efficiency standards in reducing this country’s CO₂ emissions. Following with Germany, (Remme, 2001) is an interesting reference, where a model of the German energy system done with EFOM is converted into a TIMES model. (Cosmi et al., 2009) describes the Italian TIMES model, which

was created as a part of the development of the Pan European TIMES model. In (Chiodi et al., 2013), the TIMES Ireland model is used to assess, in the 2050 temporal horizon, the impacts of ambitious emissions reductions in that country in line with European targets. (Vaillancourt & Waaub, 2013) perform a study on the electrification of road transportation in Canada in the 2050 horizon using a TIMES-Canada model. The transportation sector is analysed in great detail in (McCollum et al., 2012), where a TIMES model for California is used to analyze measures for ambitious greenhouse gas emissions reductions in 2050, in line with this State's political goal (-80% with respect to 1990). (Chuang & Ma, 2013) use a MARKAL model of the energy system in Taiwan in order to assess how this country's energy policies affect some energy security indicators. MARKAL/TIMES models have also been used for South Africa (Tomaschek et al., 2012), Kazakhstan (Ismagulova et al., 2012), Norway (T. Martinsen, 2011; Seljom et al., 2011), China (Chen, 2005; Chen et al., 2007) or India (Kanudia & Shukla, 1998; Shukla et al., 2007).

Focusing on Spain, the most notable exponent is the TIMES-Spain model developed and maintained at CIEMAT, a Spanish energy research centre. This model is described in (Caldés et al., 2008). Then, for instance, (Labriet et al. 2010) uses it to evaluate the strategies that should be implemented in Spain for achieving the objectives in the EU's 20/20/20 package. Lastly, the author of this PhD thesis and colleagues at the BP Chair on Energy and Sustainability have also developed a TIMES-based model of the Spanish energy system. The first version is explained in (del Dujo et al., 2009); in (García-Maestro et al., 2010) we used it to analyze the plans of the Spanish Government regarding the penetration of electric cars; an improvement of the electricity sector's representation was done in (García-Barredo et al., 2011); and lastly, (Pérez et al., 2012) performs a detailed description of the Spanish transportation sector.

Lastly, regarding methodological developments closely related to TIMES, (Pina et al., 2011) explains how to model hourly dynamics in electricity systems within a TIMES framework, and (Remme et al., 2001) presents MESAP (a user interface for energy models with decision support analysis), which is for instance used in (Pusnik et al., 2012) to analyze Slovenian energy policies.

III.3.2. Bottom-up partial equilibrium simulation modeling: **POLES**

III.3.2.a. Description

*Figure 26: introductory table containing the main features of the POLES model.
Source: own elaboration.*

	POLES
Economic representation	Partial Equilibrium
Env. Feedbacks	No
Modelling technique	Simulation
Technological detail	Bottom-up
Geographic perspective	World (46 regions)
Time representation	Dynamic
Future foresight	Myopic (recursive dynamic)
Technological change	Endogenous (both learning by doing and
Internat. energy mkts.	Endogenous

POLES is the next model to be reviewed. *POLES* stands for “Prospective Outlook on Long-term Energy Systems”. It was developed originally in the 1990s at the *Laboratoire d'Economie de la Production et de l'Intégration Internationale*, within the *Département Energie et Politiques de l'Environnement* of the *Centre National de la Recherche Scientifique* at Grenoble, France (Criqui, 1996).

POLES is a recursive-dynamic simulation partial equilibrium bottom-up model of the world energy system (Institute for Prospective Technological Studies JRC European Commission, 2010; LEPII-EPE & ENERDATA, 2006; LEPII-EPE, 2006). It is recursive-dynamic because it simulates the year-by-year evolution of the world energy system over the future decades in a recursive way: each time step (from current time towards the future) is solved sequentially. The fact of it being solved in a recursive-dynamic way makes it have myopic future foresight capabilities, given that in principle⁷², in each year the model makes its decisions according to the information that it has within that year (which includes information about the past and about the present).

It is a partial equilibrium model where energy demand in all sectors (more than twenty) is calculated from external parameters such as population and economic activity and considering price elasticities and other income effects. The mathematical expressions used to obtain energy demand from these parameters are based on econometric techniques applied to historical data. For instance, the demand for energy in the transportation sector would depend amongst others, on the demand for mobility, which would be calculated per each region through a historically-adjusted expression of GDP per capita, population some price elasticities, etc. The demand for

⁷² In recursive dynamic models it could be made that agents making decisions in a given year somehow anticipate some information about the future, hence not being completely myopic.

energy in this sector, to continue with the same example, would not only depend on the demand for mobility, but also on the used transportation technologies (cars, bikes, etc.), which are accounted for in a bottom-up engineering fashion, having a detailed representation of the stock turnover of end-use technologies⁷³. This is, how many years an average car lasts, how many cars are and of which type are bought or decommissioned each year, or how do external variables (e.g. energy prices, policies) affect these decision and the end-use technologies stock turnover. But even if POLES does include some price elasticities, and how some sectors could react to changing energy trends (e.g. through an accelerated stock turnover towards more energy-efficient equipment), POLES does not fully account for macroeconomic feedbacks. In other words, it is a partial equilibrium model, not a general equilibrium one, although with this purpose it has sometimes been used together with macroeconomic models such as GEM-E3 (Capros, Georgakopoulos, Filippopolitis, et al., 1997; Capros, Georgakopoulos, Van Regemorter, et al., 1997).

Energy transformation and distribution are modelled using simulation/heuristic techniques. Conventional fossil fuels transformation (e.g. oil refining) is modelled through factors for aggregated conversion, transport and distribution efficiencies. Electricity generation is modelled in greater detail, considering regional disaggregation, investment and decommissioning decisions in electricity generation assets, load curves and power plants' dispatch according to their technological and economic characteristics.

POLES models the world using 46 regions. It includes about 40 energy conversion technologies, representing some of the most advanced ones like hydrogen-production and consumption, which were used for a report on the future of this energy carrier (European Commission, 2006).

POLES considers technological change endogenously, modeling both the effects of learning by doing and learning by research through two-factor-learning curves (Herzog et al., 1997; Kouvaritakis et al., 2000). However, it considers exogenous baseline technological improvements as established in the input data and parameters, which come from the *Techpol*⁷⁴ database.

The characterization of international prices of primary energy sources in POLES is done endogenously. For each region, it calculates the costs of resources' extraction as a function of the usage levels of productive capacity and the reserves/production ratios. It also includes energy resources' discovery processes, so that the level of reserves increases with prices and exploration activity. It also includes unconventional fossil resources. Prices are set globally for oil (it assumes one global liquid oil market with uniform prices) and regionally for gas and coal

⁷³ A *stock turnover* algorithm is an accounting routine which keeps record of how many units of each type of equipment are present, by considering: (i.) initial stock; (ii.) stock additions, normally through investments; and (iii.) stock retirement, normally through obsolescence or anticipated scrappage. It can be seen as a *stock and flow* routine, using the terminology of System Dynamics (Stermann, 2000).

⁷⁴ Proprietary database on energy technologies maintained by the Laboratoire d'Economie de la Production et de l'Intégration Internationale.

(it assumes three regions with three different prices for each of these energy resources), and interregional trade is allowed. POLES is implemented in the *Vensim*⁷⁵ software.

POLES accounts for all the greenhouse emissions derived from energy use, not only CO₂. Furthermore, since POLES is a partial equilibrium model of the energy sector, it does not consider the feedback effects of environmental damages into the global economy (being a partial equilibrium model it does not include the representation of the economy, so it cannot include the impacts upon it).

III.3.2.b. Strong and weak points

As said, punctuation from 1 to 5 (1 being the lowest) will be given for each feature.

- Modeling flexibility: the fact of POLES being a proprietary model implemented in Vensim makes it, in our opinion, quite inflexible in its modeling approach. Vensim models require specific software, knowledge of System Dynamics and a deep understanding on the internal relations among variables in the model. This is confirmed by personal experience of the PhD candidate⁷⁶. Punctuation: 2.
- Technological detail: although not as important as can be achieved with the MARKAL/TIMES models, a large level of technological detail is included. Punctuation: 3.
- Economic representation: the fact of POLES being a simulation model, which can include advanced econometric expressions for energy demand characterization, and which can be coupled with macroeconomic models such as GEM-E3, shows that the level of accuracy in the economic representation is significant when compared with other partial equilibrium models. Punctuation: 3.
- Real energy markets: another positive aspect of POLES is its representation of real energy markets, especially due to its flexible simulation framework, to the myopia implied by the recursive nature of the solution algorithm⁷⁷, and to its endogenous representation of global energy markets. Punctuation: 3.
- Transparency/ease of utilization: we believe that the behaviour of such a model can sometimes be hard to grasp and comprehend (because of the complex internal dynamics that, in addition, may be characterised through opaque internal parameters); hence we believe that POLES is not necessarily a transparent and easy to understand model. Punctuation: 2.
- Direct policy effect modelling: as we described in the first chapter, in our opinion (and in the context of this thesis) the relevant aspect is the effect of the policy (e.g. installed wind

⁷⁵ Ventana Systems, Inc. <http://vensim.com/>

⁷⁶ See for instance (González-Blanch et al., 2010), a M.Sc. thesis supervised by the author of this thesis.

⁷⁷ As said, myopia is a positive feature of some energy models, because it represents a realistic, although negative, feature of real markets.

capacity) more than the policy itself (e.g. wind energy subsidies). We think that, POLES being a simulation-based model implemented in Vensim, this is not easily modelled (i.e. not a clear constraint could be used for it). Some features seem to be possible to be included, such as emissions limitations, but others such as technology penetration do not seem clear to us. Some further research on the possibilities of the Vensim software would be needed here. Punctuation: 2.

- Synergies and trade-off analysis: being POLES a simulation model without a clear objective function and without the possibility of assessing shadow prices of constraints makes it, in our opinion, harder to grasp policy synergies and trade-offs. Punctuation: 1.

III.3.2.c. Interesting use examples

The European Commission uses POLES for energy prospective reports, such as the World Energy Technology Outlook-H₂ (European Commission, 2006). It represents long term world energy trends with a special focus on Europe, and includes a baseline scenario (resulting in a large increase in global greenhouse gasses emissions), a decarbonisation scenario, and a decarbonisation scenario making intensive use of hydrogen technologies in case the needed technological breakthroughs are materialized.

(Criqui et al., 1999) used POLES to calculate global costs curves for CO₂ emissions reductions (Marginal Abatement Cost, or MAC curves⁷⁸) and then to assess whether cap and trade would be a good mechanism for reducing emissions in the framework of the Kyoto protocol. More recently, (Criqui & Mima, 2012) used POLES to carry out a study about the synergies, for Europe, of climate change mitigation and energy security policies.

Lastly, in the Spanish context, a national-level version (POLES-Spain) was tentatively used, together with other models, for an energy prospective study for the 2030 horizon (Ministerio de Industria, Turismo y Comercio, 2007). The main results of these model runs are summarized in (Németh et al., 2009). The experience was not a positive one, because of lack of confidence of the team in charge of the study on the preliminary results of the model and the difficulty in understanding the reasons behind these results.

⁷⁸ This paper, interestingly, after calculating the MAC curves compares them with those obtained with EPPA, a global top-down general equilibrium model that will be reviewed below.

III.3.3. Bottom-up partial equilibrium simulation modeling: World Energy Model

III.3.3.a. Description

*Figure 27: introductory table containing the main features of the WEM model.
Source: own elaboration.*

	WEM
Economic representation	Partial Equilibrium
Env. Feedbacks	No
Modelling technique	Simulation
Technological detail	Bottom-up
Geographic perspective	World (25 regions)
Time representation	Dynamic
Future foresight	Myopic (recursive dynamic)
Technological change	Endogenous (only learning by doing)
Internat. energy mkts.	Exogenous

The World Energy Model (WEM) is the one used by the International Energy Agency to perform the analysis and calculations behind the flagship publication *World Energy Outlook* (International Energy Agency, 2012a). The following review on WEM is based on this model's documentation (International Energy Agency, 2009c, 2012f).

WEM is a simulation, bottom-up, partial equilibrium model of the global energy system. In this sense, it is similar to POLES. The world energy system is represented through 25 regions. Demand for energy services is determined through a combination of (i.) econometric relations, in a similar way as in POLES, which depend on socioeconomic drivers such as population and GDP growth, but also final energy prices (to account for price elasticities and, to some degree, for economic feedbacks); and (ii.) stock accounting algorithms for final energy use technologies. A large technological detail is achieved in energy demanding sectors: industry is separated into five sub-sectors (each including a highly disaggregated technological characterization of industrial devices); energy demand from buildings is split into six end-uses (e.g. space heating/cooling, hot water, lighting, cooking); and transport demand is separated into four modes, with special detail given to road transportation due to its relevance.

Considering energy transformation, the electricity sector is modeled through an algorithm that accounts, in each year, for installed generation capacities per region (considering decommissioning and investment decisions). This installed capacity, corrected with a capacity credit (e.g. low value for intermittent renewables) must be larger than peak demand. If it is not, the model invests in new capacity depending on the long run marginal cost of each technology. There is a dispatch algorithm executed in four load levels per year which computes the generation per technology according to its installed capacity and in order of growing variable costs. The variable cost of the last needed technology sets the wholesale electricity price. An advanced algorithm for renewable energies is included, which includes regional computation on financial incentives and renewable potentials and costs, using *dynamic cost-resource* curves as

introduced in the Green-X European project (Huber et al., 2005). An oil-refining module is also included, which includes light, medium and heavy oil products, computes new capacity additions, and calculates refining activity according to an optimization process in order to balance supply and demand per each product category.

Production of primary fossil energy (oil, natural gas, coal) is determined per region with a bottom-up approach based on existing and probable reserves, current extraction, and investment decisions in developing new production projects (considering expected profitability). It includes both conventional and unconventional sources. The international prices of primary energy are given as an external input to the model; they are not derived internally based on production costs as in POLES. One global market is assumed for oil and coal, and regional markets are considered for natural gas. As regards technological learning, only learning by doing is endogenously considered, using exogenous learning rates (i.e. level of cost reduction per unit of increased use of each technology). In any case, baseline technological improvements are given by external data (i.e. how would technologies improve even in the case of no utilization and hence no learning-by-going).

III.3.3.b. Strong and weak points

As said, punctuation from 1 to 5 (1 being the lowest) will be given for each feature.

- Modeling flexibility: as happened with POLES, the fact of WEM being a proprietary mode implemented in Vensim makes it, in our opinion, quite inflexible in its modeling approach. Punctuation: 2.
- Technological detail: it has a very important level of technological detail, in all the stages of the global energy supply chain: (i.) primary energy discovery and production, both in fossil energies and in renewables (using dynamic cost-resource curves); (ii.) energy conversions such as electricity production (considering economic dispatch, load levels, adequacy and reliability constraints) or oil refining (three types of oil products and different refinery types); (iii.) energy transportation and distribution (specially detailed modeling of power grids and their losses, capacities, investments and operation costs); and (iv.) final energy use sectors (with an important disaggregation of end use sectors, technologies and energy services). Punctuation: 4.
- Economic representation: in a similar manner as done in POLES, WEM uses econometric characterizations in order to model demand for energy services using as inputs socioeconomic factors (e.g. population, GDP) and considering price elasticities, so we consider that economic representation is adequate for a partial-equilibrium model. Punctuation: 3.
- Real energy markets: WEM uses mathematical functions (e.g. Weibull, Logit) in order to calculate technology penetration, to more realistically consider how new technologies are adopted. This could be considered to follow the traditions of algorithms such as the *technology penetration algorithm* in SAGE (see above). In addition, it is solved in a yearly recursive-dynamic way, which adds myopia in the model's future foresight. These issues would point to an adequate representation of real energy markets. However, global

energy markets' prices are exogenous, what we consider an important drawback of this model (because it is a global one, where this hypothesis is critical). Even more, energy conversion investments are decided in a purely optimizing manner (using for example, for power generation assets, long run marginal costs), what we believe is not necessarily true in real energy markets, where utilities take other strategic issues into consideration when assessing investments. Some of the aspects above are clearly positive from the perspective of real energy markets modeling (e.g. mathematical functions for technology penetration, myopia). Others (e.g. exogenous international prices, or optimization-based investment decisions in energy conversion assets), could also be considered positive by a reader, arguing that sometimes it is better to make something exogenous rather than having an unreliable or untrustworthy internal algorithm (indeed, we will defend a similar position later, when presenting our dynamic model). However, in this point of the PhD thesis we will consider them as negative, because from the modeling perspective (assuming that we had a very powerful modeling team, good data availability, etc.) it does not closely represents real energy markets. And they are (in our opinion) negative enough to make this whole area (i.e. real energy markets) have a low punctuation in WEM, even if it includes positive aspects (i.e. mathematical functions for technology penetration, myopia). Punctuation: 2.

- Transparency/ease of utilization: linked to the previous point, we believe that the behaviour of such a model can sometimes be hard to grasp and comprehend; hence we believe that WEM is not necessarily a transparent and easy to understand model. Punctuation: 2.
- Direct policy effect modelling: similarly as happened with POLES, because WEM is also a Vensim-based simulation model, a clear constraint representing this cannot be included (although more research on Vensim could be useful) In any case, as also happened with POLES, policies can be included (e.g. premiums, tariffs, etc.) which is also a good modelling feature. Punctuation: 2.
- Synergies and trade-off analysis: just as happened with POLES, WEM being a simulation model without a clear objective function and without the possibility of assessing shadow prices of constraints makes it, in our opinion, harder to grasp policy synergies and trade-offs. Punctuation: 1.

III.3.3.c. Interesting use examples

As said, the only but very relevant use of WEM is the analysis and calculations behind the *World Energy Outlook* (International Energy Agency, 2012a).

III.3.4. Bottom-up partial equilibrium optimization modeling: PRIMES

III.3.4.a. Description

*Figure 28: introductory table containing the main features of the PRIMES model.
 Source: own elaboration.*

	PRIMES
Economic representation	Partial Equilibrium
Env. Feedbacks	No
Modelling technique	Optimization
Technological detail	Bottom-up
Geographic perspective	Extended Europe
Time representation	Dynamic
Future foresight	Myopic or perfect
Technological change	Endogenous (only learning by doing)
Internat. energy mkts.	Exogenous

PRIMES stands for “Price Inducing Model of the Energy System”, and has been developed, since the 1990s, at the National Technical University of Athens in close collaboration with the European Commission (Capros et al., 1998; E3Mlab of ICCS/NTUA, 2005, 2011).

It is a bottom-up partial equilibrium model of the European energy system, including the European Union 27, the countries in the Western Balkans, Switzerland, Norway and Turkey. Even if it is a partial equilibrium model, it has some macroeconomic inputs (normally coming from the GEM-E3 model) that are used to calculate the levels of energy demand (which include price elasticities). It is an optimization model but presents a fundamental difference from MARKAL/TIMES. Instead of optimizing a global objective function for the entire energy system (e.g. minimize total system costs), each agent in the energy system solves its own optimization problem (e.g. maximizing their benefit/utility) and different agents interact in the markets for final energy through energy prices. This aims to more fundamentally represent liberalized energy markets and how each agent has its own interests. It simulates the market equilibrium for all forms of energy: the model is solved in an iterative manner until all energy markets reach equilibrium, that is, until prices reach a value in which all agents are in their optimum (no agent has the incentive to deviate from that point). PRIMES is formulated as a non linear Mixed Complementary Problem (MCP) written in GAMS and solved with the PATH solver. The MCP formulation is mathematically very useful because it allows to conveniently representing non linear problems, and also to model each agent having a different objective function, instead of being a global objective function for all agents (MCPs are also used, for instance, in equilibrium models of the electricity sector⁷⁹, or in computable general equilibrium models, as will be seen below). The fact of it being non-linear allows for including important details such as power and

⁷⁹ The research Institute where this PhD thesis has been developed (IIT, Comillas University, Madrid), has large experience in this field.

gas grids (including network expansion and energy flows), imperfect competition in some markets, non-linear energy commodities supply curves, or endogenous learning-by-going technological progress.

The market equilibrium is static in each time period (5-year periods), but is repeated in successive periods whose successive equilibriums are dynamically related. Capital stock turnover is accounted for, considering temporal vintages (different types of equipment depending on technological advances available at each year). Primary energy prices are exogenous, which makes sense because PRIMES only represents Europe, which is a relatively small player in global energy markets (represents less than 15% of global energy use) and is foreseen to become even smaller in relative terms. Official price projections are used, taken from models such as POLES or from prestigious reports such as the World Energy Outlook.

As an idea of the level of technological detail, it is useful to mention that the version of PRIMES used for the European 2050 Energy Roadmap (Capros, 2011a; European Commission, 2011b) considered: (i.) twelve industry sectors, subdivided into more than twenty sub-sectors which used energy in twelve generic industrial processes (e.g. furnaces, ovens, air compressors,); (ii.) five tertiary sectors, using energy in six processes (e.g. air conditioning, office appliances); (iii.) four house types considering more than ten types of electrical appliances; (iv.) four transport modes, ten transport means (e.g. bus, bikes, cars,) and ten vehicle technologies (e.g. hybrid, combustion engine, etc.); (v.) almost fifteen fossil fuel types, new fuel carriers such as hydrogen and biofuels, and ten renewable energy types; (vi.) power and steam generation with 150 technologies and considering grid interconnections and reinforcements; (vii.) seven types of polluting emissions; (viii.) gas supply, oil refining, biomass supply, primary energy extraction or hydrogen production and consumption. PRIMES is programmed in a modular manner so that individual modules could be separately improved.

Considering technological learning, it is endogenously modelled, using learning by doing on top of the baseline technological improvements that are given by external data. An important feature of PRIMES is that it is able to consider important features of real energy markets such as myopia (recursive dynamic execution, although in some sectors such as electricity it performs intertemporal optimization, representing perfect foresight), psychological issues (e.g. habits, comfort), high discount rates in individual energy consumers, or imperfect competition/oligopoly. It considers European trade of electricity and gas, considering capacity limitations and network expansions. For more detail on the latest version of PRIMES refer to (Capros, 2011a, 2011b; E3Mlab of ICCS/NTUA, 2011).

III.3.4.b. Strong and weak points

As said, punctuation from 1 to 5 (1 being the lowest) will be given for each feature.

- Modeling flexibility: PRIMES is programmed in a modular manner, which allows improving certain parts of the model independently, providing important modeling flexibility. Punctuation: 3.
- Technological detail: as said, PRIMES has a very significant level of technological detail, considering a large number of technologies and important issues of the energy sector

such as networks (including energy flows and grid capacities and reinforcements), detailed dispatch algorithms for the electricity sector (considering load levels and reliability constraints) or stock turnover of energy use equipment considering investment and decommissioning decisions. Punctuation: 5.

- Economic representation: PRIMES is a partial equilibrium model with elastic demands, so the level of responsiveness from the rest of the economy is fair but not great. In our opinion, PRIMES does not use expressions as advanced as POLES or WEM to estimate demand based on drivers, hence its economic representation is slightly worse to the one in those models. However, as a positive note, PRIMES can be linked with macroeconomic models such as GEM-E3 and this can be improved. Punctuation: 2.
- Real energy markets: another largely positive feature of PRIMES is its realistic representation of liberalized (and imperfect) energy markets. Each agent is represented with its own objective function and they all interact in the market through energy prices. A non linear mathematical formulation is used and the model is solved in a recursive dynamic manner. This allows representing issues such as imperfect competition in some markets, psychological habits or preferences, or myopia/high discount rates. A negative aspect of PRIMES concerning the representation of real energy markets could be the fact that international primary energy prices are given as exogenous data. However, we do not consider this as negative as in the case of WEM because PRIMES (contrarily to WEM) is a regional model only representing Europe (which is a relatively small region in the world energy markets, consuming less than 15% of primary energy in the world). Hence this area (i.e. real energy markets) obtains a good punctuation in PRIMES Punctuation: 5.
- Transparency/ease of utilization: mathematically, PRIMES is a non-linear Mixed Complementary Problem (MCP), solved iteratively until equilibrium is reached in all energy markets. This is a complex mathematical structure, what we believe makes it complex for non familiarized policymakers to understand. Obtained results may be counterintuitive and hard to grasp. Hence we believe that the lack of transparency/ease of understanding is one of the main weaknesses of PRIMES. Punctuation: 1.
- Direct policy effect modelling: this point is in our opinion favourable, because PRIMES being an optimization problem, it could include constraints to simulate a policy effect as already having taken place. This may be hard to implement from a mathematical/programming perspective, but it could be done. Punctuation: 3.
- Synergies and trade-off analysis: just as happens with simulation models like POLES and WEM, or with optimization models with decentralised objective functions (i.e. each agent having hers, such as PRIMES, EPPA and WITCH in its non-cooperative mode), PRIMES is a model without a clear objective function (each agent has her own objective function). Even more, it has a complex mathematical structure. These issues make it complex to include policies as constraints and analyze their shadow prices what, in our opinion, complicates the task of grasping policy synergies and trade-offs. Punctuation: 1.

III.3.4.c. Interesting use examples

The most important and notable uses of PRIMES are the energy prospective studies carried out by the European Commission, such as the *Energy Roadmap 2050* (European Commission, 2011b) or the *EU Energy Trends to 2030* (European Commission, 2010). Other interesting studies using PRIMES are (Bulte et al., 2007), which looks at the role of electricity in future energy systems; (Eurelectric, 2010) or which analyses pathways to obtain a carbon-neutral electricity system in Europe in 2050. PRIMES has also been used to analyze policy proposals from the European Commission, such as the 2008 EU policy package on climate change and renewables (Capros et al., 2008).

III.3.5. Bottom-up general equilibrium simulation modeling: NEMS

III.3.5.a. Description

*Figure 29: introductory table containing the main features of the NEMS model.
Source: own elaboration.*

	NEMS
Economic representation	General Equilibrium
Env. Feedbacks	No
Modelling technique	Simulation
Technological detail	Bottom-up
Geographic perspective	USA (sub divisions)
Time representation	Dynamic
Future foresight	Myopic or perfect
Technological change	Endogenous (only learning by doing)
Internat. energy mkts.	Endogenous

NEMS stands for “National Energy Modeling System” and it is one of the main models used by the US Government (within the Energy Information Administration, which belongs to the Department of Energy) to perform their energy forecasts (e.g. the Annual Energy Outlook) and analysis (EIA U.S. Department of Energy, 2009, 2012a).

NEMS is similar to PRIMES in its main modeling approach, where each agent has its own interests and hence its own objective function and they all interact in the energy markets through produced/consumed energy quantities and their associated prices. It is also modelled in a modular fashion, facilitating model maintenance and improvements (what is more, the different modules of NEMS can be executed independently). However NEMS explicitly includes a macroeconomic module which receives (from the rest of NEMS) energy prices and simulates the adjustment of the rest of the economy in order to provide (to the rest of NEMS) economic

activity in all economic sectors⁸⁰: this is a further improvement compared to PRIMES, and it allows us to classify NEMS in the general equilibrium category.

It is solved in a recursive dynamic way, going forward year by year up to 2035. For each year, the so-called *Integrating Module* of NEMS solves each module iteratively until convergence is reached (uses the *Gauss-Seidel* algorithm⁸¹). It is a bottom-up model because it has a large level of technical detail, accounting for several tens of technologies in each sector (residential, commercial, transportation, power, coal production, etc.), as shown in (EIA U.S. Department of Energy, 2012b). NEMS represents the United States of America through different sub national divisions according to the necessities of each energy sector.

We classify it as a simulation model because, although it has some modules that are solved by optimization (e.g. the coal market module, which is a linear programming module), some others are solved by stock turnover accounting algorithms and other *soft* methods, hence in our opinion, the overall model cannot be classified as optimization, being simulation a more adequate term. Other authors also classify NEMS as a simulation⁸² model (Das et al., 2007; Mundaca & Neij, 2009; Timilsina, 2011), although this is not clear in the literature, as some consider NEMS as an optimization model (Bhattacharyya & Timilsina, 2010). This is a main difference with PRIMES, which is indeed an optimization model because all modules (i.e. agents) solve an optimization problem (programmed in GAMS and solved iteratively using the PATH solver, as said above).

Concerning foresight, just as happened in PRIMES, different hypothesis can be made for different agents: myopia, adaptative expectations or rational expectations (i.e. perfect foresight) can be used. NEMS endogenously determines the prices of international energy markets⁸³ (oil, oil products, natural gas), using an International Energy Module (for oil products), a Coal Market Module and a Natural Gas Transmission and Distribution Module. This is another fundamental difference from PRIMES, and it makes sense because the US is a larger player in world energy markets than Europe, representing around a fifth of world energy consumption. Lastly, regarding technological improvements, NEMS includes learning-by-doing in sectors such as electricity generation (Gumerman & Marnay, 2004). Environmental feedbacks (e.g. reductions in economic activity due to energy-driven environmental impacts) are not considered in NEMS.

⁸⁰ More variables are received and produced by this module, such as employment levels or interest rates, but only energy prices and economic activity are mentioned in this PhD thesis for clarity purposes.

⁸¹ Even if this algorithm is intended for linear systems of equations, it works in NEMS (some equations are non-linear) because they are all monotonically increasing (e.g. supply curves) or monotonically decreasing (e.g. demand curves) (EIA U.S. Department of Energy, 2012b).

⁸² We are considering the *accounting* models as included in the *simulation* category, because in the end what they do is account for stock turnover, what can be considered as a simulation of this process. This is relevant here because in one of these references, the authors consider NEMS as an *accounting* model.

⁸³ Normally, at the relevant delivery point for the US market

III.3.5.b. Strong and weak points

As said, punctuation from 1 to 5 (1 being the lowest) will be given for each feature.

- Modeling flexibility: NEMS is programmed in a modular manner, which allows improving certain parts of the model independently or even executing them independently, for individual studies or model's maintenance/improvements. Punctuation: 3.
- Technological detail: just as PRIMES, NEMS has a very significant level of technological detail, considering a large number of technologies and important issues of the energy sector such as networks (including energy flows and grid capacities and reinforcements), detailed dispatch algorithms for the electricity sector (considering load levels and reliability constraints) or stock turnover of energy use equipment considering investment and decommissioning decisions. Punctuation: 5.
- Economic representation: we consider NEMS to be a general equilibrium model (contrary to PRIMES) because it is permanently linked to a macroeconomic module⁸⁴ which computes the reactions of the rest of the economy to developments in the energy sector calculating the adjustment of the rest of the economy (activity per productive sector, employment levels or interest rates). This is one of the key advantages of NEMS in our opinion. Punctuation: 4.
- Real energy markets: another largely positive feature of NEMS is its realistic representation of energy markets. Each agent is represented with its own decision algorithm, and they all interact in the energy markets, solved by the iterative integration algorithm in NEMS. This gives NEMS enough modelling flexibility to represent issues such as myopia or anticompetitive behaviours. In addition, NEMS performs an endogenous representation of global energy markets, which is a positive feature. Punctuation: 5.
- Transparency/ease of utilization: computationally NEMS is set of interconnected modules, each with its own internal logic, solved iteratively until equilibrium is reached in all energy markets. This is a complex structure, what we believe makes it complex for non familiarized users to understand. Obtained results may be counterintuitive and hard to grasp. Hence we believe that the lack of transparency/ease of understanding is one of the main weaknesses of NEMS. Punctuation: 1.
- Direct policy effect modelling: this point is in our opinion similar to POLES and WEM, because NEMS is also a simulation model, hence constraints to represent this issue cannot be included. In any case, as happened with POLES and WEM, the policies themselves can be represented (e.g. feed in tariffs, etc.), which is a good feature. Punctuation: 2.

⁸⁴ Developed by IHS Global Insight, Inc. <http://www.ihs.com/products/global-insight/index.aspx>

- Synergies and trade-off analysis: just as happened with POLES, WEM and PRIMES, NEMS is a model without a clear objective function (each agent has its own guiding principles/objective function). Even more, it has a complex computational/mathematical structure. These issues make it hard to include policies as constraints and analyze their shadow prices what, in our opinion, complicates the task of grasping policy synergies and trade-offs. Punctuation: 1.

III.3.5.c. Interesting use examples

The United States Energy Information Administration uses NEMS to develop several studies and projections, being the Annual Energy Outlook among them (EIA U.S. Department of Energy, 2012a)

It has also been used for some special analyses at the request of the U.S. Administration, Congress or other government agencies. For instance, it was used to analyze the energy and economic impacts the American Clean Energy and Security Act of 2009 (i.e. the Waxman-Markey Bill, which intended to create an emissions trading scheme in the U.S.). It was also used to assess the impacts of the 25% renewable electricity standard that was included in the American Clean Energy and Security Act.

III.3.6. Top-down general equilibrium optimisation modelling: the EPPA Family

III.3.6.a. Description

*Figure 30: introductory table containing the main features of the EPPA model.
Source: own elaboration.*

	EPPA
Economic representation	General Equilibrium
Env. Feedbacks	Mainstream EPPA no. Yes, if coupled with IGSM or EPPA-HE.
Modelling technique	Optimization
Technological detail	Top-Down
Geographic perspective	World (16 regions)
Time representation	Dynamic
Future foresight	Myopic or perfect
Technological change	Endogenous
Internat. energy mkts.	Endogenous

EPPA stands for “Emissions Prediction and Policy Analysis”. Refer to (Babiker et al., 2001) for documentation on EPPA version 3, and to (Paltsev et al., 2005) for EPPA 4, the last official full-fledged version (although EPPA5 is under development at the moment). It is the human activity module in MIT’s IGSM (Integrated Global System Model) model, which is MIT’s integrated assessment model (Sokolov et al., 2005). But apart from IGSM, EPPA can be used as a standalone model.

EPPA is a top-down computable general equilibrium (CGE) model of the world economy. For a good review on CGE modeling, its economic foundations, advantages, assumptions and drawbacks, refer to (Rodrigues, 2009). EPPA being a CGE top-down model, it is fundamentally different from all the above models. It represents the evolution of all economic sectors of the world economy (including how energy is demanded and consumed) and the associated emissions and other environmental impacts such as land use change. Its level of technical detail is much lower (it is a top-down model) and its modeling rationale is more of a purely economic one. In it, all the agents in an economy are represented: (i.) firms of any sector (energy or any other), which provide goods and services while demanding production factors (normally labor and capital) and have a profit-maximizing behavior (ii.) households, which demand goods and services while providing production factors and have a utility-maximizing behavior; and (iii.) governments which are a purely distributional agent providing goods and services in exchange for taxes. International trade of goods and services can also be modeled.

EPPA 4 represents the world through 16 regions, it includes 14 sectors (5 being energy industries, i.e. coal, crude oil, refined oil, gas, electricity) and considers 11 production factors (3 being limited fossil fuels i.e. coal, oil and gas). Compared to previous versions, EPPA 4 includes significant degree of detail in energy sectors such as electricity, oil and gas, as well as a better representation of natural gas international trade. Within the electricity sector, ten generation technologies are considered. It also models the required backup capacity for intermittent sources of power production. Five types of gas are considered in the gas sector, three types of oil in the crude oil sector, biofuels are included in the refined oil sector. The household transportation sector (another of the 14 represented sectors) considers 4 technologies.

EPPA's main exogenous inputs are: (i.) the growth in population and productivity; (ii.) the reserves of fossil fuels in each region; (iii.) some values to determine the peoples' preferences for saving their income or to spend it in various goods; (iv.) and some exogenous parameters to define technological evolution in the energy sector, called *autonomous energy efficiency improvement* (AEEI). This allows EPPA to represent in a dynamic manner, among others: (i.) the process of capital accumulation (accounting for new investments and capital depreciation); (ii.) the demand and provision of goods and services throughout the economy and the prices in all these markets, which multiplied (quantities times prices) allows to compute GDP in all regions; (iii.) and, derived from this, the energy demand per region, fossil fuels depletion and emissions.

Another basic input for CGE models such as EPPA is the social accounting matrix (SAM), which is a representation of a country's national accounts and represents the flows of all economic transactions that take place within an economy. They provide the information on how much of each good/service is required in the economy to produce a unit of other good/service (in firms) or a unit of utility (in households). In this sense, EPPA relies on the GTAP dataset, which provides actualized and complete SAM matrixes for all the modeled regions, considering international trade.

Mathematically, EPPA is formulated as a mixed complementary problem (MCP) problem where each agent performs its own optimization, without the existence of a global optimization, until equilibrium is reached (through prices) in all markets (for all goods and services). This is a

similar approach to PRIMES, and hence we also classify it as an optimization model. It is solved in a dynamic manner from the present to the future. EPPA is written in the MPSGE language (Rutherford, 1998), a subset of GAMS which greatly simplifies the formulation of CGE models, but can also make it less flexible.

There are several versions of EPPA, each of them representing a sector in greater detail, all developed from the original EPPA in order to carry out different specific studies. For example: (i.) EPPA-HE models in greater detail the health impacts of emissions, hence accounting for environmental feedbacks into the economy; (ii.) EPPA-HTRN models the household transportation sectors accounting for different types of vehicles and transportation policies (Karplus, 2011) and it is used to analyze policies affecting this sector such as the CAFE fuel efficiency standards in the United States (Karplus & Paltsev, 2012); (iii.) EPPA-AGRI disaggregates the primary sector into forestry, crops and livestock; (iv.) EPPA-LUC is a further refinement of EPPA-AGRI which also represents land use changes and has been used to analyze the impact of biofuels production (Gurgel et al., 2007); (v.) EPPA-ROIL improves the representation of oil refining; (vi.) or EPPA-EURO, which further disaggregates European countries to better analyze energy policies in Europe. Some of these enhancements will be included in the next publicly released version of EPPA (EPPA5).

Concerning future foresight, there are two main versions of EPPA: the mainstream one (all EPPA versions mentioned above belong to this one) is recursive dynamic, where a static CGE is solved period after period sequentially, each agent optimizing its own objective function in the considered period only having information about present and past, and keeping a correct accounting of intertemporal relations such as cumulative emissions, capital accumulation and depreciation, or resource depletion. This version therefore represents myopia. A forward-looking version of EPPA has been also developed (Babiker et al., 2009) which maximizes intertemporal utility or the discounted present value of profit based on both current and future prices and where all periods are solved simultaneously. This case represents perfect foresight and policy anticipation from agents. As said above, in reality, none of these extremes are real: certain myopia and uncertainty about the future exist, but decisions are not purely myopic as agents may learn from past experience and can have some forecasting/anticipation skills, as stated by the above-mentioned “theory of rational expectations”.

Regarding technological change, EPPA has three main exogenously established parameters: (i.) labour productivity increases; (ii.) land productivity growth; (iii.) an exogenous improvement of productivity in the use of energy as an economic input (*Autonomous Energy Efficiency Improvement*, AEEI). In addition to this, EPPA being a CGE model, it also has some endogenous features, which are inherent to the modeling philosophy of most general equilibrium models (i.e. the very concept of production function⁸⁵) and which can be considered to represent (although in a limited manner) technological change (Jacoby et al., 2006). Even more, it does include the future penetration of explicit advanced technologies if they are competitive from the economic viewpoint. This allows us to assert that EPPA does include

⁸⁵ In economic theory, a production function is used to relate which inputs and in which proportions are needed to produce each unit of output. It represents the underlying production processes and technologies.

endogenous technological change, but in a somehow different manner as bottom-up engineering models which use concepts such as learning-by-doing and learning-by-research.

Lastly, the representation of international energy markets is also endogenous: the model receives as exogenous inputs the reserves of fossil fuels in different regions, considers the extractive sectors explicitly (through their production functions), and models the supply, demand and trade of primary energy, obtaining the resulting prices.

Within EPPA's research group at MIT, some other similar models exist. USREP (Rausch et al., 2009) is another world CGE model but in this case with a special level of detail of the United States. China-in-Global Energy Model (C-GEM) and China Regional Energy Model (C-REM), currently being developed⁸⁶, are similar models but in this case with a special focus on China (specially the second one) in order to analyze climate and energy policies in this important country (D. Zhang et al., 2012, 2013; X. Zhang et al., 2013).

III.3.6.b. Strong and weak points

As said, punctuation from 1 to 5 (1 being the lowest) will be given for each feature.

- **Modeling flexibility:** even if CGE modeling implies a large level of economic knowledge and important data inputs, we believe that two facts could point at some level of modeling flexibility in EPPA: (i.) so many different versions of EPPA (and similar models such as USREP or the China models) have been developed, each of them putting special focus on one region or sector (e.g. agriculture/land use change, oil refining, etc.); (ii.) the EPPA research group at MIT⁸⁷ continues further improving and developing EPPA, most notably (from this thesis' perspective) trying to include bottom-up detail of energy sectors such as electricity or oil refining, in order to advance towards hybrid top-down bottom-up models⁸⁸. However it must be noted that in order to attain this, important modeling teams are working on it, so this is not the type of modeling flexibility defended in this PhD thesis. Even more, CGE models are far less flexible than bottom-up models in representing technological detail, as said above. Punctuation: 2.
- **Technological detail:** since EPPA is a top-down general equilibrium model, the level of technological detail that it achieves is not the adequate one to treat important issues such as the electricity sector: in it, the fact that electricity cannot be stored at large quantities (implying the need to have a constant balance of supply and demand at all moments), the intermittency of renewables' generation and other technical issues, imply that special modeling bottom-up approaches (e.g. load levels or technical issues in generation dispatch) must be used. As said, however, work has been and is currently being carried out at MIT to overcome these difficulties, For example, (Rausch & Mowers,

⁸⁶ Within an ambitious collaborative research project between MIT (USA) and Tsinghua University (China), called "China Energy & Climate Project". <http://globalchange.mit.edu/CECP/>

⁸⁷ MIT Joint Program on the Science and Policy of Global Change

⁸⁸ Prof. Pérez-Arriaga, one of the advisors in this PhD thesis, is actively involved in some of these works.

2012) present a *soft-link* (an iterative exchange of results between two models) between USREP and ReEDS (a bottom-up model of the power sector in the U.S.). We also think that, although some technological disaggregation is being attained in the energy production sectors, the same may not be true for energy demanding sectors, where much of the future energy policies will be targeted (in order to improve energy efficiency and produce energy savings). Punctuation: 2.

- Economic representation: very solid, with a full integration of the energy sector in the rest of the economy and even with the possibility of including environmental feedbacks into the economy through the IGSM model, which is more detailed in its effects than the typical damage functions used in other models such as RICE (Nordhaus & Boyer, 1999) or WITCH (Bosetti et al., 2009), as will be seen next. By this, we mean that IGSM includes a kind of a bottom-up approach to environmental damages (e.g. explicitly considering the reduced productivity of land, the health problems which reduce the labour force, or the reduced availability of water as an economic input), which is more detailed than damage functions that just relate an increment in temperatures with a reduction in GDP. Refer to (Sokolov et al., 2005) for more details on IGSM. Punctuation: 5.
- Real energy markets: we believe that the representation of real energy markets is also good in EPPA, because it explicitly models the decentralized decision making process (each agent having its own optimizing behaviour without necessarily considering the global optimum) and the myopia (in its recursive-dynamic versions). However, the fact of considering one production function per sector implies assuming perfect competition, what may not be the case in capital-intensive and technologically complex sectors such as energy. Punctuation: 3.
- Transparency/ease of utilization: EPPA is a complex model from a theoretical, mathematical and computational perspective. It relies on an extensive database such as GTAP, being the SAM matrix (a CGE's model backbone) a concept that is not straightforward to grasp. Obtained results may be counterintuitive and difficult to understand. Hence we believe that the lack of transparency/ease of understanding is one of the main weaknesses of EPPA. Punctuation: 2.
- Direct policy effect modelling: since EPPA is an optimization model, constraints can be included. In addition, although it is a top-down model, it includes some technological detail. Hence we think that the type of constraint upon a certain technology that would be needed to represent this issue could be included. Punctuation: 3.
- Synergies and trade-off analysis: just as happened with previous models, EPPA is a model without a clear objective function (each agent has its own guiding principles/objective function). Even more, it has a complex computational/mathematical structure. These issues make it hard to include policies as constraints and analyze their shadow prices what, in our opinion, complicates the task of grasping policy synergies and trade-offs. Punctuation: 2.

III.3.6.c. Interesting use examples

EPPA and similar models (e.g. USREP, both China models) are being used for various and interesting energy, climate and even economic policy questions. For instance, USREP has been used to analyze the effects of a carbon tax in the United States: if it would be a sensible fiscal policy for dealing with its budget deficit while addressing emissions, taking into account a possible double dividend⁸⁹ and distributional effects (Rausch & Reilly, 2012). In (Morris et al., 2008, 2012), the EPPA model is used to carry out an analysis on CO₂ global marginal abatement costs (MAC) curves. It has also been used to analyze transportation policies such as the CAFE fuel efficiency standards in the United States (Karplus & Paltsev, 2012) or how these would interact with a cap on carbon emissions (Karplus et al., 2012). (Paltsev et al., 2012) analyze the role that China should play in mitigating global climate change, and its associated costs. EPPA has also been used to analyze the consequences of the shale gas phenomenon in U.S. energy and climate policies (Jacoby et al., 2011), or for the consequences of a nuclear-free future in that country (Jacoby & Paltsev, 2013). Impacts of European biofuels and climate policies on the car fleet are analyzed in (Gitiaux et al., 2012). The above-mentioned China models are used to analyze renewable development in that country (X. Zhang et al., 2013), how a fossil energy cap would affect (D. Zhang et al., 2013), or the consequences of CO₂ intensity targets (D. Zhang et al., 2012).

⁸⁹ The concept *double dividend* is used in environmental economics to refer to the advantages of a *green tax reform*. If a tax is levied on some type of negative environmental externality (e.g. emissions or pollution) and the produced income is used to reduce direct taxes on productive activity (e.g. taxes on salaries or on corporate profits), two benefits are obtained: reduced negative externalities and improved economic activity. There is broad academic and practical evidence of this approach of “taxing the bads and not the goods”.

III.3.7. Top-down general equilibrium optimisation modelling: WITCH

III.3.7.a. Description

*Figure 31: introductory table containing the main features of the WITCH model.
 Source: own elaboration.*

	WITCH
Economic representation	General Equilibrium
Env. Feedbacks	Yes, IAM
Modelling technique	Optimization
Technological detail	Top-Down
Geographic perspective	World (12 regions)
Time representation	Dynamic
Future foresight	Perfect
Technological change	Endogenous (both learning by doing and learning by research)
Internat. energy mkts.	Endogenous

The last mainstream energy model to be reviewed is WITCH, acronym standing for “World Induced Technical Change Hybrid”. It has been developed at the Fondazione Eni Enrico Mattei (Bosetti et al., 2006, 2009).

WITCH is a global model for climate change policy analysis, i.e. an integrated assessment model, which explicitly represents environmental feedbacks, i.e., the economic damages produced by climate change. It is a general equilibrium model with a good level of technological detail, especially due to its representation of technological change. In any case, even if the authors classify it as a *hybrid* model, we do not think that it has enough technological detail to be classified as such. In the literature, apart from WITCH, there are models which combine top-down and bottom-up approaches but all of them, WITCH included, put a stronger emphasis in one or the other, and this is why we would not classify them as *hybrid*. In our opinion, both EPPA and WITCH are top-down models, even if ongoing research is taking them close to the *hybrid* category. One interesting feature of WITCH is that it combines the bottom-up and top-down rationales with a *hard-link* approach. Instead of solving the top-down and the bottom-up modules iteratively until convergence is reached, as done in NEMS or in (Rausch & Mowers, 2012) where USREP and ReEDS are linked, WITCH solves both at the same time. Decision variables in the bottom-up representation of the energy sector are decided at the same time as those in the top-down model of the rest of the economy, i.e. a *hard-link*. These decision variables normally represent investment / consumption choices. EPPA also presents these features.

WITCH is a global model, simulating the world in 12 regions, and it is dynamic because it represents the future up to the year 2100. It has perfect foresight, as it simultaneously maximizes the discounted flow of consumption up to 2100. It maximizes consumption under the assumption that it is a good proxy for welfare, which is a common assumption in CGE modeling.

The main external drivers of WITCH are population increases and total factor productivity growth which, together with other internal variables such as investments in capital and labour, condition global GDP growth. For the bottom-up representation of the energy sector, needed external parameters include costs (investment and operational), fuel efficiencies, capacity factors of power generators, life and depreciation rates (different to the social discount rate used in the global optimization).

Environmental feedbacks are modelled using damage functions: with energy use, greenhouse gas emissions are calculated, which then are fed into a climate module. This module links these emissions to GHG concentrations in atmosphere and oceans, and from them estimates increments in temperature which, through the mentioned damage functions, calculate welfare losses (reductions in the consumption levels that are being maximized). Non-energy sources of GHG such as forestry, agriculture are also considered.

The representation of international energy markets is endogenous: the price of fossil fuels and other exhaustible resources is calculated by computing regional demand, trade and supply. Supply is characterized through the regional marginal costs of extraction, which in turn are calculated through present and cumulative extraction rates and a regional mark-up.

WITCH considers one final good "Y" in each region, which can be used either for consumption or investment (it could be considered as a form of economic capital). To generate this good in each region, energy services, capital and labour are used, and this process is represented by a certain production function⁹⁰. Climate damage (non linear function of the increment in temperature from pre-industrial era) produces in each region a gap between gross output of the produced good "Y" and net output, i.e. the greater the climate change the greater the lost output, with a non-linear relation. Energy services are produced by a combination of physical energy use and "energy efficiency knowledge". This means that energy services can be produced either by consuming real energy or by improving energy efficiency in the region. The amount of "energy efficiency knowledge" stock can be increased through research and development (R&D) expenditure (in the region) or through diffusion / experience (which is accumulated at a global level). Energy consumption can be produced through electricity consumption or non-electric consumption. The electric sector considers nuclear, coal, IGCC with CCS⁹¹, oil, gas, wind & solar (aggregated, because both are intermittent), large hydro and, finally, a *backstop technology* which intends to model a breakthrough technology. The non-electric energy sector is composed of traditional biomass, coal, oil, gas, biofuels and another backstop technology (in this case mainly conceived as an abatement option in the transportation sector). Each region's efficiency and backstop technology's costs are affected by the stock of energy knowledge in the region, which is determined by regional R&D expenditure and by global experience.

⁹⁰ Capital and labor are aggregated with a Cobb-Douglas production function, being this nest then aggregated with energy services through a constant elasticity of substitution production function.

⁹¹ Integrated gasification combined cycle with carbon capture and sequestration.

WITCH has an interesting game-theoretic setup. For each region, a forward-looking agent maximizes its discounted social welfare function (i.e. consumption minus externalities). International externalities are mainly three: (i.) climate change, which is caused/born differently in different regions; (ii.) energy prices (one global price is assumed, although as seen, marginal extraction costs are different per region); and (iii.) global energy experience (representing learning by doing), which depends on global installed capacities. Two solution modes are possible, which intend to replicate two possible storylines of global climate negotiations: a cooperative and a non-cooperative one. In the cooperative solution, a global optimization is done for all regions at the same time and fully incorporating all regional externalities into the global optimization. Its solution represents the global optimum. In the non-cooperative one, each region is optimized separately in a loop (only considering its own externalities and partially the others') until the Nash equilibrium is reached. Regarding computer implementation, WITCH is programmed in GAMS.

As said, WITCH includes endogenous representation of technological improvement, driven both by innovation (learning by research) and diffusion (learning by doing) and accounting for interregional spillovers. Learning by doing affects wind & solar, and both backstop technologies. R&D affects the energy efficiency stock and both backstops technologies.

III.3.7.b. Strong and weak points

As said, punctuation from 1 to 5 (1 being the lowest) will be given for each feature.

- Modeling flexibility: similarly to what happened with EPPA, WITCH does not include enough technological detail (both are, in our opinion, top-down models), and is conceptually quite complex, so as to achieve enough modeling flexibility as defined in this thesis. Punctuation: 2.
- Technological detail: a fair level of technological detail is achieved, better than in EPPA (mainly due to its representation of technological change), although of course, smaller than that of bottom-up models. Punctuation: 3.
- Economic representation: we think that this is a good point of WITCH, because of its top-down nature, which includes a general equilibrium approach. Punctuation: 4.
- Real energy markets: the hypotheses of perfect foresight, perfect competition and fully rational agents which are behind the maximization of the discounted consumption (by the forward-looking agent in each region) are somehow hard hypotheses. Energy markets are largely imperfect and perfect foresight does not exist, avoiding agents to react to policies in advance, as probably happens in WITCH. Even if decision making is decentralised and international energy markets are endogenously represented, this entire area (i.e. real energy markets) still has a low punctuation. Punctuation: 2.

- Transparency/ease of utilization: a simulator based on WITCH (not the code) is publicly available in their web page⁹², which allows the wide public to access it and perform their own simulations. We think that this is a very interesting and positive exercise which, together with its equations and hypothesis, available in (Bosetti et al., 2009) greatly improves the transparency of the model. Even so, it is not an easy model to understand, because of its complex internal dynamics and modeling methodology. Punctuation: 3.
- Direct policy effect modelling: we believe that the large political intervention in the energy sector could be implemented in WITCH thanks to its optimization nature and to the fact that it achieves a fair level of technical detail. Punctuation: 3.
- Synergies and trade-off analysis: although a global objective function exists in the cooperative mode and hence shadow prices could be extracted, their interpretation can be hard given the mathematical structure of the constraints and the obtained units and data formats. In the non-cooperative mode, the fact of a global objective function not existing (the same happens with EPPA) makes synergies and trade-off analysis hard. Punctuation: 2.

III.3.7.c. Interesting use examples

WITCH has been used for many studies and publications. Here we briefly mention some of the latest ones. (Carraro et al., 2012) analyses the effects in the global economy, particularly in investments and public finance, that carbon taxation as an incentive for a transition towards a green economy would have; (Bosetti et al., 2013) assesses if international climate coalitions would be interesting/feasible/stable in the framework of international negotiations; (Carraro & Massetti, 2012) proposes a realistic way to address climate change based on the results of the 2009 Climate Summit in Copenhagen; and (Massetti, 2011) looks at realistic emissions reductions targets that could be adopted by China and India climate negotiations.

III.3.8. Summary table

The next table summarizes the reviewed information on the above energy models. The table has two main parts. First, we show the nine features that have been summarized in the individualized tables above. Below that, we assign a numerical punctuation (being 1 the lowest and 5 the highest) to the seven features that have been addressed under the “Strong and weak points” sections above. In the next chapter, where we propose the models developed in this PhD thesis, we will come back to this table, where we will locate them in order to clearly visualize how they relate to the reviewed mainstream models.

⁹² <http://www.witchmodel.org/index.html>

Figure 32: summary table with the main information about the reviewed models.
Source: own elaboration.

	MARKAL/TIMES	POLES	WEM	PRIMES	NEMS	EPPA	WITCH
Economic representation	Partial Equilibrium	Partial Equilibrium	Partial Equilibrium	Partial Equilibrium	General Equilibrium	General Equilibrium	General Equilibrium
Env. Feedbacks	No	No	No	No	No	Mainstream EPPA no. Yes, if coupled with IGSM or EPPA-HE.	Yes, IAM
Modelling technique	Optimization	Simulation	Simulation	Optimization	Simulation	Optimization	Optimization
Technological detail	Bottom-up	Bottom-up	Bottom-up	Bottom-up	Bottom-up	Top-Down	Top-Down
Geographic perspective	Customizable	World (46 regions)	World (25 regions)	Extended Europe	USA (sub divisions)	World (16 regions)	World (12 regions)
Time representation	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic
Future foresight	Perfect	Myopic (recursive dynamic)	Myopic (recursive dynamic)	Myopic or perfect	Myopic or perfect	Myopic or perfect	Perfect
Technological change	Exogenous	Endogenous (both learning by doing and learning by research)	Endogenous (only learning by doing)	Endogenous (only learning by doing)	Endogenous (only learning by doing)	Endogenous	Endogenous (both learning by doing and learning by research)
Internat. energy mkt.	Exogenous	Endogenous	Exogenous	Exogenous	Endogenous	Endogenous	Endogenous
Modelling flexibility	5	2	2	3	3	2	2
Technological detail	5	3	4	5	5	2	3
Economic representation	2	3	3	2	4	5	4
Real energy markets	1	3	2	5	5	3	2
Transparency/ ease of utilization	2	2	2	1	1	2	3
Direct policy effect modelling	3	2	2	3	2	3	3
Synergies/ tradeoff analysis	3	1	1	1	1	2	2

III.4. OTHER ENERGY MODELS

III.4.1. Review of other models and techniques

In this section, we will briefly review some other relevant energy models present in the literature. We will start reviewing optimization-based models, and then simulation and accounting⁹³ models. In the end, we will identify some features in them which could be useful for this thesis.

MESSAGE (Strubegger Messner & Strubegger, 1995) stands for “Model for Energy Supply Strategy Alternatives and their General Environmental impact”. It was developed at the International Institute for Applied Systems Analysis (IIASA). It is a bottom-up dynamic optimization model used for medium- to long-term energy system planning. It is very similar to TIMES: it also uses the reference energy system concept, processes and energy flows philosophy, and it works by minimizing the total discounted energy supply cost (although multi objective optimization is allowed). One of its main advantages is that the IIASA web page includes analysis tools (some based on MESSAGE) available online, what greatly increases transparency of this and associated tools. Also, MESSAGE is the subject of a special agreement between IIASA and the International Atomic Energy Agency (IAEA). This may allow some users to access (for a low cost) a modified version of MESSAGE through the IAEA, including a graphical front-end as well as training on how to use it. This is very interesting for developing countries which need an affordable and tested tool for energy policy analysis. Myopic and stochastic versions of MESSAGE have also been developed. There is a global version of MESSAGE (represents the world in 11 regions), and it has also been linked with macroeconomic models (MESSAGE-MACRO). Other interesting versions of MESSAGE include an stochastic one (Sabine Messner et al., 1996), which tries to capture the uncertainty in technologies’ investment costs; and a myopic one (Keppo & Strubegger, 2010), which tries to better replicate agents’ decision-making, using a sequential decision algorithm similar to the one in SAGE (see MARKAL/TIMES section, above) and IKARUS (see below).

OSeMOSYS (Howells et al., 2011; Welsch et al., 2012) is another model, very similar to TIMES in its philosophy, but very compact (significantly less equations and variables) and made freely available online⁹⁴. Indeed, its acronym stands for “Open Source Energy Modeling System”. Its developers encourage users worldwide to download and make use of it, what again, can be very interesting for some small developing countries which do not have the means to develop new methodologies.

⁹³ We call *accounting* models to a specific type of models which simply consist on keeping track of an energy system’s developments over time, without any type of advanced mathematics (e.g. optimizations). In other words they just perform simple arithmetic operations. Some authors see them as a type of simulation models.

⁹⁴ <http://osemosysmain.yolasite.com/>

Other global models with a similar philosophy as TIMES are: **GET**, and used for studies in the transportation sector (Azar et al., 2003; Grahn, 2009; Grahn et al., 2003) or about carbon capture and sequestration (Azar et al., 2006); **REDGEM70** (Takeshita & Yamaji, 2006; Takeshita et al., 2006); or **IKARUS** (D. Martinsen et al., 2006, 2007; Weber & Martinsen, 2012), which represents myopia in an interesting way using variable time steps and has been mostly applied to energy policy studies in Germany.

Now, some simulation and accounting models will be reviewed. The first one that we consider here is **EnergyPLAN** (Lund, 2011), developed at Aalborg University in Denmark, and it is user friendly and freely available for download in internet. It is a static model (i.e. analyses only one year) with an hourly resolution. It only represents operation of a national energy system (i.e. not investments, in other words, capacities are fixed), which can be graphically represented using diagrams similar to the reference energy concept in TIMES. It is a partial equilibrium model (energy demands are inputs, and can consider certain price elasticity). Even if it does optimize the operation of the energy system, it does so with a heuristic iterative algorithm, so we do not classify it as an optimization model. It has been used for the analysis of energy policies and several energy systems in Europe, with a special focus on issues such as a large scale penetration of renewables: Denmark (Lund & Mathiesen, 2009), Romania (Gota et al., 2011), Ireland (D. Connolly et al., 2010), Italy (Franco & Salza, 2011), Greece (Alagialoglou, 2011) or Switzerland (Ballistreri et al., 2010); or the future role of district heating systems (Lund et al., 2010).

LEAP (Long range Energy Alternatives Planning system) is another accounting/simulation model for analyzing local, national or regional energy systems (Heaps, 2002, 2008). It is distributed freely on the internet⁹⁵. LEAP simulates several year in a year by year dynamic manner, using a purely accounting algorithm. It includes the possibility of both exogenous and endogenous capacity expansion decisions, and it calculates electricity dispatch based on load curves, using simulation algorithms. Recently, it has been coupled with the optimization model OSeMOSYS (which is also freely distributed online) to include optimal decisions in power generation expansion and operation. LEAP also includes a tool for cost-benefit analysis. It has been used in more than one hundred countries worldwide. Some examples are cited next: (Limmeechokchai & Chawana, 2007) analyses the adoption of more sustainable energy sources (i.e. small biogas digesters and improved cookstoves) for rural areas in Thailand; (Heaps, 2009) analyses a scenario of ambitious reduction in China's carbon emissions; (Bautista, 2012) looks at future scenarios for the Venezuelan power sector; and (Sgouridis et al., 2013) uses a LEAP-inspired model to present scenarios for sustainable energy transitions in the United Arab Emirates (this model is designed specifically to account for important issues in this region such as water desalinization).

Green-X (Huber et al., 2005) is a European dynamic simulation tool developed at the Technical University of Vienna to analyze renewable penetration and the costs and benefits of support policies, including aspects such as subsidies, taxes, or externalities, etc. It is mainly used

⁹⁵ <http://www.energycommunity.org/>

to analyze RES support policies. It is technologically very detailed but its core strength is the policies' representation and the development of dynamic cost-resource curves. It normally uses, as input data, scenarios developed with the PRIMES model. This issue of using the outputs of one model as inputs to another one is a widely adopted modeling practice which consists on using models in a hierarchical and sequential process. As has been defended throughout this PhD, models are for insights, and a complementary use of different models, used to answer different questions, is a very desirable exercise.

The DECC 2050 Pathways Calculator is a very important model within the framework of this PhD thesis. This is because it is an intuitive, transparent, online tool (placed in United Kingdom's Department of Energy & Climate Change web⁹⁶) to analyze emissions reductions pathways for 2050 in the UK. Citing from their web, "(...) is a user-friendly model that lets you create your own UK emissions reduction pathway, and see the impact using real UK data. The Calculator helps everyone engage in the debate and lets Government make sure our planning is consistent with the long-term aim". It is based on an open-source Excel-based accounting model fed with real data from the UK and inspired in the same philosophy as the relevant book by David MacKay "Sustainable Energy - Without the Hot Air" (MacKay, 2009). We think this is a very relevant and interesting methodology: a simple *energy calculator*, without complex mathematical algorithms, fed with real data and put at everyone's disposal in order to engage as many stakeholders as possible in a sound, transparent, data-based energy policy debate which is supported by ballpark figures. This is basically the same type of motivation that has inspired this PhD thesis. Within this general approach, the author of this thesis has supervised an undergraduate engineering thesis (Pugnaire et al., 2010) that aimed at building an accounting model to analyze the energy efficiency measures established by the Spanish Government.

A very relevant modeling technique, which has inspired many of the simulation models reviewed here (e.g. NEMS, POLES, WEM) is *System Dynamics* (Ford, 1997; Forrester, 1989, 1991; Morecroft, 2007; Sterman, 2000), originally developed in the 1960s and 1970s by the MIT professor Jay W. Forrester. It has been applied in a number of models of energy systems, such as the **COAL1** model, which then evolved into **COAL2** (Naill, 1977) and, eventually, into the **FOSSIL1** model. According to (Backus & Amlin, 2009) the FOSSIL1 model substituted PIES, the Project Independence Evaluation System (Hogan, 1975) and became the mainstream model for energy policy evaluation in the U.S. during the oil crises in the 1970s. The following point is very relevant to this PhD thesis. According to (Backus & Amlin, 2009), some of the main reasons behind the substitution of PIES (optimization-based) by FOSSIL1 (System Dynamics-based) were: (i.) it was much faster to execute (12 seconds vs 4 days), which was critical during the oil crisis; (ii.) policymakers were skeptical to the hypothesis of optimal decision making and perfect rationality implied in PIES; and (iii.) it was more transparent and the internal dynamics were more intuitive and easy to grasp by politicians. Later, with the participation of Professor John D. Sterman, FOSSIL1 then evolved into **FOSSIL2** (Naill & Belanger, 1992). FOSSIL2's evolution was the **IDEAS** model (The AES Corporation, 1993), which afterwards, according to (Backus & Amlin,

⁹⁶ <https://www.gov.uk/2050-pathways-analysis>

2009), evolved into **Energy2020** (Systematic Solutions, Inc., 2013), also using concepts from Andrew Ford's **EPPAM** (Ford & Yabroff, 1979). Lastly, also within the family of System Dynamics, it is interesting to mention Climate Interactive, an initiative that has developed two open web-based System Dynamics-based models: **En-ROADS**, for global energy pathways analysis (Climate Interactive, 2013a); and **C-ROADS**, for global climate policy analysis (Climate Interactive, 2013b).

Some Spanish researchers have also worked on System Dynamics applied to the energy field. They have developed a model of the world economy, considering energy use and resource exhaustion (including issues such as Hubbert's theory and EROEI factors), which they have used to several studies on energy transitions, resource scarcity and renewable energy potentials (de Castro, 2007; Mediavilla et al., 2011a, 2011b). Other relevant System Dynamics applications to energy field are (Bunn & Larsen, 1997; Dyner & Bunn, 1997; Dyner, 2000; Smith et al., 2005). This PhD candidate has also done some work on the field, but focused on the power sector (Centeno et al., 2008; López-Peña et al., 2009; Sánchez et al., 2007a, 2007b, 2008).

An example of how System Dynamics can be used to represent aspects of real (i.e. imperfect) energy markets is (Dyner & Franco, 2004), where a model is used to analyze the level of bounded rationality in energy consumers. A similar approach, although different, as explained in (Borshchev & Filippov, 2004), is *Agent-Based Modeling*, used for instance in the field of power markets, is EMLab (de Vries et al., 2013).

III.4.2. Summary

In this section, we have reviewed some other energy models apart from the mainstream ones (e.g. MARKAL/TIMES, POLES, PRIMES, etc.) reviewed above. Some useful conclusions that could be obtained from them are:

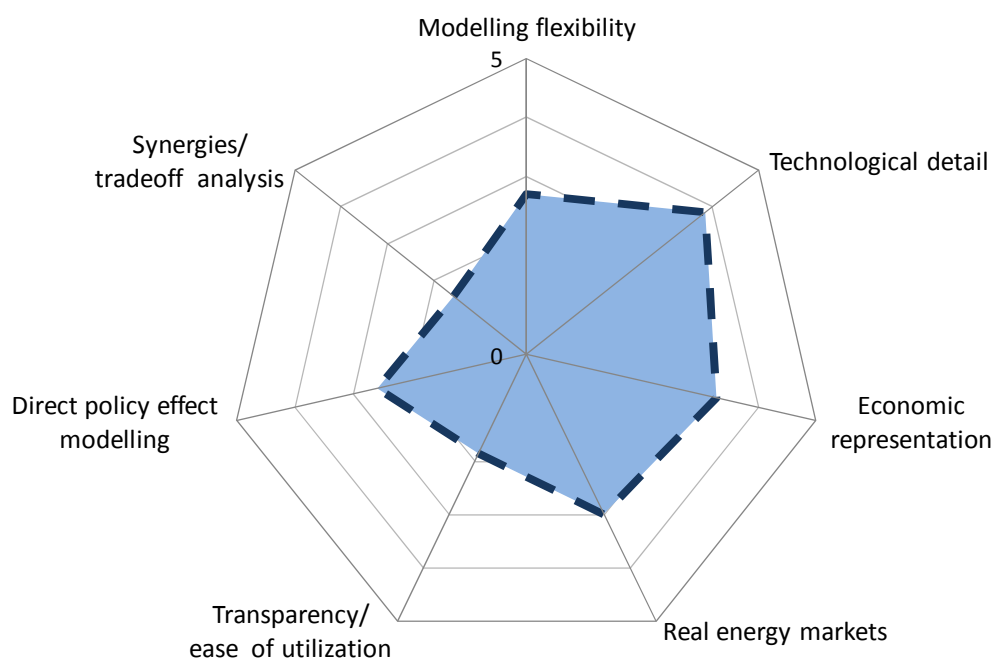
- There is indeed a trend in the literature towards more transparent/simpler/open source models, as proven by OSeMOSYS, EnergyPLAN, MESSAGE, LEAP, the DECC 2050 Pathways Calculator, or En-ROADS and C-ROADS. For a recent review on this issue, refer to (Bazilian et al., 2012)
- The modeling framework in MARKAL/TIMES has inspired many other models, such as OSeMOSYS, MESSAGE, GET, REDGEM70 or IKARUS.
- Obscure, complex-to-understand models with hard hypotheses can indeed be distrusted by policymakers, as proven by the transition from PIES to FOSSIL1 during the 1970s in the U.S.
- Transparent models with intuitive internal dynamics seem to be preferable, even if the numerical/technical detail is not as large. This is not only true for policymakers, but also for the wide society, which needs to be involved in the complex debates that we must face nowadays regarding energy policy. This is clearly shown by the fact that the DECC 2050 Pathways Calculator, which is an intuitive, transparent, online tool which yields ballpark figures about energy and climate policy, is placed in one of the UK Government's web pages, encouraging everyone to use it. As said, this model and David MacKay's book

“Sustainable Energy - Without the Hot Air” (MacKay, 2009), have been a key source of inspiration in this PhD thesis.

III.5. CONCLUSIONS OF THE STATE OF THE ART: THE GAP TO BE COVERED BY THIS THESIS.

We have carried out an in-depth literature review of the energy modelling field, first defining key concepts and techniques, then reviewing mainstream and widely used models, and finally reviewing some other relevant models. We have also evaluated numerically each mainstream model’s performance in most of the main features that we deem necessary in a sustainable energy policy making tool as explained in chapter 1: modeling flexibility; technological detail; economic representation; real energy markets; transparency/ease of utilization; direct policy effect modelling; and synergies/trade-off analysis. These results have been summarised in the form of a table (Figure 32). By simply computing the algebraic mean of the punctuations of all reviewed mainstream models in each feature, we can get a first proxy on how the reviewed features are represented in the mainstream models in the literature. This is graphically shown in Figure 33. As can be seen, the best-represented features are technological detail and economic representation, respectively. This is due to the important presence of bottom-up partial equilibrium and top-down general equilibrium models in the literature. On the other hand the analysis of policy synergies and trade-offs, the transparency/ease of utilization and the direct policy-effect modelling seem to be less treated in the reviewed models. This points out at a gap in the literature, where this thesis tries to stand.

*Figure 33: level of treatment of each assessed features in the reviewed models.
 Source: own elaboration.*



In most of the mainstream models we have identified, to a certain extent, a common characteristic: *opacity*. They can sometimes be complex models, with large data and bulky results, difficult internal structures and advanced mathematical techniques. This implies that the policy maker using them for studies and projections can sometimes see them as *black boxes*, where the influence of data, hypothesis and other inputs upon results is frequently difficult to understand. Of course those complexities have a reason: they try to capture the reality as precisely as possible, modelling the highly complex energy sectors accurately.

These models can be adequate for studies where there is a solid and well trained modelling team, in charge of a large, sound and well-maintained database, which deeply understands the main hypothesis, limitations and internal dynamics of the models and their effects on the results, and where extensive sensitivity analysis on the main parameters are carried out, to obtain the main trends and the most robust conclusions. But this involves a great work load: these models fail in providing, with a reasonable amount of analysis in a short time period, simple but sound and useful conclusions about the *big picture* of energy policymaking. This is why sometimes they are distrusted by policymakers, and why the wide public cannot be engaged into the energy debate, which is a pressing need in the current days, where very complex political decisions need to be made to reach the path to energy sustainability. Two examples of these issues could be:

- The criticism that arouse in Europe because of the use of a complex model such as PRIMES for the long-term analytical assessments of the European Energy Roadmap 2050. Although this model underwent a thorough, scientific, peer-review process which confirmed its suitability for such an analysis, its underlying principles are complex to grasp by a large percentage of society and energy sector stakeholders, some of them being potentially affected by its results and associated policy implications. Even more, regardless of the internal characteristics of the model (which may be very sound, as in this case), if the society is not able *to see inside the model*, distrust may easily arise.
- The clear acknowledgement from the European Commission, in its recent Green Paper “A 2030 Framework for Climate and Energy Policies”, of the fact that energy and climate policies have complex and important interactions and trade-offs which must be holistically considered, which was maybe not fully done when the 2020 objectives were being designed. There is a need for models with which policy synergies or trade-offs can be easily understood.

Some *optimization* models (e.g. TIMES and most of its derived ones) normally make the hypothesis of perfect markets, perfect rationality and perfect foresight, which can be somehow optimistic. Also, LP optimization models may sometimes produce extreme (e.g. knife-edge) results, which can be far from reality. The PhD candidate has experienced this while working with a TIMES-based model of the Spanish energy system (García-Barredo et al., 2011; García-Maestro et al., 2010; Pérez et al., 2012). To solve this, *simulation* models (e.g. NEMS, WEM, POLES), can model more realistic behaviours (myopia, some degree of bounded rationality, etc.). But, for this, the modeller relies on a (potentially large) number of internal parameters, some of them without clear physical interpretations, which can be hard to estimate, significantly affect the results of the model and finally, reduce user’s confidence in the model. The PhD author has

also experienced these issues, during the realization of his Master's thesis (López-Peña et al., 2009), and during the development of a simulation model of the world energy system (González-Blanch et al., 2010). Again, large databases are needed, extensive sensitivity analysis on main parameters should be carried out, and significant amount of work is involved to be able to extract solid conclusions about the needed big picture.

Spain, where this thesis focuses, is one of the few large European countries without a clear politically agreed long-term energy strategy, and where the energy debate has not taken place in a transparent and comprehensive manner, as we claim in the annual Observatory of the BP Chair on Energy and Sustainability (López-Peña, Linares, Pérez-Arriaga, et al., 2013). This may also be due to the lack of publicly available, transparent and sound models of the Spanish energy system. CIEMAT (a reputed Spanish public energy research centre) has developed and maintains the TIMES-Spain model (Caldés et al., 2008). It is a sound and detailed model of the Spanish energy system, developed, maintained and used by top-of-the class professionals. However, it is not precisely a transparent model: its database is proprietary and it can only be run by the experts working in the institution (who, in turn, use Veda, a proprietary interface for TIMES). Also, the Spanish politicians up to now have not asked them (to our knowledge) to issue long term projections of the evolutions of the Spanish energy system under different policy scenarios, which would be a very good starting point to have a useful energy debate. Up to now, this model has mainly been used for Europe-wide studies (as a part of the Pan European TIMES model). A notable exception is (Labriet et al., 2010), a Spain-focused study, which in any case was done as part of a European project and with a special interest on renewables, not on the complete energy sector.

This thesis is motivated by these findings: the author of this PhD thesis believes that there is the need for models that, still being quite simple and transparent, are also able to capture in a sound way the *big numbers* of sustainable energy policy making, allowing us to directly represent policy effects and to understand policy trade-offs and synergies. This thesis sustains that, from a realistic perspective, in some countries like Spain it is better to provide some easily-understandable quantitative assessments on these issues, than complex studies that cannot be understood by those who have to make the actual decisions. Given that this thesis intends to be useful (and used) from the policy makers' perspective, it tries to dwell in that middle point. In the hands of a policy maker, the tool that has been developed in this PhD thesis can be seen as a powerful *energy calculator*, as previously mentioned when reviewing the DECC 2050 Pathways Calculator. We believe that there is a clear deficit in Spain in this respect.

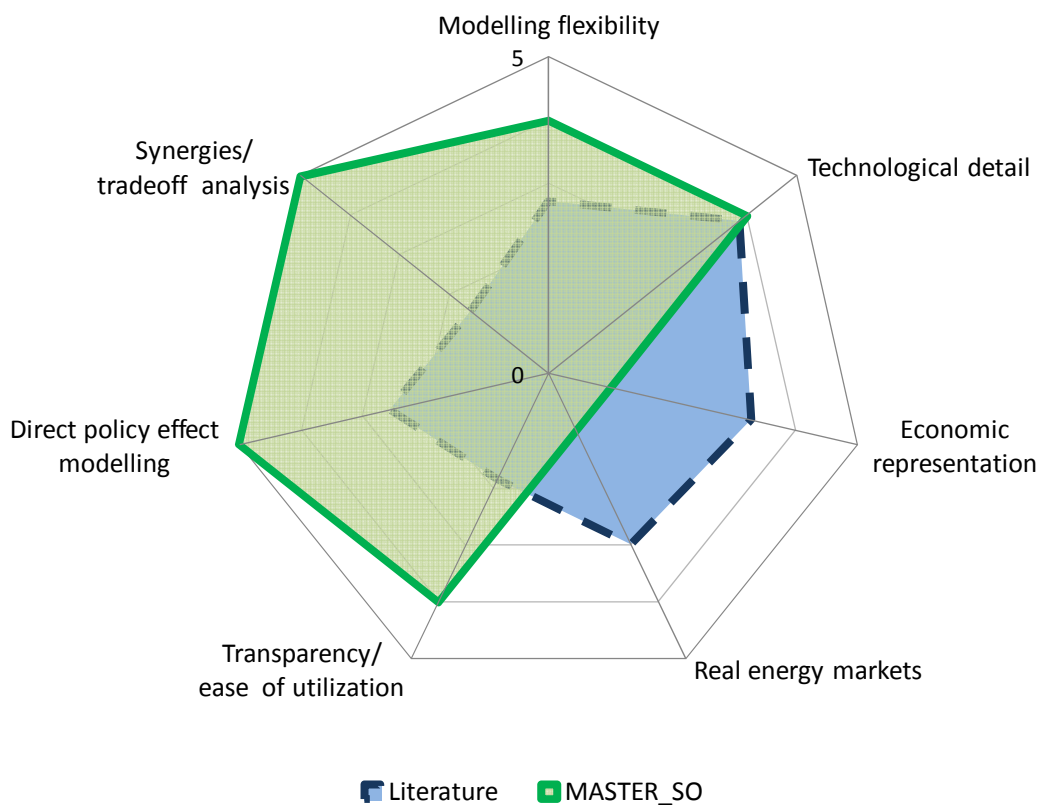
With the two models that are proposed in this PhD thesis and the proposed method of utilization, we have tried to capture the best features (for the explicit purpose of designing energy policy) of static and dynamic models, simulation and optimization, or scenario-based utilization versus a more dynamic representation of the decision-making process.

The first model we propose is MASTER_SO, a static optimization model which is quite simple in its mathematical representation (linear programming) but contains enough detail to achieve a sound representation of the complete energy system. As can be seen in Figure 34, it adds significant value to the literature where it is more needed in our opinion, especially in

terms of transparency, synergies/trade-offs analysis and direct policy effect modelling, slightly improving modelling flexibility and keeping technological detail. Its performance in (i.) economic representation, and (ii.) real energy markets, is not as good. This is due to (i.) the use of a partial-equilibrium approach with inelastic demand, and (ii.) because it has an optimization approach assuming perfect energy markets and perfect foresight.

Figure 34: level of treatment of each assessed features in this thesis's main model (MASTER_SO) versus the reviewed models in the literature.

Source: own elaboration.



The second model we propose, MASTER_DS, has a dynamic simulation approach and will try to achieve a good representation of real energy markets, while also keeping transparency and ease of utilization. We propose to use them in a sequential process, in which MASTER_SO is used to analyse the energy system from a static perspective for a point in the future (e.g. the year 2030), and then MASTER_DS is used to assess how to get to that point from the current situation (e.g. from 2013 to 2030). This will be explained in detail in Chapter 4.

Chapter IV.

METHODOLOGICAL JUSTIFICATION AND PROPOSAL

IV.1	Outline of this Chapter	129
IV.2	Methodological Justification	129
IV.3	Methodological Proposal	131

IV.1. OUTLINE OF THIS CHAPTER

In this chapter we will briefly recap what was said in the introduction (Chapter 1) and will enhance it with the main conclusions that we obtained in the thesis context (Chapter 2) and in the review of the state of the art (Chapter 3). This will allow us to justify, in this chapter, the methodology that we are proposing. Then, we will describe this methodology, structuring this chapter under the following sections: (i.) overview; (ii.) energy sector representation; (iii.) data, magnitudes and units; (iv.) sustainability indicators; (v.) modelling framework; (vi.) the static model; (vii.) the dynamic model; and (viii.) output. These proposals, as will be seen, are all related and complementary and, together, they constitute in our opinion a sound and comprehensive methodological corpus able to deal with the main challenges and gaps that have been identified.

IV.2. METHODOLOGICAL JUSTIFICATION

IV.2.1. Main conclusions from previous chapters

Our current world energy system (largely based on the use of fossil fuels) is unsustainable, and it is foreseen to remain so unless aggressive policy action is taken. The Spanish case is not an exception. In some OECD countries, the liberalization of energy industries and the introduction of markets seem to have provided some efficiency gains. However, important market failures are present, being a very important one the fact that they do not price correctly (sometimes at all) the huge existing externalities. Hence markets seem not to be enough to provide long-term guidance to our energy systems, which are certainly not following the path towards sustainability. Sustainable energy policies are needed to complement and guide the market.

Energy policymakers, whose final aim should be to maximise long-term social well-being (for which sustainability is a necessary condition), are the agents responsible for the analysis and implementation of these policies. This PhD thesis adopts the viewpoint of such a policymaker, although the methodologies used here could be used by other agents such as business managers, lobbyists, consultants, etc. For the analyses of such policies, computer-based mathematical models are very useful tools because they allow representing the large complexities of the studied system and to observe its outcome and behaviour under different policy scenarios.

There is a broad range of mathematical techniques that are currently being used with this purpose, and many models are developed and used by some of the most reputable institutions in the energy sector worldwide, such as the International Energy Agency, the U.S. Energy Information Administration or the European Commission. Some of them have an optimization approach whereas some others are based on simulation; they can represent different levels of interaction between the energy system and the rest of the economy and the environment; they

can have different levels of technological detail (bottom-up, top-down or hybrid); from the geographical perspective they can be global, regional, national or even sub national; or they can use different hypothesis to represent time and the associated uncertainties, rationality, forecasting errors, or technological evolution. A review of these techniques and the main energy models has been carried out in the State of the Art section of this thesis (Chapter 3), and we have identified certain drawbacks and a gap in the literature, where this PhD thesis tries to stand (refer to the last section of the chapter).

IV.2.2. Justifying our methodology

This thesis proposes a methodology that, being simple, tries to capture the *big numbers* in sustainable energy policy making. This is something that, as seen in the previous chapter, is already being done in other countries, such as in the United Kingdom with its DECC 2050 Pathways Calculator. The central idea is to provide an improved and so far inexistent set of tools based on public and contrasted data, with a sound –but at the same time simple and transparent– methodology, which allows to represent an energy sector’s evolution under different policy assumptions and to evaluate its sustainability. We intend to show that the real difficulty is not in the tool itself but in understanding, with a comprehensive but simplified quantitative analysis, the policies’ mutual implications and trade-offs, how a policy can be counterproductive with another or the relative weight of each policy in achieving higher-level policy objectives (such as maximising the sustainability of the energy sector, maximising domestic energy supply, or minimising total costs while maintaining reasonable values of the other metrics). We will set our focus in the case of Spain, although our methodology could be applied to other countries. We will provide some ideas on how to measure the sustainability of an energy sector (which, as said in Chapter 2, encompasses more elements than just purely-environmental ones).

The next section proposes such a methodology. An extensive process of abstraction, representation and data collection has been done in order to characterise the studied energy system with public and contrasted data. Intuitive ways of presenting the models’ outputs, based on Sankey diagrams, are provided. Used magnitudes and units can also make a difference, as will be seen, and a specific proposal in this sense is done. Finally, two complementary models are proposed (and used in the next chapters) to evaluate actual energy policy issues for the case of Spain, one under static conditions and a second one that considers the temporal evolution of the energy system. These two models are complementary not just in their temporal representation (one being static and the other dynamic) but also in their philosophy: the static one is optimisation-based, providing normative information (e.g. how should the energy system be in 2030?), whereas the dynamic one is simulation-based and provides (normally, although not exclusively, in a second analysis stage) descriptive information (e.g. how to get from where we are now to that 2030 system that we have decided, with the static model, to be the goal?). Our methodological proposal also suggests how these two models should be used to make full use of their complementarities.

IV.3. METHODOLOGICAL PROPOSAL

IV.3.1. Our proposal: overview

Our proposal is based on the following pillars, which will be detailed in the next pages:

- A specific representation of the entire energy sector based on ideas from the MARKAL/TIMES models (Loulou et al., 2005) combined with the Sankey diagrams developed by the author for the BP Observatory on Energy and Sustainability in Spain (López-Peña, Linares, Pérez-Arriaga, et al., 2013).
- A special focus on a detailed bottom-up representation of energy demand sectors. Instead of externally specifying⁹⁷ the demand for final energy such as gasoline or electricity, we will specify the demand for energy services (e.g. mobility, illumination), and the model will choose the mix of end use technologies to supply it (e.g. different types of cars or lamps). Our representation is grounded on a detailed database of: (i.) demands for energy services and their possible reduction measures (e.g. promotion of teleconferences to reduce mobility, or improved insurance in buildings to reduce heating needs); and (ii.) end-use energy technologies (e.g. different types of cars, bikes, heating devices, etc., each with its technical and economic specifications). This database has been built from scratch using public and contrasted data for Spain, and will be made publicly available. This is one of the key added values of this PhD thesis, and it is of capital importance given that (as previously stated and as widely reported in the literature), much effort should be put in demand-side policies, especially in energy-inefficient countries such as Spain.
- Related to it, we use public and contrasted data obtained from widely available and recognized sources. The documentation of the data processing is clear and transparent, and hypotheses are made explicit.
- The use of uniform and intuitive magnitudes and units in the representation of all figures (both inputs and outputs of the model) in all parts of the energy system. This allows easily visualizing, relating and comparing policy trade-offs and effects.
- A modeling framework specifically designed to evaluate sustainable energy policies, with the possibility of including quantitative indicators of energy sustainability. This modeling framework makes use of two complementary models, the “MASTER” models, which stand for “Models for the Analysis of SusTainable Energy Roadmaps”. One is a static optimisation model (“MASTER_SO”) whereas the other is a dynamic simulation one “MASTER_DS”.

⁹⁷ This implies that we will follow a partial equilibrium approach, as will be seen next.

- A specific representation of the outputs of the models, based around the use of Sankey diagrams similar to the ones in the BP Observatory on Energy and Sustainability in Spain, which allow for an intuitive understanding of the main effects of the studied policies upon the complete energy system.

IV.3.2. Our proposal: energy sector representation

As said, our methodology should be comprehensive enough to include the entire energy system under study, its main components and interactions, and a fair level of technical detail. But without going too much into details that may require excessive mathematical complexity or too many internal parameters, which could muddle the main relations and conclusions and create the feeling that the results are dominated by the more or less arbitrary choice of these parameters. By including the entire energy sector, the model should be able to represent the relations between the different energy subsectors (electricity, gas, oil products, etc.) and the fact that a policy applied to one subsector can produce unexpected, synergic or counterproductive effects in another. This section details our proposal in this sense, and it has two main parts: (i.) a general description of the proposed representation; and (ii.) a more detailed qualitative description of the modeling approach used for each energy subsector (electricity, natural gas, oil products, etc.). The detailed mathematical representations are given in subsequent chapters.

IV.3.2.a. Description of the proposed representation

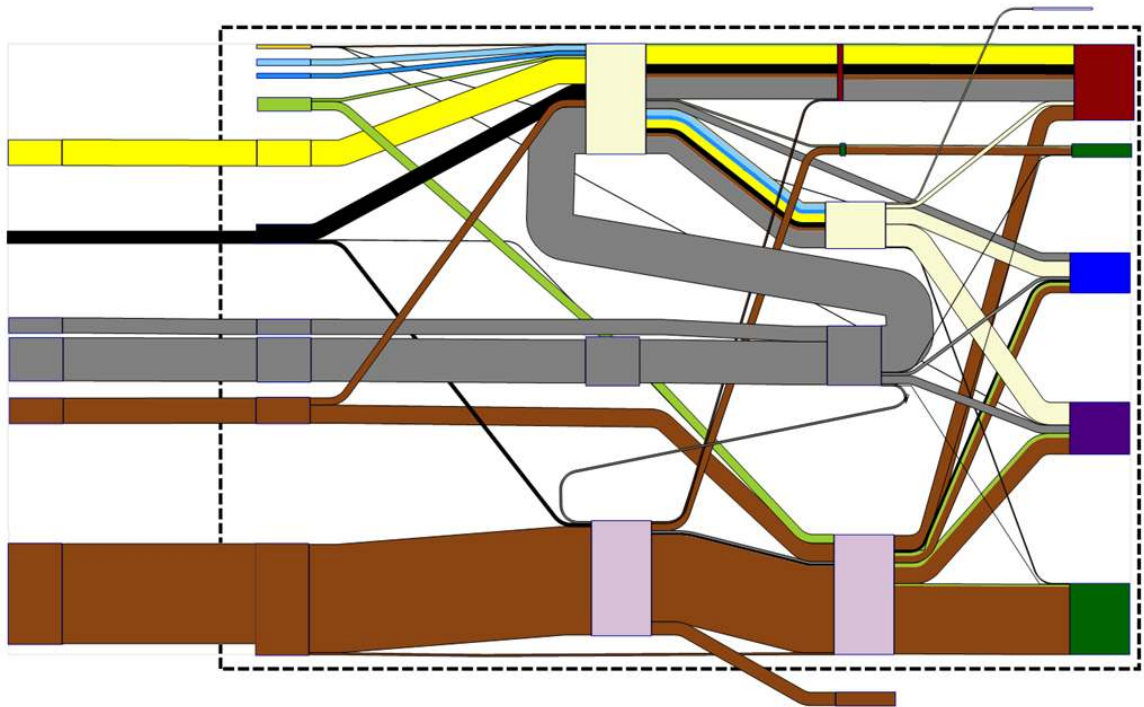
Overview

The representation of the Spanish energy sector that we have adopted (it could also be used for other countries, as said), is largely based on two main pillars: (i.) the energy Sankey diagram developed by the author for the BP Observatory on Energy and Sustainability in Spain, which was introduced in Chapter 2 and is reproduced in Figure 35 (in this case a simplified version without the text labels⁹⁸); and (ii.) the *process* and *reference energy system* concepts used in the MARKAL/TIMES family of models (Loulou et al., 2005) which, in our opinion, adequately combine with the Sankey diagram representation and provide important modeling flexibility. These two concepts will be explained next.

⁹⁸ The text labels, in any case, can be consulted in the analogous Sankey diagram included in Chapter 2, because it is exactly the same diagram, representing the same processes and with the same underlying quantities.

Figure 35: Sankey diagram of the Spanish energy sector in 2011.

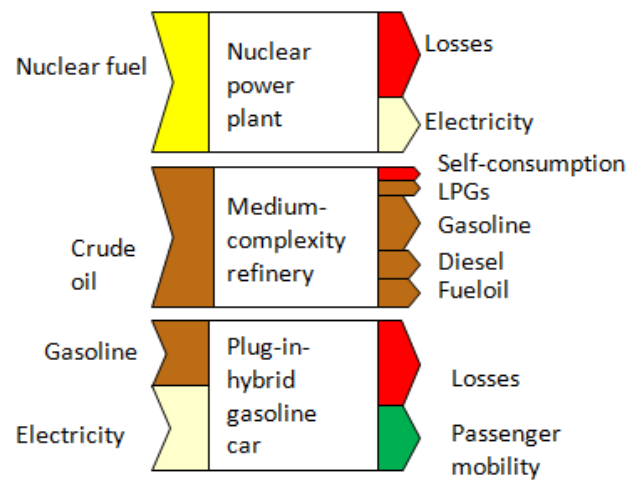
Source: own elaboration, originally published in (López-Peña, Linares, Pérez-Arriaga, et al., 2013)



A *process* is simply a technology which converts some inputs into some outputs, and for doing so, has some technical constraints and creates some costs in the studied system. Examples of processes could be a nuclear power plant, an oil refinery, an electric vehicle, a biomass furnace, an air conditioning unit or a solar thermal panel for water heating. The *process* concept can be easily understood looking at Figure 36, where some of these examples have been represented. In the figure: (i.) a “nuclear power plant” is a process that converts one input (“nuclear fuel”) into two outputs (“losses⁹⁹” and “electricity”); (ii.) a “medium-complexity refinery” is a process that transforms “crude oil” into “self-consumption”, “LPGs” (i.e. liquefied petroleum gasses, such as propane and butane), “gasoline”, “diesel” and “fueloil”; and (iii.) a “plug-in-hybrid gasoline car” converts “gasoline” and “electricity” into “losses” and “passenger mobility”. Each of these processes has some technical limitations. For instance: (i.) the maximum instantaneous electricity produced by the nuclear power plants cannot be greater than the installed capacity, measured in GW; (ii.) the shares of oil products produced by a refinery are limited by the complexity of the refinery and the quality of the incoming crude oil or (iii.) the losses produced in each process will be given by its efficiency. In addition, each process has some costs associated, for instance, to each unit of capacity or to each unit of produced output.

⁹⁹ In this thesis we use the term “losses” to refer to all the energy (of any type) that is lost in a process. It can be due to different technological reasons, such as wasted energy in a nuclear reactor (e.g. unused nuclear fuel), wasted heat in the case of thermal power plants, thermal and mechanical losses in the case of motorized vehicles, or self-use in the case of oil-refineries. Being aware of this fact, and for the sake of simplicity, we will aggregate them into a generic family called “losses”, which contains all losses and self-consumptions in all processes, no matter the type of energy that they represent (heat, mechanical energy, electricity, etc.). We know that this is a significant simplification from the technical perspective.

Figure 36: illustration of the concept of “process”, as will be used within this PhD thesis.
 Source: own elaboration.

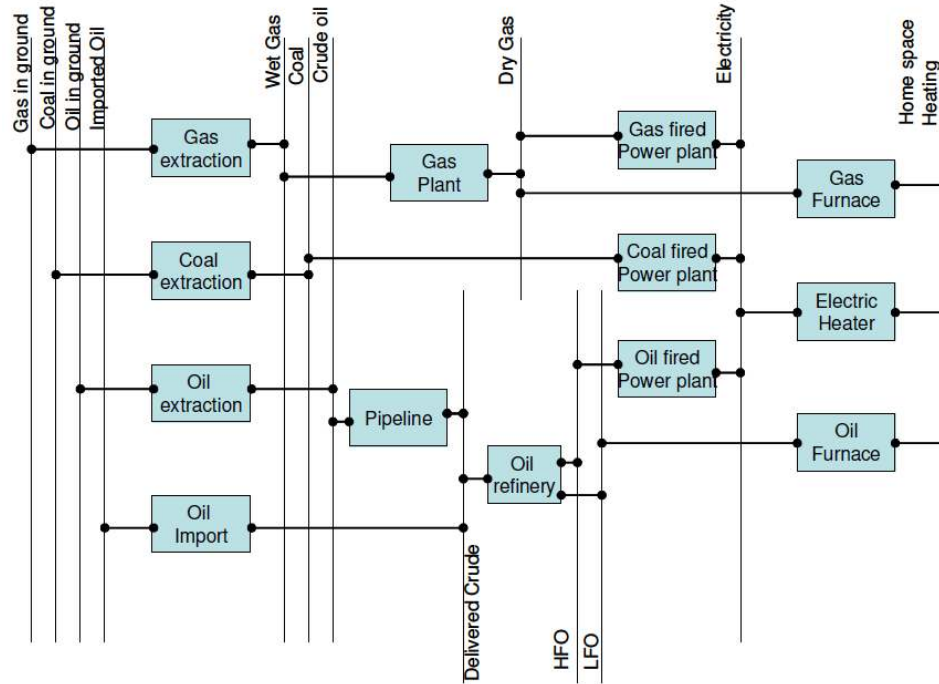


The *reference energy system* concept is a topological¹⁰⁰ representation of the studied system, which consists on (i.) processes and (ii.) energy commodities (e.g. electricity, gasoline, crude oil, etc.) flowing among them. An illustration, extracted from the TIMES documentation (Loulou et al., 2005), is plotted in Figure 37, where energy flows from primary energy (on the left) to final energy use (on the right). Energy commodities are represented as vertical lines, and energy can flow from them to some energy processes, which convert them to other commodities. Only some links are possible (e.g. an electric heater can only use electricity and not crude oil), which are represented by the horizontal links. This possible links are given as external data, after a qualitative analysis of the studied energy system. This representation is similar to a *graph* (in mathematics terminology), where the *nodes* are the processes and the *arcs* are the allowed energy flows.

This modeling framework provides TIMES with large flexibility and modeling capabilities: in some TIMES models, several hundreds of technologies are represented. It is also able to model any non-energy commodities such as materials (e.g. for construction of energy infrastructures) or water (e.g. for refrigeration or energy extraction), associating costs and use limitations to each of them. We believe that this level of achievable modeling detail and flexibility is very useful and it has inspired much of our modeling. Therefore, our representation could also be expanded to consider other energy technologies or, even more, non-energy commodities such as water, as happens in TIMES.

¹⁰⁰ We call this a *topological* representation because it is a graphical representation of how energy processes are linked in the studied system and how energy flows among them. Two definitions of “topology”, according to the Collins English Dictionary (www.collinsdictionary.com), are relevant in this sense: (i.) “the arrangement and interlinking (...) in a network” and “the anatomy of a specific (...) structure”.

Figure 37: illustration of the reference energy system concept in TIMES.
 Source: (Loulou et al., 2005).



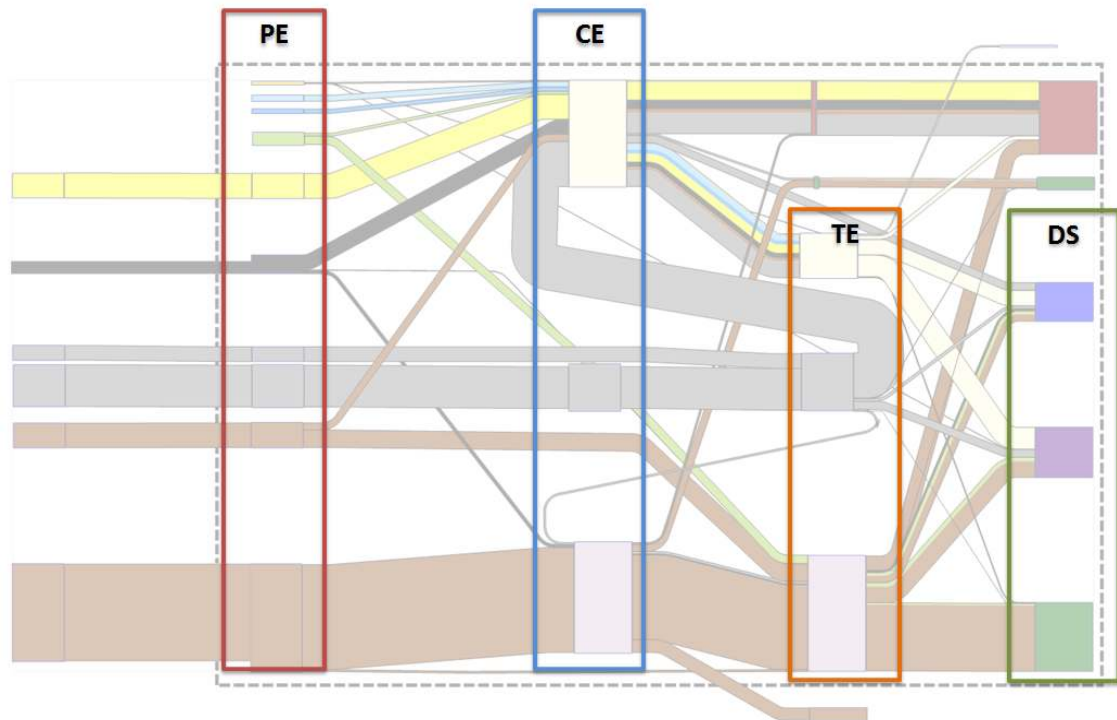
Within the above-represented Sankey diagram¹⁰¹ (Figure 35), it can be imagined how each *box* (e.g. power generation, LNG regasification, etc.) is composed of several of these *processes* (e.g. power plants of different technologies, regasification terminals, etc.). The energy flows can be seen as an aggregation of allowed links which take positive values (i.e. there is a positive amount of energy flowing). For instance, the flow of electricity going from the electricity network *box* to the industrial demand *box* is an aggregation of the electricity flows going from the network to all the electricity-demanding devices consuming power in the industrial sector.

In order to develop a mathematical model based on this topological representation of an energy system, an abstraction phase must be carried out first. Using the mathematical programming/optimization terminology, this abstraction will allow us to model each of those processes/boxes as an element in a set of the model. For example, each power generation technology (e.g. nuclear, coal, or wind power plants) can be considered as elements within the “power generators” set, or more generally, within the “energy conversions” set. Then, and still using the optimization terminology, the energy flows could be represented as variables of the optimization model, containing the information of how much energy is flowing from process to process. This abstraction process, which is an important part of our modeling philosophy (and which is inspired in TIMES), will be further explained next.

In our Sankey diagrams (as explained in Chapter 2), the dotted line represents the imaginary border of the country represented, in this case Spain. Within that border, four imaginary columns of processes/boxes can be identified, as represented in Figure 38.

¹⁰¹ As said, refer to the diagram in Chapter 2 if the text labels want to be consulted.

*Figure 38: columns that can be identified within the Sankey diagram.
 Source: own elaboration*



The first column, marked as “PE” (standing for “Primary Energy”), represents the total amount of each type of primary energy (nuclear, natural gas, renewables, etc.) that is used in the country. The second column is marked as “CE” (“Conversion of Energy”) and it represents the energy conversion processes, mainly electricity generation (on top), oil refining (bottom) and liquefied natural gas (LNG) regasification (center). They convert primary energy (e.g. nuclear energy, crude oil) to final energy (e.g. electricity, gasoline). From these conversion processes, some losses and self consumptions are produced, which are represented in the top right of the diagram (red box for losses and dark green box for self-consumptions). Below losses and self consumptions, the other two columns in the diagram can be seen (“TE” and “DS”). The third column is marked as “TE” (standing for “Transportation of Energy”) and represents the energy transportation and distribution networks that deliver final energy to where it is demanded for end use. In the fourth column “DS” (standing for “Demand Sectors”) the economic sectors that demand final energy are represented. In this case, three sectors are represented: industry on top (in blue), other uses (residential, services and agriculture) in the centre (purple) and transportation sector in the bottom (green). In the far left, beyond the country’s border, the primary energy imports can be identified. Final energy exports can be seen as well: electricity on top of the figure, coming out of the electricity network, and oil products (mainly gasoline) on the bottom of the figure, coming out of the oil refining process.

Each of these columns is integrated by processes of each type (energy conversion, energy transportation, etc.) between which energy can or cannot flow. These possible energy flows are defined by exogenous parameters after a qualitative analysis of the studied energy system. This modeling framework allows us to represent different energy systems with different topologies in the most general way: the mathematical structure of the model is always the same, only the processes and their possible flows change between different models, and this information is

fully provided through data. This modeling philosophy is inspired in the MARKAL/TIMES models (Loulou et al., 2005) which, as said in chapter 3, are also fully specified through data. But it is specifically developed keeping in mind the Sankey representation, as will be seen next. In other words, as said, our representation of the energy sector combines ideas from the MARKAL/TIMES models with the Sankey diagrams developed by the author for the BP Observatory on Energy and Sustainability in Spain (López-Peña, Linares, Pérez-Arriaga, et al., 2013).

The main differences between our methodology and TIMES are: (i.) we have a much smaller (but sufficient) level of technical complexity (e.g. number of processes), which allows us to reduce the use of hard-to-understand parameters and which increases the transparency in our model; (ii.) the code of the model has been completely developed and maintained by the PhD candidate, putting a clear emphasis on transparency and easy interpretation, whereas TIMES is a model-generator with closed code and a proprietary graphical interface; (iii.) our structure of processes is clearly conceived to be able to easily represent the output of the model in the form of Sankey diagrams (which could also be possible in TIMES, although not as straightforward as here); (iv.) as will be seen below, our objective function is conceived as a measurement of energy sustainability, which is not necessarily the case in TIMES, and allows us to more easily represent policy trade-offs and synergies; (v.) our model is based upon a database built from scratch based on public and contrasted data, and which will be made open, which is not the case for TIMES-Spain, the existing TIMES model of the Spanish energy sector (Caldés et al., 2008). Also, when compared specifically to TIMES-Spain¹⁰², our model achieves a larger level of technical detail in end-use technologies.

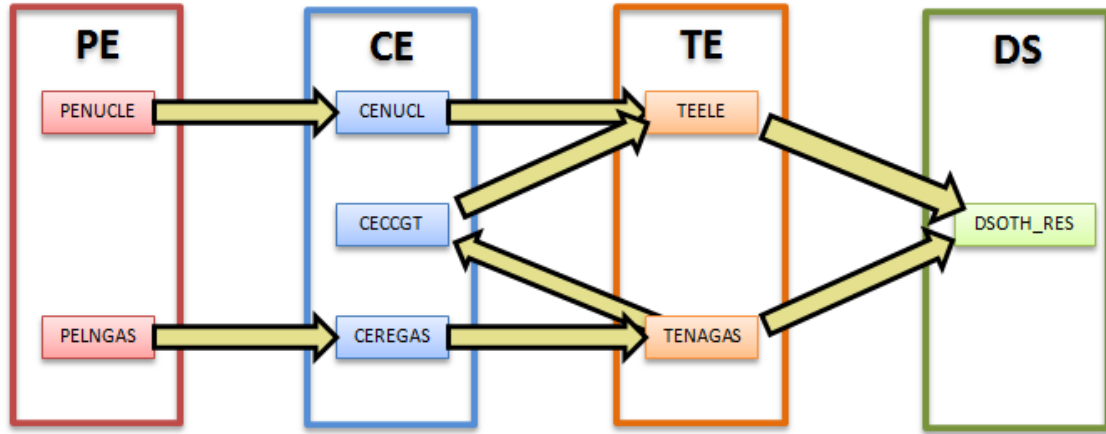
Let's clarify our approach through a simple example. Let's imagine an energy system in which there is only one demanding sector which consists of households. This sector will be called "DSOTH_RES", standing for "Demand Sector Other uses Residential". Let's assume it only consumes electricity and natural gas (it does not consume any other type of energy as could be liquefied petroleum gasses, heating diesel or biomass). Electricity is delivered to this demanding sector from a process called "TEELE" (standing for "Transportation of Energy Electricity", which models the electricity transmission and distribution grids) and gas is delivered from a process called "TENAGAS" (which models the gas networks). Electricity is produced only from two technologies: nuclear power plants ("CENUCL", standing for "Conversion of Energy Nuclear") and combined cycle gas turbines ("CECCGT"). CCGTs consume their gas from the natural gas network (just as the households sector does). The gas network is supplied from a LNG regasification terminal "CEREGAS", which is considered to be a CE process because it converts the primary energy "PELNGAS" into the final energy "TENAGAS"¹⁰³. The nuclear power plant consumes its energy from the process "PENUCL". These relations can be graphically represented as done, with arrows, in Figure 39. In this figure, for the sake of simplicity, we will

¹⁰² This has been done with some very useful help from colleagues from CIEMAT, the Spanish energy research center where TIMES-Spain has been developed.

¹⁰³ In our modeling, we have assumed LNG to be a primary energy and natural gas to be a final energy, as will be seen.

ignore the upstream of both primary energies (i.e. their import processes) and the losses/self-consumptions.

*Figure 39: simplified energy system representation, including processes and possible energy flows.
Source: own elaboration*



Using the GAMS terminology, which is the language where much of our modeling has been implemented (and is useful in this example), all the processes can be considered to belong to a *set* called “proc”, as shown in Figure 40. For a reference on GAMS and its terminology, refer to (Rosenthal, 2010).

*Figure 40: the “proc” set in our example, including elements and their description.
Source: own elaboration*

proc	
PENUCL	"PE Nuclear"
PELNGAS	"PE Liquefied Natural Gas"
CENUCL	"CE Nuclear Power"
CECCGT	"CE Combined Cycle Gas Turbine"
CEREAS	"CE Regasification Terminal"
TEELE	"TE Electricity"
TENAGAS	"TE Natural Gas"
DSOTH_RES	"DS Other Uses Residential Sector"

Still using the GAMS modeling terminology, the PE, CE, TE and DS processes are elements of “pe (proc)”, “ce (proc)”, “te (proc)”, and “ds (proc)”, which are *subsets* of the “proc” set. This implies that this is a logical subclassification, where all “processes” are further classified into “CE processes”, “TE processes” and so on. This is illustrated in Figure 41.

*Figure 41: the different subsets in our example.
Source: own elaboration*

pe (proc)	ce (proc)	te (proc)	ds (proc)
PENUCL	CENUCL	TEELE	DSOTH_RES
PELNGAS	CECCGT	TENAGAS	
	CEREAS		

Next, the allowed flows between processes can be provided (still using the GAMS notation) using *double sets*, as shown in Figure 42. When this is done in GAMS, only the variables related to these double sets can have a value. This is precisely what is intended here: if in our model we declare a variable called for instance “ENERGYFLOW(proc,proc)”, whose value represents the energy flow between two processes, we force it to be non-negative, and we only define it over the existing double sets, the model will understand that the variable can only have a positive value over the processes related in these double sets. In other words, energy can only flow between the processes related in the double sets and in the direction defined by them (because the variable is non-negative). These double sets will be called “peceflows” for the allowed flows from a PE to a CE process, “ceteflows” for the allowed flows from a CE to a TE process, and so on.

Figure 42: the double sets in our example.

Source: own elaboration

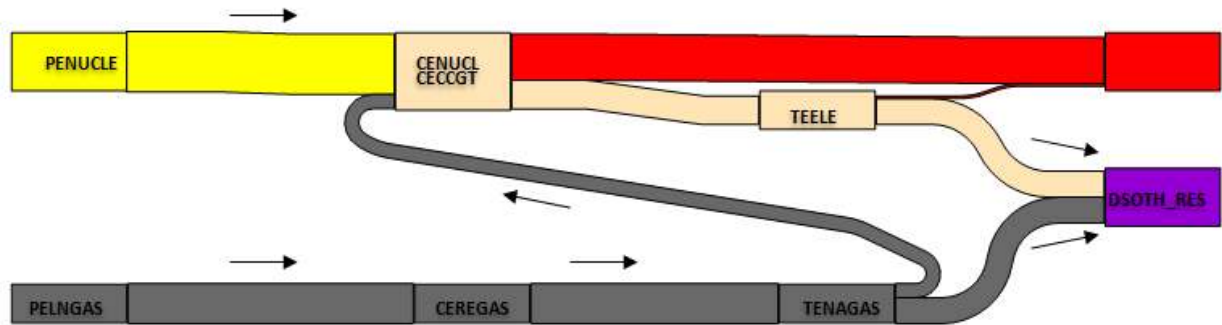
peceflows (proc,proc)	ceteflows (proc,proc)	teceflows (proc,proc)	tedsflows (proc,proc)
PENUCL.CENUCL	CENUCL.TEELE	TENAGAS.CECCGT	TEELE.DSOTH_RES
PELNGAS.CEREGAS	CECCGT.TEELE		TENAGAS.DSOTH_RES
	CEREGAS.TENAGAS		

Once this is done, our model can be completely defined (its data, variables, equations, objective function, etc.) using these “ENERGYFLOW(proc,proc)” variables, and we will be sure that only allowed flows will take place.

To end with the example, we can now illustrate how this modeling framework relates with the Sankey representation. Let’s assume that the model of our simplified energy system has been implemented and solved, for instance, using a cost-minimization rationale. The resulting energy flows can be graphically presented in a Sankey diagram¹⁰⁴ as shown in Figure 43. In it, just for illustrative purposes, some arrows indicate the directions of energy flows: broadly (as in all the Sankey diagrams seen above) primary energy is in the left and final energy use in the right; hence energy flows from left to right. The only exception is the flow going from the natural gas network to electricity generation, exception done in order to keep the *columns* representation seen above, where TE processes are to the right of CE processes.

¹⁰⁴ The main characteristic of a Sankey diagram, it must be reminded, is that the bigger the underlying represented quantities, the thicker the flows.

Figure 43: Sankey representation¹⁰⁵ of our example.
 Source: own elaboration



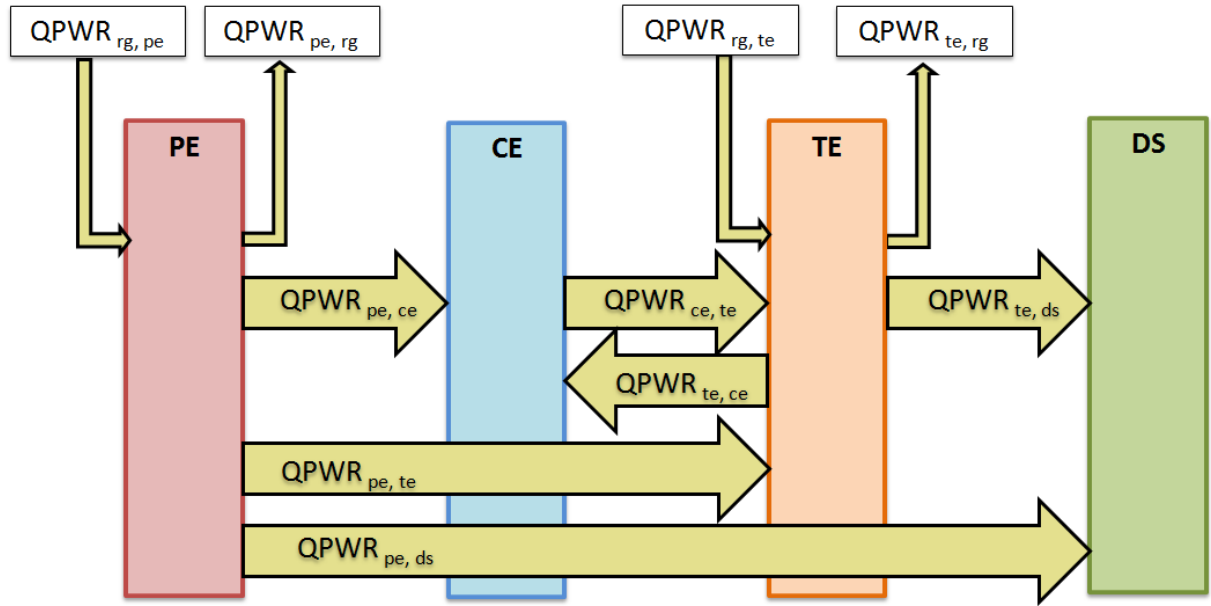
Temporal representation

In order to account for temporal variations of energy demand (e.g. greater electricity demand in peak hours, greater gasoline demand in working days or greater use of gas for heating purposes in winter), and production (e.g. due to the intermittent production of some renewables), our model can be solved for a number of temporal time steps. Instead of defining it in energy terms for a full year and obtain a yearly Sankey diagram representing energy flows (for instance in ExaJoules, EJ), it can be defined in power terms for a number of load levels in the year, obtaining the same number of Sankey diagrams which in this case represent power flows (e.g. in GW). The energy Sankey diagram can be simply obtained by multiplying each power value (e.g. in GW) by the duration of the corresponding load level (e.g. in hours) and performing the necessary unit change (e.g. from GWh to EJ).

In this case, instead of “ENERGYFLOW(proc,proc)” as above, the flows between each pair of processes could be called “QPWR(proc,proc)” (or “QPWR_{proc, proc}” if using the subscripting notation), standing for Quantity of Power, and they would be measured in power units (e.g. GW). The sub indexes still mean, as above, the origin and destination of each power flow. These power flows will be the main variables in our models, they will have associated costs and they will be subject to constraints representing issues such as capacity limitations, energy balances or environmental constraints, as will be explained later. A generalized graphical representation of all the allowed power flows within our modeling framework is shown in Figure 44. In this figure, apart from power flows inside the modeled country, imports and exports of both primary and final energy to/from a generic region “rg” are also represented.

¹⁰⁵ In this diagram, the same color codes used in the Sankey diagrams for the BP Observatory on Energy and Sustainability in Spain are kept (refer to Chapter 2). Mainly: yellow for nuclear energy; grey for LNG and natural gas; light beige for electricity generation, electricity flows and electricity grid; red for losses; and purple for the Other Uses demand sector.

Figure 44: generalized representation of the allowed power flows within our modeling framework.
 Source: own elaboration



Representation of end-use technologies

There is a broad consensus in the literature (refer to chapter 2) that demand-side measures should play a key role in any future sustainable energy policy in every country, and certainly in Spain. By demand-side policies, following the same classification as in Chapter 2 (section 5), we mainly refer to those aiming at changing how energy is used by demanding sectors. They can be based on: (i.) promoting fuel switching, (ii.) shifting demand between different times, (iii.) improving technological energy efficiency to achieve savings, (iv.) actually reducing the demand for energy services or (v.) a combination of these. Giving the importance of demand-side policies, we have implemented a high level of detail within the DS column, in order to be able to model end-use technologies and the above policies.

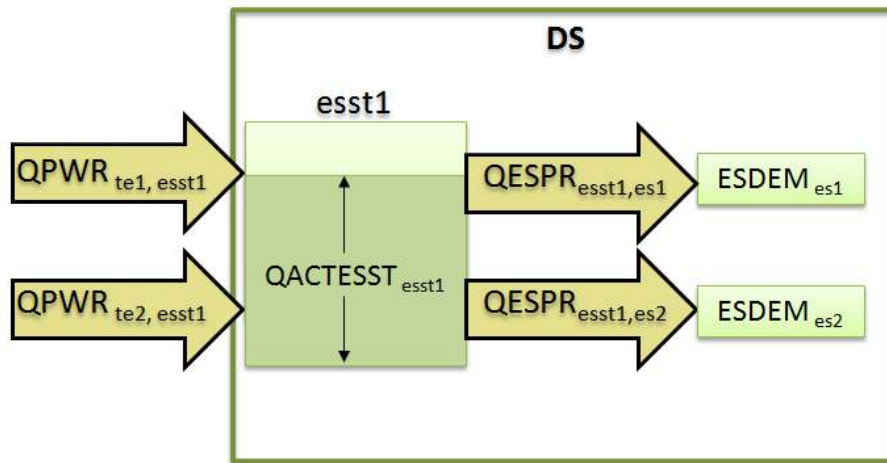
The foundations of our end-use modeling are: (i.) the difference between demand for *final energy* and for *energy services*; (ii.) the idea of *energy services supply technology*; and (iii.) the concept of *activity* within a process, which is also inspired in the MARKAL/TIMES models. The concept of energy service was defined in Chapter 1, but is reproduced here for the reader's convenience: *energy services* ("ES", from now on) refers to the actual services that energy is used for, such as lighting, space heating, industrial production, passengers' mobility, etc., in opposition to *final energy* which are actual energy vectors such as electricity, gas, coal or gasoline. Next, in our model, an *energy services supply technology* ("ESST") is a process which consumes final energy in order to supply an energy service. Some examples could be a gasoline car (consumes gasoline to produce passengers' mobility), a gas boiler (consumes natural gas to produce heat), a solar thermal panel (consumes solar energy to produce hot water) or a lamp (consumes electricity to produce lighting). Some ESSTs can consume more than one type of energy (e.g. a plug-in-hybrid gasoline car consumes both electricity and gasoline), some others can produce more than one energy service (e.g. heat pumps can produce both space heating and space cooling, or gas boilers can produce both space heating and hot water), or any other

combination. All these possible combinations provide large modeling flexibility, but at a cost: an extra variable is needed, the *activity* in each ESST. This *activity* variable models the level of utilization of each ESST in each time step, and allows us to flexibly convert from consumption of different types of energy to production of different types of energy services. For this, two groups of external conversion parameters are needed, and a smart use of units and magnitudes is required, as will be seen. This modeling (using the *activity* variables) is especially useful for ESSTs that produce different energy services which are measured in different units (e.g. a boiler producing space heating measured in GWh of heat and hot water measured in liters).

An illustration of this modeling is given in Figure 45. In the figure, the first thing to be noticed is that the above-introduced column “DS” now has been split into two sub columns of processes: a first one (left side) where the ESSTs are located, and a second one (right side, which would be a “fifth column” in the global diagram from Figure 38) which represents the demand for energy services (“ESDEM_{es}”). In Figure 45, there is only one energy service supply technology (“esst1”) which has an activity level “QACTESST_{esst1}”. By having this activity level, it is producing two energy services “es1” and “es2”, whose level of demand is “ESDEM_{es1}” and “ESDEM_{es2}”. This production of energy services is illustrated with the “QESPR” variables (standing for “Quantity of Energy Service Produced”), more precisely “QESPR_{esst1, es1}” and “QESPR_{esst1, es2}”. In order to have this activity level, our ESST has to consume two types of final energy, coming from the energy transportation processes (networks) “te1” and “te2”. The amount of energy services of each type produced by each unit of activity in each ESST is an external parameter (as said). The amount of energy of each type that has to be consumed by each ESST in order to have one unit of activity is also an external parameter.

Figure 45: illustration of the concept of activity within an ESST (energy service supply technology).

Source: own elaboration



Let us provide a numerical example for further clarity. We will apply the above illustrative diagram (ESST consuming two energy types and producing two energy services) to the case of plug-in-hybrid gasoline vehicles. This numerical example is illustrated in Figure 46 and Figure 47. It will be explained from right to left, in order to keep similarity with the logic behind the previous figure (Figure 45). In our example, let us assume that we have a represented time period (i.e. load level) with a duration of 10 hours. In it, there is a demand for two energy

services: “urban passenger mobility” (“upm”) and “interurban passenger mobility” (“ipm”). The respective demands are 240 pkm (passengers-kilometers¹⁰⁶) and 150pkm. To provide it, we have only one possible ESST technology, which is plug-in-hybrid gasoline vehicles “pihgv”. The level of activity for this technology is measured in vkm (vehicle-kilometers). As said, in our modeling framework the units for measuring activity (vkm in this case) can be freely decided by the modeler, provided that she is consistent with the units in which energy services are measured and with the units of the conversion factors. This freedom provides our model with great modeling flexibility. Following with the numerical example, our technology has a conversion factor (“Factor2”) from activity to produced energy services of 1.2pkm/vkm for the case of “upm” and 1.5pkm/vkm for the case of “ipm”. These factors are fixed through external data and, in this case they are equivalent to the utilization factor of each vehicle, in passengers/vehicle (in other cases, depending on the units used, these conversion factors may not have such an immediate interpretation). Simply by doing a division and an addition, it can be concluded that in order to be able to fully supply the demand for energy services in this time period, our technology needs to have an activity level of 300 vkm (200 vkm for supplying “upm” and 100 vkm for “ipm”). These 300 vkm of activity in a period of 10 hours are equivalent to one single vehicle running for 300 km (at an average speed of $300\text{km}/10\text{h} = 30\text{km/h}$), two cars running for 150km each (at 15km/h), 30 cars running for 10km each, or any other combination. This is irrelevant for our model, because in all these combinations we assume that they will consume the same total amount of energy (provided that all cars are exactly equal, they all have the same energy efficiency, and so on, which is the case because they all are one single ESST). This is one of the key features of our model, and one of the reasons behind the important usefulness of the *activity* concept. Now, let us assume that one single vehicle has an energy consumption of 0.55 kWh of energy, be it gasoline or electricity, per km (this value is equivalent to 6 liters of gasoline per 100 km for one vehicle, using the average volumetric energy density for gasoline which is around 9.22 kWh/l). Let’s also assume that our plug-in-hybrid vehicles consume 40% of their energy as electricity and 60% as gasoline. Hence our ESST will consume 0.22kWh of electricity per vkm, and 0.33 kWh of gasoline per vkm (“Factor1”). If the total activity of our ESST was 300 vkm, and the duration of the time period is 10 h, this implies an energy consumption (expressed in terms of power, given that we are obtaining the “QPWR” variables as seen above) of 6.6 kW of electricity and 9.9kW of gasoline (during the complete duration of our time period, i.e. 10 h).

¹⁰⁶ This is a common unit for measuring mobility. In this case, 240pkm is equivalent to 240 passengers moving 1km each, or 24 passengers moving 10km, or 48 passengers moving 5km, or 1 passenger moving 240 km, or any other combination. In all cases, the total amount of mobility is the same.

Figure 46: numerical example of our ESST modeling. Part I/II: schema.
 Source: own elaboration

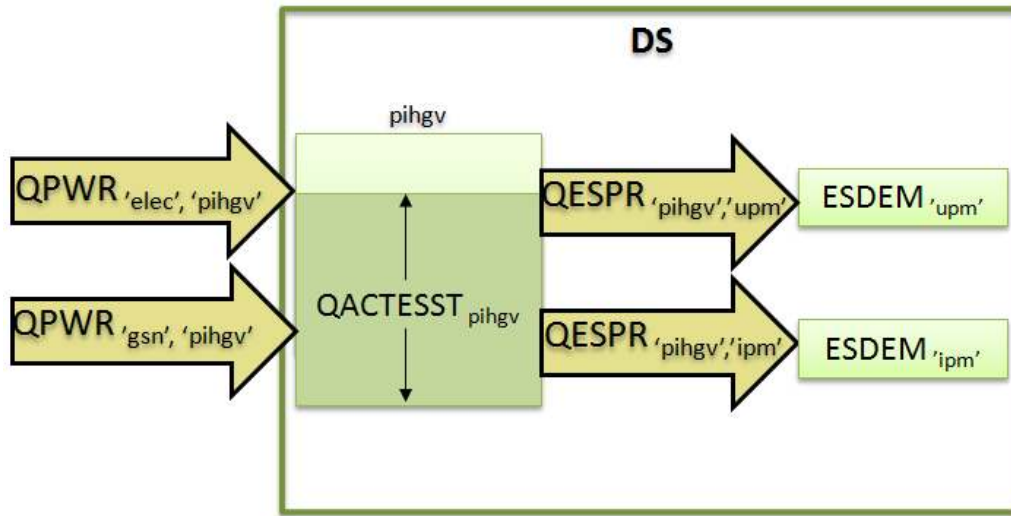


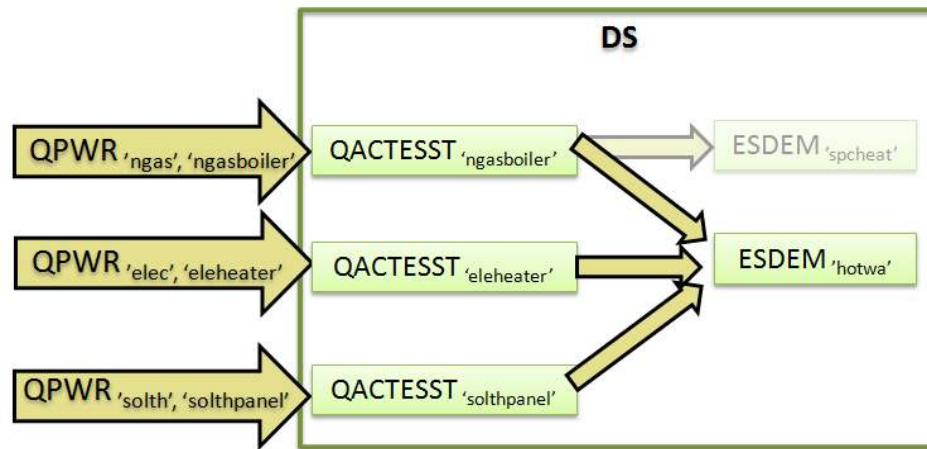
Figure 47: numerical example of our ESST modeling. Part II/II: numerical implementation.
 Source: own elaboration

QPWR	DURATION	FACTOR1	QACTESST	FACTOR2	EDEM
elec: 6.6 kW elec	10 h	0.22 kWh elec / vkm	300 vkm $\frac{200 \text{ vkm}}{100 \text{ vkm}}$	1.2 pkm/vkm	upm: 240 pkm
gsn: 9.9 kW gsn		0.33 kWh gsn / vkm		1.5 pkm/vkm	ipm: 150 pkm

Once again, the strength of this approach rests on the abstraction behind the concept of *activity*, combined with external parameters to convert energy to activity and activity to energy services, and making an intelligent use of units. Indeed, activity can be measured in whatever units the modeler decides to, provided that she is consistent with the units of the demands for energy services and the units for the conversion factors. This is very useful since, as said, each energy service may be measured in different units.

Lastly, it should be mentioned that there may be a number of ESSTs (consuming the same or different types of energy) all producing the same energy service, and that will all participate in the full supply of the total demand for each energy service. A graphical example is provided in Figure 48. In it, the demand for the energy service “hot water” is supplied (in different percentages) through the activities in three ESSTs (“natural gas boiler”, “electric heater” and “solar thermal panel”), which in turn consume three types of energy (“natural gas”, “electricity” and “solar thermal”). The natural gas boiler is also providing another energy service (“space heating”), although this is irrelevant in this specific example.

Figure 48: example of several ESSTs providing a single ES.
 Source: own elaboration



This modeling approach has been successfully implemented in the MASTER_SO model, using almost 40 energy services in all sectors of the economy, which are provided by more than 260 energy services supply technologies, consuming around 20 types of energy. The key is to be consistent with the units used and to have a complete database of input parameters. In the case of MASTER_SO, we have successfully developed a database for all this representation using realistic data for the case of Spain.

IV.3.2.b. Modeling approach of each energy subsector

In the previous section, our energy sector representation has been described and five “columns” have been identified (PEs, CEs, TEs, ESSTs and ESDMs). In this section we will provide a qualitative overview of the modelling of each energy subsector (electricity, natural gas, oil products, biofuels, coal, nuclear, renewables and final energy use) that has been done in the MASTER models for the Spanish case. More details on the detailed modelling (specific equations, mathematical expressions, etc.) will be given in the next chapters. These energy subsectors have been modelled trying to strike a balance between technical accuracy and modelling simplicity. For this, three main inputs have been used: (i) a broad literature review on how these sectors are represented in other models (mainly the ones reviewed in Chapter 3); (ii.) discussions with experts in different energy subsectors, including visits to the Spanish National Energy Regulatory commission (CNE) or to BP’s oil refinery in Castellón (eastern Spain); and (iii.) the expertise of the PhD candidate, his supervisors and his colleagues, which is mainly within the electricity and gas subsectors.

As said, the following modelling approach is specific to the case of Spain (technologies used, data values, qualitative assumptions, etc.), and is the result of a meticulous (and sometimes hard or even frustrating) process of data collection, understanding, comparison, and elaboration in order to build, based on public and contrasted data, a comprehensive, coherent and complete database for the mathematical representation of the Spanish energy sector. These works started in 2009 with the elaboration of the first Sankey diagrams for the BP Observatory on Energy and Sustainability in Spain (López-Peña et al., 2010).

These qualitative descriptions of: (i.) the modelling and assumptions done for the representation of Spanish energy subsectors, and (ii.) of data hypothesis, conversions, calculations, sources, etc., including the resultant numerical values, are intended to be made publicly available to anyone reading this PhD thesis: they are detailed in the annexes of this document. This is one of our main contributions, because no public, comprehensive, detailed and explained documentation and database for the modelling of the Spanish energy system seems to exist in our country. In the next pages, the modelling for each subsector is described. For further details on data sources, assumptions and the used values, refer to the Data Documentation Annex.

Electricity system modelling

- Flexible technological representation of electricity generation: around 20 technologies have been included, considering the ones that are (or will be) relevant to the Spanish case. Some of the included technologies are nuclear, national coal, imported coal, supercritical coal, integrated gasification coal, CCGTs, gas turbines, fuel-oil, four types of hydro, three types of onshore wind, offshore wind, solar photovoltaic, solar thermoelectric, or three types of biomass. Realistic installed capacities, costs and efficiencies have been used, based on data for Spain (Ministerio de Agricultura, Alimentación y Medio Ambiente, 2013; Red Eléctrica de España, 2012; UNESA, 2007) and on forecasts by the most reputed international institutions (EIA U.S. Department of Energy, 2010b; European Commission, 2011b; International Energy Agency, 2010b, 2010c). The model can decide investments in new generation capacity. Short term constraints in generators (e.g. ramps, technical minima or must-run requirements) have not been considered. Concerning operation and maintenance (O&M) costs, we have assumed them to be constant irrespective of the amount of cycling due to intermittent renewables' penetration, which may not be the case (especially for cycling CCGTs).
- All generation technologies include their CO₂ emission factors, as reported in the Spanish Emissions Inventory done by the Environment Ministry (Ministerio de Agricultura, Alimentación y Medio Ambiente, 2013).
- Coal-fired and natural gas-fired power plants with carbon capture and storage (CCS) have also been included. Following the International Energy Agency's "Technology Brief" on the issue (International Energy Agency, 2010d), in comparison with their baseline technology (without CCS), they reduce a large amount of emissions (more than 80%), but at the expense of a reduced plant's efficiency and higher investment and O&M costs.
- Cogeneration in large industries has also been modelled, mainly using data from the Spanish IDAE (Instituto para la Diversificación y Ahorro de la Energía, 2010a, 2010b). Coupling with district heating networks has also been done.
- Renewables with different resource qualities (i.e. load factors) and potentials (i.e. maximum installed capacity for each level of resource quality), based on realistic data for Spain (see below).

- Generation reliability constraints are also included, represented as an *adequacy* and a *reserves* constraints, as described in (Batlle et al., 2007). The first one establishes the need for installed *firm* capacity (calculated using statistical firm capacity factors, i.e. *capacity credits*, obtained from the literature¹⁰⁷ and from personal communications with experts) to be above peak demand with a 10% reserve margin. The second one establishes that in each load level, the amount of reserves in the system must be greater than the sum of the following three terms: (i.) the largest possible power plant that could fail in the system (estimated to be a 1GW nuclear plant), (ii.) the demand uncertainty (around 4% of demand in each period) and (iii.) the uncertainty in intermittent supply (assumed to be 20% of renewables production). These reserves must be provided by flexible generation (calculated through a flexibility factor, also obtained from the literature and the researchers' expertise) being warm but idle (i.e. ready to produce but not producing, what implies that it is paying all investment, fixed and variable O&M costs, but not fuel costs¹⁰⁸). An interesting line for further research could be to include if and how reserves can also be provided by interconnections (if we could rely on the European generators, placed beyond our interconnections, to provide them) or end-use devices/measures (e.g. plugged electric vehicles, active demand management)¹⁰⁹. More detailed on these constraints is given in their mathematical definition in Chapter 5.
- Endogenous hydro management and optimization, including: large hydro plants with reservoirs, pumping storage plants, run off-the-river production and minihydro. An average hydraulic year was considered, with monthly water availability resolution, as reported in the yearly reports from the Spanish electric transmission system operator (Red Eléctrica de España, 2012). For hydro power plants with reservoirs, we have made the hypothesis that no water is kept from month to month (total hydro production each month must be equal to monthly water availability). Within each month, however, the model freely decides when to generate electricity, which typically will be in high demand periods, where the most expensive power plants would have to produce otherwise. Concerning pumping storage, we have assumed daily pumping/generation cycles which, after some consultations with experts at Red Eléctrica de España, have been deemed reasonable for a future power system with a higher penetration of intermittent generation. We have also assumed it to be pure pumping storage, i.e. no natural hydro inflows.
- Up to 96 load levels to account for electricity load variation: 12 months, 2 day types within each month (weekday/weekend) and 4 load levels within each day type (super peak, peak, medium and off-peak). The super peak includes only the 1% hours of highest

¹⁰⁷ Considering for instance the values used by Red Eléctrica de España, the Spanish Transmission System Operator.

¹⁰⁸ This is a simplification since in reality an idle power plant needs to burn some fuel to remain hot. This level of detail is not modeled.

¹⁰⁹ In this second line, research is already being done at the research institute where this PhD thesis has been developed, that is, the IIT at Comillas University, Madrid.

demand in each day type, in order to adequately capture the peak demand in the system (key for the adequacy constraint mentioned above).

- Electricity interconnections: import/export capacities, their foreseen evolution according to the latest infrastructure plans by the European Commission and the Spanish Government (Ministerio de Industria, Turismo y Comercio, 2011b) and the prices at which power is traded. We have for the moment considered interconnections (both electric and gas) to be fixed at these levels (i.e. the models cannot invest in increasing capacities), since the administrative and political processes behind interconnections are quite complex. However, this would be an interesting future research line, especially if associated with the enhanced capacity to integrate renewables or the reliability provided to the system by increased interconnections (as should be according to the recent European policies on the Internal Energy Market).
- Electricity networks: modelled as a single node with average mean losses and cost factors. These try to account for the costs of transport, distribution (depending on the modelling done for distributed generation) and the Technical System Operator, as documented in the yearly reports from the Spanish National Energy Regulatory Commission (Comisión Nacional de Energía, 2012). Other regulated costs which are included in the Spanish network access tariff are not included here, because they are not networks costs *per se*, but energy policy costs. The cost factor has been calculated through an econometric approach (detailed in the Data Documentation Annex) to account not only for the amount of energy transported (energy term) but also to the installed capacity, notably intermittent (capacity term): the idea behind this was to try to replicate the cost increment that renewables may cause to the electricity networks, according to their intermittent character which demands well-meshed grids and sophisticated system operation (the extra cost in terms of needed backup capacity is also accounted for, but in this case in the adequacy and reserves constraints mentioned above). This issue should however be subject to further research, because it is arguable whether network costs are only explained by total delivered energy and by installed intermittent capacity, being other factors (e.g. peak demand, geographic characteristics) possibly important too. In addition, with our modelling, intermittent technologies which are forecasted to become cost competitive in Spain, such as wind and solar, seem to be much penalised (through the increased costs of electricity networks). This econometric approach is explained in detail in the Data Documentation Annex. In any case, this was just a first approach, with important limitations, and it is just a parameter within our model which could be easily modified. From another perspective, we are aware of the limitations of the single-node representation, but improving it is a very complex issue, and hence this approach is common in other energy models (e.g. TIMES-based models). We believe that it provides a good approximation in the case of developed, highly-meshed networks, as it is the case in Spain. Adding a more detailed network representation (e.g. based on congestion zones) would add significant mathematical complexity to the models.
- Centralised and distributed generation are modelled through the use of a set of different TE processes, hierarchically related through allowed power flows, which model

electricity transmission and different distribution grids. Some generating capacity delivers its energy to the transmission grid, whereas others deliver it to the different distribution grids. Each different TE process has different cost and loss factors (losses are normally higher in distribution than in transmission and, within distribution, higher in residential areas than in industrial areas where voltage is higher).

Natural gas system modelling

- Imports can be both as liquefied natural gas (LNG) and through pipeline. Exports only through pipeline (Spain does not have LNG liquefaction terminals). Domestic gas production (maybe shale gas in the future) could be included, but it has not.
- A benchmark regasification terminal is included, with real capacities, costs, efficiencies and emissions calculated as an average of Spanish values, as reported by the gas system technical operator (ENAGAS, 2012) and the Spanish Regulatory Commission (Comisión Nacional de Energía, 2006, 2010, 2011). Investments in new regasification capacity are allowed. We have made the hypothesis of LNG being a primary energy and natural gas being a final energy, so that regasification terminals can be modelled within the energy conversions (CE) family. We have included technical minimum constraints which are normally used in regasification terminals to recover boil-off gas (i.e. BOG), while all installations are kept cold and 100% available in stable functioning conditions (ENAGAS, 2010).
- The same load levels as applied to the electricity sector are applied here, which allows us to better represent variations in demand, supply, costs or prices. This has been done because of the algebraic definition of our model (the same time steps must be applied to the complete energy system), but it is much less critical in the gas sector than in the electricity sector, because there is a fundamental difference: gas can be stored in large quantities at reasonable costs, hence supply and demand need not to be balanced at all times.
- The gas network's technical constraints have been represented as a simple energy balance, which is a fair approximation if two hypotheses are considered: (i.) constant pressure; (ii.) only operative gas is used (i.e. usage of *cushion gas*¹¹⁰ is assumed to be null).
- Gas interconnection capacities with Africa (Tarifa and Medgaz pipelines) and Europe are included, and also their foreseen evolution (again, based in European and Spanish infrastructure plans).
- Concerning the prices at which gas is traded, for the future we have used reputed forecasts such as the World Energy Outlook (International Energy Agency, 2012a), and we have taken into consideration possible future effects such as LNG exports of U.S. shale

¹¹⁰ *Cushion gas* is the best translation we have found from the Spanish "*gas talón*". We mean the minimum level of gas that, under any circumstance, must be maintained in the gas pipelines.

gas. For present prices, given that Spain lacks a transparent spot price (due to the absence, for the moment, of an Iberian gas hub), and that most gas is purchased through private contracting, we have used the information provided by Spanish Customs (Aduanas), to whom private agents must disclose some information about their gas purchases.

- The gas network has also been modelled as a single node, with average losses and costs. These try to account for the costs of transport, distribution and the Technical System Operator, as documented in the yearly reports from the Spanish National Energy Regulatory Commission (Comisión Nacional de Energía, 2010). Only an energy term is used here, as opposed to the econometric approach used for the electric networks. Methane emissions have not been included in our model, hence fugitive emissions from the gas network are not considered. Concerning the use of a single-node approach, the same explanation as the one presented for the electricity grid applies, mainly because our gas network is also well-meshed.
- Gas storage has not been modelled, being an interesting line for future research (especially if the intra-year variation of gas prices is modelled, or if storage capacity is used to compute security of supply indicators). Useful information on this could be found in ENAGAS, CNE and CORES.

Oil products system modelling

- The modelled products are: gasoline, diesel, LPGs (liquefied petroleum gases), kerosene, fuel-oil and a sixth generic product called “others”.
- Three types of oil refineries are considered: low, high and very high complexity. Investments in new oil refining capacity (of any type) are allowed. The greater the complexity, the wider the flexibility in the obtainable ranges of output products¹¹¹, but the greater the costs, self consumptions and emissions. This modelling has been specially difficult, because of the large technical complexity in the refining sector and the lack of data, especially regarding costs. We have mainly based our representation on how it is done in TIMES models (Loulou et al., 2005), on several discussions with experts from oil companies and the Spanish National Energy Commission, on information about the hydrocarbons sector in Spain (CORES, 2012), on publications about the European

¹¹¹ The shares of output products obtained from an oil refinery are a very important characteristic of this activity. In general, and in the case of European markets, lighter products (such as LPGs, kerosenes or gasolines) have higher prices and are hence more profitable for a refinery than heavier products such as fuel-oil. But the technical characteristics of the refining process do not allow for a 100% share of production of these light products. Heavier products are generally obtained as sub-products. The lighter the crude oil (different crude oils have different properties) the larger the share of light (and profitable) products obtained by a same refinery, but a light crude is also generally more expensive than a heavy one. Hence some companies opt to invest in high complexity refineries which, through complex processes, are able to amplify the flexibility in achievable shares of different products that are obtained from each crude. Thanks to these investments they may be able to obtain larger proportions of light products even from a heavy crude. However, greater transformation complexities also involve greater self consumptions and emissions.

refining industry (CONCAWE, 1999), on governmental reports (Ministerio de Medio Ambiente y Medio Rural y Marino, 2004), and on several books (Fahim et al., 2010; Favennec, 2001; Gary & Handwerk, 2001; Lluch Urpí, 2008). However, the representation of oil refining in Spain could be further improved, being a potential line for future research, especially issues regarding calibration and sensitivity analyses.

- The same load levels as applied to the electricity sector are applied here, which allows us to better represent variations in demand, supply, costs or prices. The same comment done for the case of natural gas applies here.
- The oil products network has also been represented as a single node. Average losses and average costs per unit of delivered energy have been used, which depend on the product (gaseous products such as LPGs are generally more expensive to deliver than liquids). However, data availability for Spain is scarce. The main source has been CLH (Compañía Logística Hidrocarburos), the Spanish oil products logistics company which according to (International Energy Agency, 2009d) transports around 80% of motor fuels in Spain. A simplification has been done: part of the logistics of oil products is done through trucks and trains, not through a network of pipelines. The costs and energy use of these trucks and trains should in theory be included in the oil products TE process, and not in the transportation end use (DS) sector. Indeed, the energy used in trucks (normally oil products such as diesel) could be seen as a self-consumption in the oil products TE process. However, no specific data on this has been found, so this effect has not been considered and some double-accounting may be happening. In any case, we consider this effect to be small (given that 80% of motor fuels are transported through CLH's pipelines), and even smaller for the future because oil products are expected to decrease in our energy mix, and because the efficiency of trucks is assumed to improve).
- Imports of crude oil (PE) and imports/exports of oil products (TEs) have been considered without capacity limitations (done mainly by ship). A single crude quality has been considered. International prices are external parameters obtained from reputed forecasts such as the World Energy Outlook (International Energy Agency, 2012a). For oil products, which do not appear in those reports, a forecast has been done as described in the Data Documentation Annex.
- Crude and products storage has not been modelled, being an interesting line for future research (especially if intra-year oil products' prices variation is modelled, or if storage capacity is used to compute security of supply indicators). Useful information on this could be found in CLH, CNE and CORES.

Biofuels system modelling

- Two commodities have been represented: first-generation biodiesel and bioethanol. Second generation biofuels have not been modelled, being an interesting line for future research.
- One benchmark production plant for each commodity has been included, with realistic costs, efficiencies, and considering actual installed capacities in Spain. The model can

decide to invest in more capacity. Data availability was, however, scarce. With better data, more than one type of production plant for each commodity could be modelled, for instance, to represent different production methods. This could be interesting for a field such as biofuels, where much research and technological innovation is taking place.

- The inputs (normally cereals for bioethanol and seeds for biodiesel) can be either domestic or imported, with realistic costs and availabilities based on data found for Spain.
- HVOs (Hydrotreated Vegetable Oils) have not been included because its participation is forecasted to remain marginal (Instituto para la Diversificación y Ahorro de la Energía, 2011a).
- International biofuels trade has also been introduced, so that the model can choose whether to import them or to produce them locally, and when to export. Forecasts for the prices of bioethanol and biodiesel have been done, based on the limited data availability.
- Biofuels transportation TE processes have been assigned average losses and costs extracted from the literature, and considering the specific technicalities of biofuels transportation (e.g. the possible chemical interactions of ethanol), and the fact that they are a modern energy vector without a well-developed infrastructure, which tend to make them more expensive to transport than petroleum-based liquid fuels.
- Biofuels have been assumed to be emissions-free, assuming that they comply with the strictest European sustainability regulations and that they are completely carbon-free (compared to the substituted fossil fuel). This is just a working hypothesis which could be easily modified, because we are well aware of the large debate that this generates. Indeed, there are important sources of emissions within the biofuels supply chain, such as the transportation and treatment of materials, or the possible non-reposition of the biomass used for the manufacturing, and it is unclear whether the emissions throughout the full lifecycle of biofuels (which is the relevant parameter) are null.

Coal system modelling

- Even if coal is forecasted (by most sources, but not all) to reduce its participation in the Spanish energy matrix, and to limit its use to some heavy industries (e.g. metals) or, maybe, power generation, we have also modelled it. Two types of coal are modelled, domestic (Spanish) coal and imported coal (one single type has been used). Even if coal is sometimes used directly for final uses, we have considered it to be a primary energy (PE).
- Domestic coal production is limited to a maximum yearly value (in energy terms), which has been assumed to be the maximum historical value as obtained from the BP Statistical Review (BP, 2012), which corresponds to year 1984. The cost of domestic coal has been calculated considering the subsidies that are given to Spanish coal mining industry, as reported by the Spanish Energy Ministry (Ministerio de Industria, Energía y Turismo,

2012). Fugitive emissions from coal production have not been included because they are mainly methane, which is not modelled as said above.

- Capacities for imports/exports of coal have been assumed unlimited (given that it is done by ship). The prices at which coal is traded have been extracted from the forecasts in the World Energy Outlook (International Energy Agency, 2012a).
- The TE process associated to coal transportation within Spain has been characterised, but data availability was almost null. We have assumed that this process only carries coal from the PE process to end-use sectors (not to power plants), and we have used adapted data from the U.S. (Edgar, 1983, 2011; EIA U.S. Department of Energy, 2010c) assuming that this transportation is done 80% by train and 20% by truck and an average distance of 300km. A similar provision applies as with the case of oil products, regarding the possible double-counting of the costs and energy consumption in this TE process.

Nuclear system modelling

- As said in Chapter 2, in the BP Chair on Energy and Sustainability, we consider nuclear energy in Spain as 100% imported, given that neither mining nor uranium pre-treatment take place domestically.
- We have considered unlimited import capacity, and the present and future costs of nuclear fuel have been extracted from (Deutch et al., 2009; UNESA, 2007; World Nuclear Association, 2011).
- Nuclear energy is assumed to flow straight from the PE process to the CE nuclear power plant processes: no TE process is associated.

Renewables modeling

- Wind: three resource qualities (i.e. equivalent hours) and potentials (i.e. maximum installed capacity for each level of resource quality), have been included for onshore wind, and one for offshore. They are all based on realistic data for Spain extracted from sources such as the Renewable Energy Plan (Instituto para la Diversificación y Ahorro de la Energía, 2011a), or the assessments of renewable potential in Spain by Greenpeace (Greenpeace, 2005). The forecasted technology costs are obtained from (EIA U.S. Department of Energy, 2010b; European Commission, 2011b; International Energy Agency, 2010b, 2010c).
- Solar for electricity generation: similar approach as with wind, using the same sources, and in this case considering potentials, equivalent hours and costs for centralised installations (solar PV farms, with tracking, and solar thermoelectric) and for rooftop installations (only PV, without tracking). The current building normative in Spain (Código Técnico de Edificación, CTE) imposes rooftop PV development on newly built commercial buildings (no obligation exists for residential buildings). This has also been considered, based on the assessments in (Instituto para la Diversificación y Ahorro de la Energía, 2011a). For solar thermoelectric (concentrated solar power, CSP), no energy

storage has been modelled, although this is certainly a key feature in this technology. Most of the information on costs and potentials has been obtained from (Greenpeace, 2005; Instituto para la Diversificación y Ahorro de la Energía, 2011a). Net balance and self-consumption with PV (which represents an important potential in Spain) has not been modelled, and it represents an interesting line for future research, in order to account for the potential benefits to the electric system in terms of reduced losses and costs in power grids. It should be done along with an adaptation in the parameters used to represent distributed electricity generation, as mentioned above.

- Solar for thermal uses: it is assumed to produce low-temperature heat, mainly for hot water as reported in (Instituto para la Diversificación y Ahorro de la Energía, 2011a), and in residential and commercial buildings (although it could also be used in sectors such as food and paper industries). A similar approach as for distributed solar PV has been used, also considering the installation obligations contained in the buildings normative (which in this case also applies to residential buildings). Most of the information has been obtained from (Instituto para la Diversificación y Ahorro de la Energía, 2011a).
- Biomass for electricity generation: we have considered three technologies, all of them being centralised power plants (as opposed to distributed generation). These are plants based on energy crops, plants based on agriculture waste, and plants based on forest residues. The costs of technologies have been obtained from the same sources as the other power generation technologies, reported above. The costs and yearly potentials of used fuels (three biomass types) have been obtained from (Instituto para la Diversificación y Ahorro de la Energía, 2011a). Yearly potentials (in energy terms) are an important limiting factor, since we have assumed biomass to be entirely domestic (international trade in this case may not make much sense, given the normally low volumetric energy density of biomass, which significantly increases transport costs, although some international trade does exist). Emissions associated to biomass have been considered null, although this is currently subject to debate.
- Biomass for thermal uses: we have assumed it to be used for space heating and water heating purposes in commercial and residential buildings. It also has important potential in agriculture and in many industrial sectors, what has been approximated in an aggregate way. We have modelled its transportation costs when used in final use sectors, which can be important due the low volumetric energy density. For that, we have created a TE biomass process. Emissions associated to biomass have been considered null, although this is currently subject to debate. Once again, this being one of the advantages of our approach, this is easily changed in the data used by our model.
- Biogas: in theory it can be either cleaned and injected into the natural gas network (biomethane), or used directly, for thermal uses (e.g. heating, transportation) or for distributed cogeneration plants. We have not found reliable data on cleaning processes, yearly potentials (depend on the amount of residues generated) or costs, so we have not included it, although it can be an interesting line for future research (it is forecasted to

play significant roles in many north European countries, especially for transport and district heating).

- Solid waste could have important potential for thermal uses in some industries such as cement or paper. We have also considered it for power generation, with data on potentials and costs coming from (Instituto para la Diversificación y Ahorro de la Energía, 2011a). These sources only consider part of its potential as renewable (around 50%), and we have only used this part. Hence emissions associated to solid waste have been considered null.
- Geothermal for power generation: we have ignored it, because it seems to have a relatively small potential for Spain and the objective in the national Renewable Energy Plan for 2020 is only 50MW (Instituto para la Diversificación y Ahorro de la Energía, 2011a).
- Geothermal for thermal uses: according to (Instituto para la Diversificación y Ahorro de la Energía, 2011a) it seems to only have potential in Spain in very low-temperature uses, e.g. heat pumps. According to (Greenpeace, 2011) they will only be used in heat mode (not for cooling). However, no accurate data has been found, so we have not included this technology which, however, could play an important role.
- Wave and tidal energy have not been included because they are forecasted to probably remain in experimentation phase at least until 2030 (Instituto para la Diversificación y Ahorro de la Energía, 2011a).

Final energy use sectors

- As said above, we have modelled energy services' demand for around 40 energy services in all sectors (transportation, residential, commercial, primary, industry, etc.). Their demands up to 2030 have been estimated for Spain using official data and studies from reputed experts and institutions. Examples of included services are passengers' and freight' mobility in urban, metropolitan, interurban, national and international contexts; space heating, space cooling, hot water, lighting or electric appliances for commercial buildings; or space heating, space cooling, hot water, cooking, ovens, fridges, washing machines, dishwashers, lighting or other electric appliances in the residential sector.
- Around 260 energy use technologies (ESSTs), which provide those services and consume final energy carriers (electricity, gasoline, etc.), have been modelled. Examples of included technologies in the transportation sector are cars (gasoline with different efficiency levels, diesel with different efficiency levels, biodiesel or bioethanol-powered, hybrids, plug-in hybrids, electric, LPG-powered, natural gas cars, etc.), motorcycles, bikes, buses (with different efficiencies such as the Euro IV and Euro V standards, biofuels-powered, natural gas-powered, or hybrids), metro, trains (diesel-powered, biofuels-powered, electric with regular speed, or high speed), airplanes (fired with kerosene or with kerosene-biofuel blends), ships (powered with diesel, biodiesel or LNG), or vans and trucks (powered with diesel, biodiesel, natural gas, hybrid, or electric). For household or commercial sectors, we have considered technologies such as natural

gas- or LPGs-fired boilers (atmospheric, low temperature and condensation), diesel boilers, biomass furnaces, heat pumps (COP2¹¹² and COP6), electric heating devices (both for space heating and hot water), microcogeneration units, district heating, solar thermal panels for hot water, three types of lighting (incandescent, halogen and LEDs), conventional and efficient electric appliances, or different types of cooking devices (burning natural gas or LPGs, or using electricity with different efficiency levels). Each technology has its technical parameters (conversion from energy to activity and from activity to energy services, CO₂ emissions factor, etc.) and its associated (non-energy) usage costs. These parameters are based on the meticulous development of an extensive database for end-use technologies using realistic Spanish data from a large number of sources. The inclusion of non-energy costs of ESSTs (e.g. investment, non energy- related O&M, etc.) is of great importance for our models: it allows the optimization to consider the trade-off between: (i.) older, energy inefficient and (economically) less costly; and (ii.) modern, more efficient and (presumably) expensive technologies. If these non-energy usage costs were not included, the model would only choose the most energy efficient technologies, without considering other costs. For instance, in the case of cars, without considering the non-energy costs of the vehicle itself, the model would choose to only use electric cars. This is because, from an energy-only perspective, they may be less costly than their traditional, fossil fuel-based, counterparts (due to their improved energy efficiency and reduced energy costs in a hypothetical system where electricity is generated with a high efficiency, low cost generation mix). However, if the (non-energy) costs of the vehicles (i.e. investment costs) are included in the optimisation, electric cars may not be as favourable.

- If energy savings/switching/demand shifting are to be achieved, this can be done changing the ESSTs but also changing the demand for energy services. For instance, a reduction of gas demand for space heating in the residential sector can be achieved installing by more efficient boilers (e.g. condensation instead of atmospheric), what achieves a smaller consumption for the same amount of demanded energy service, but also by improving the thermal insulation of houses, what reduces the demand for the energy service. In this sense, “Energy Service Variation Measures” (ESVM) have been included. They are characterised by an implementation cost (e.g. the cost of improving thermal insulation) and the produced effects on energy services demands (they can produce reductions in some energy services and sometimes increment in others, i.e. a switching). Some examples of the included measures are improving thermal insulations in residential or commercial buildings, changing windows, or promoting teleconferences in business (which reduces demand for passengers’ mobility, but increases electricity demand from electric appliances).
- We have also modelled the possibility of shifting energy demand between different time slices within the year (without involving any reduction/increment in the total demand

¹¹² Coefficient of Performance: a measurement of the efficiency, which is used for heat pumps and air conditioning units.

for energy services in the year, or any change in the type of energy used or in the total energy demanded in the complete year). Each ESST can operate in three modes: no load shifting allowed, intradaily or intraweekly shifting. The (possible) lost utility of demand due to load shifting is also considered, even if this is still an ongoing research field (e.g. the loss of comfort that may mean to put the washing machine in the middle of the night).

IV.3.3. Our proposal: data, magnitudes and units

As has just been described, a structured, detailed and comprehensive representation of the entire Spanish energy system has been done, which allows us to mathematically model it. It is based on the abstraction of our Sankey diagrams with the identification of five “columns” within the energy sector (PE, CE, TE, ESST and ESDM), each of these columns being integrated by a number of processes, between which power can flow according to the allowed links (represented as double sets in GAMS). In addition, we have used public data from contrasted sources of information. More information on the mathematical implementation is given in next chapters, and details on the data hypothesis and numerical values can be found on the Data Documentation Annex. The idea behind this PhD thesis is that it will all be made available to anyone reading this thesis and to the wide public, so that anyone not agreeing with some results could fully analyze the data and perform her own calculations. When the author of this thesis/modeler is not confident about the value given to a parameter, this is clearly stated so that it is well identified, easing the process of redoing the calculations with a new value or performing a sensitivity analysis.

This brings transparency and helps building confidence on our data, partially fulfilling the objectives of this PhD thesis. However it is not enough to achieve another of our objectives: intuitive extraction of insights about the *big picture* of the energy system under study. For this, other aspect of our methodological proposal is very helpful: the correct use of uniform and intuitive magnitudes and units, as explained next.

The above-described modelling is methodical and structured. All the different energy subsectors are reduced to a set of PE, CE, TE, ESST and ESDM processes, all of them having the same basic parameters such as capacities, costs, efficiencies and other technical, economic or environmental ones. These processes are connected with the allowed power flows. This allows us to see that, in the end, no matter the energy subsector, all processes can be modelled with very similar representations, and all the flows are, in the end, energy and/or power (be it electricity, diesel, gasoline or natural gas, for instance).

However, this is sometimes not clear in the daily activity of energy professionals. Those in the electricity sector tend to use units such as TWh for energy, GW for power/capacity, or €/MWh for prices/costs. Those in the gas sector use GWh (thermal¹¹³) or cubic meters for

¹¹³ Some authors in the power sector differentiate between thermal and electric units (e.g. GWht and GWhe), the first being normally the energy contained in fuels, and the second referring to the electricity that can be generated with them (which of course depends on the generator used). Such differentiation may have its purpose, but it will not be

IV.3. Methodological Proposal

energy, GWh/day for power/capacity, or €/MWh and €/bcm (i.e. billion cubic meters) for prices/costs. Those in the oil sector use units such as barrels or tons for energy, barrels/day for power/capacity, or €/litre or €/ton for prices/costs. This becomes even more complex when other units are used, such as joules, tons of oil equivalent or tons of coal equivalent (and their multiples e.g. kJ, Mtoe, GJ, etc). Furthermore, it may be still more complex when British or American units are used (e.g. British thermal units, gallons, pounds, feet, etc.), or even different currencies. What is more, sometimes different units are used for the prices of the same product depending on the situation, as happens with the prices of gasoline and other oil products, which are measured in €/t at wholesale level, and in €/l at retail level. An illustration of this issue is showed in Figure 49, obtained from one of the yearly statistical publications in the Spanish energy sector. The text in the figure is hence in Spanish, but the reader does not have to understand it: the point is just to see the large number of different units used, in the third column.

Figure 49: example of the number of units used in the energy sector.

Source: (CORES, 2012)

Indicadores económico-energéticos de España

Indicadores	Fuente	Unidades	2006	2007	2008	2009	2010	2011
Consumo y demanda								
Total productos petrolíferos	CORES	kt	73.954	74.910	72.535	68.445	67.096	64.291
G.L.P.'s	CORES	kt	2.076	2.063	1.980	1.840	1.852	1.654
Gasolinas	CORES	kt	6.940	6.696	6.296	6.013	5.677	5.299
Querosenos	CORES	kt	5.410	5.708	5.630	5.133	5.246	5.596
Gasóleos de automoción	CORES	kt	24.585	25.772	25.126	23.785	23.588	22.601
Gas natural	CORES	GWh	389.436	406.298	450.726	404.555	404.315	377.792
Comercio exterior								
Importación de crudo	CORES	kt	60.475	57.509	58.508	52.297	52.461	52.147
Importación de gas natural	CORES	GWh	407.661	408.941	457.572	410.556	412.928	399.100
Coste CIF del crudo importado	CORES	€/Bbl	48,82	50,36	64,01	42,99	58,60	78,00
Saldo productos petrolíferos	CORES	kt	17.960	19.918	16.453	15.277	12.758	9.872
Saldo balanza energética	DGA	M€	-32.614	-33.180	-44.476	-26.679	-34.490	-39.934
Petróleo/S. balanza comercial	DGA	%	25,09	21,33	29,91	32,20	43,49	63,14
Refino y stocks de petróleo								
Materia prima procesada	CORES	kt	61.945	60.392	61.091	57.738	58.154	57.152
Utilización de la capacidad de refino	CORES	%	91,36	89,07	90,10	85,16	82,45	81,03
Stocks de crudo y productos (a 31 diciembre)	CORES	kt	18.568	18.448	18.837	18.143	18.164	18.157
Producción interior								
Crudo de petróleo	CORES	kt	140	143	127	107	122	100
Gas natural	CORES	GWh	709	202	179	158	664	588
Grado de autoabastecimiento (petróleo)	CORES	%	0,19%	0,19%	0,18%	0,16%	0,18%	0,16%
Grado de autoabastecimiento (gas)	CORES	%	0,18%	0,05%	0,04%	0,04%	0,16%	0,16%
Precios crudos y productos								
Precio Brent (cotización media anual)	REUTERS	\$/Bbl	65,29	72,49	97,26	61,84	79,52	111,17
Cotización media anual	BCE	\$/€	1,2556	1,3705	1,4708	1,3948	1,3257	1,3920
PVP gasolina 95 l.O. (media anual)	MINETUR	c€/litro	103,30	104,86	112,33	100,39	116,33	131,82
PVP gasóleos automoción (media anual)	MINETUR	c€/litro	95,71	96,96	114,14	91,20	107,57	126,71
PVP botella de butano 12,5 kg (a 31 diciembre)	MINETUR	€/bombona	11,77	12,29	13,76	10,69	12,79	15,09
Tarifa GN T1/TUR1 doméstico y comercial (a 31 diciembre)	MINETUR	c€/kWh	6,7099	6,8729	8,0428	6,7845	7,3808	8,4214

Some of the statements just made can be seen as provocative, confusing or counterintuitive, e.g. barrels, litres or cubic meters are units of volume, not of energy; tons are

made in this thesis: energy is energy, be it thermal or electric, and it is up to the user to interpret it in a correct way. The Sankey-based representation will help this correct interpretation.

units of mass, not of energy, etc. Of course, there is no argument about this. The point is: these volume and mass units are ultimately being used to measure energy and, if divided by any unit of time, power. So why not express them all in the same energy or power units? This can be easily done (any undergraduate engineering or sciences student could do it) using average energy densities either in volume or in mass¹¹⁴. From such a simple exercise, some lessons could be learnt which could provide interesting insights for the energy policymaker and, especially, for the wider public. A clear and very didactic example of this is David MacKay's book (MacKay, 2009), which has inspired much of this PhD thesis. Some examples are shown next¹¹⁵, what matters in them are not the precise figures but the orders of magnitude.

- Installed power generation capacity in Spain in 2008 was around 95GW. Installed oil refining capacity was around 85GW¹¹⁶, measured as output for products, as done for electricity. Installed regasification capacity was around 80GW.
- The wholesale cost of some primary or final energy vectors in Spain (either imported or produced locally, without any taxes or intermediate costs) is at the following orders of magnitude: around 55€/MWh for wholesale electricity (of course, this varies greatly depending on the hour), around 40€/MWh for crude oil imports, around 25€/MWh for pipeline natural gas, around 20€/MWh for LNG, around 9€/MWh for imported coal, around 16€/MWh for national coal (hence the needed subsidy), around 2€/MWh for nuclear power (per MWh of thermal energy produced in the fission reaction within the fuel), around 85€/MWh for imported biofuels, around 20€/MWh for agriculture-based biomass (either energy crops or waste), 10€/MWh in the case of forestry waste biomass, or around 100€/MWh for biogas.
- The retail prices (considering all taxes and intermediate costs) of different types of energy for a private individual consumer in Spain is: around 160€/MWh for domestic electricity, around 120€/MWh for gasoline, around 60€/MWh for natural gas, around 150€/MWh for butane in a bottle (which is a Liquefied Petroleum gas), around 40€/MWh for biomass pellets or around 50€/MWh for wood for a stove.
- The average cost of transporting electricity in Spain (including transmission and distribution¹¹⁷) is around 21€/MWh and the losses are around 12%. For natural gas,

¹¹⁴ We are of course aware of the fact that, for instance, not all cubic meters of natural gas contain the same amount of energy. This depends on a number of factors, such as pressure or the gas quality. Similar issues can happen with different crude oils (Brent, West Texas Intermediate, Maya, Arab Light, Macondo, Tapis, etc.), coals, or with different biomass types. In any case, approximate figures can be obtained.

¹¹⁵ These examples have been calculated from real data for Spain, performing the necessary units' changes, as reported in the Data Documentation Annex.

¹¹⁶ We are aware of issues such power generation capacity being measured at the output of the power plant, while refining capacity being measured as processed crude oil (e.g. at the input). This can be easily solved considering the efficiency of the refinery. Of course, these issues have all been correctly taken into account in this PhD.

¹¹⁷ As said above, other regulated costs which are included in the Spanish network access tariff are not included here, because they are not networks costs *per se*, but energy policy costs

these figures are 6€/MWh and 1%. For liquid oil products transported through pipeline, the values are around 1€/MWh and 0.2%.

- The total primary energy use in a year in Spain is around 6EJ (see the Sankey diagrams in Chapter 2), and the final energy use is around 3.5EJ, losses and self-consumptions accounting for around a third of our energy use and the rest being international trade. Of those 3.5EJ, cars account for 0.5EJ, trucks for another 0.5EJ, households for 0.6EJ, industry for 0.8EJ and services for 0.4EJ. The rest is used by other transport modes and other sectors.

The figures within the methodology proposed in this PhD thesis, either data inputs or results, shall be expressed in uniform magnitudes and units, using official energy densities and conversions, such as those published by the International Energy Agency. As said, we are aware of the fact that these numbers are approximations. We know that, for example, using an average energy density to express in €/MWh the price of a barrel of crude oil in the year 2030 involves some numerical error. However, by doing it we gain some insights and, even if the original (per barrel) units were kept, this would not bring data accuracy, simply because it is difficult to predict the price of oil in whichever units. We are not interested in (supposedly) very accurate numbers which, in any case, rely on uncertain data: trying to achieve such accurate forecasts may be even naïve. We are interested in ballpark figures, in orders of magnitude that allow us to see the main interactions, trends and the *big picture* of the studied system.

An easy-to-implement and interesting line of future work, with the motivation of engaging the wide public into the Spanish energy debate, would be to translate all these units to easily-understandable units, following similar approaches as in (MacKay, 2009). For instance, all energy units could be expressed in “equivalent years of power consumption from a working television”: everyone understands the (relatively small) energy consumption from a TV (when it is turned on, consuming for instance 200W). Hence it could be useful to make the public aware that the energy consumption of an average car (6litres/100km) is equivalent to almost 3h of TV per each kilometre, or that the total energy consumption of all cars in Spain in a year is equivalent to that same 200W television being on for around 80,000 millenniums. Other alternative would be to express these magnitudes in terms of the total yearly consumption of all TVs in Spain. It would also be useful to express the cost of the total energy supply in Spain, which is around 120billion€/year¹¹⁸ in per-capita terms, i.e. around 2700€/person and year¹¹⁹, and how different energy policy scenarios may change this in the future.

Illustrative examples of the possible advantages of using uniform magnitudes and units can be seen in Annex 1. In it, two *back of the envelope* (i.e. simple arithmetical ballpark

¹¹⁸ Including the annuities and fixed and variable O&M costs of all energy infrastructures, plus all the costs of domestic energy production and energy imports, minus the revenues of energy exports, and without considering externalities or losses of utility due to unsupplied energy.

¹¹⁹ This figure refers to the total energy consumption of the country divided by the population. It includes all the sectors in the economy.

calculations) examples show the hypothetical effects of a policy scenario resulting in large-scale adoption of electric cars for private users.

The methodology we propose in this thesis (thanks to the use of mathematical models that allow us to consider all interactions within the energy sector, which is not the case in the simple arithmetic calculations within the annex) allows us to see the big numbers of the studied energy policy. For the case of large-scale adoption of electric cars, we could for instance see: (i.) the increased needs for electric energy generation, transmission and distribution capacity and the costs it would cause for society; (ii.) the reduced energy dependence (i.e. reduced oil imports); (iii.) the reduced environmental externalities for society. Even more it would ultimately allow us to see, assuming that for instance the high-level policy objective is to reduce social costs for the country (i.e. economic costs + externalities), if it is better to do so through electric cars' promotion, through stricter energy efficiency standards for buildings, supporting rooftop solar panels for hot water, or phasing out coal-fired power plants. Some of these issues were treated in (López-Peña, Pérez-Arriaga, et al., 2012b), where the use of electric cars vs. biofuels was assessed for cost-effective carbon emissions reductions from Spanish cars in the 2030 horizon, under a country-level point of view and considering all interactions within the energy system.

This brings us to the next issue to be treated: which should the high-level policy objective be? To minimise social costs for the country? To minimise final energy prices? To maximise environmental sustainability? Any other?

IV.3.4. Our proposal: energy sustainability indicators

Since the aim of our methodology is to assess sustainable energy policies, our proposal would allow the user to (quantitatively) measure the sustainability of the energy system from a broad perspective (as seen in Chapter 2, not only regarding environmental aspects). We propose, therefore, the high-level policy objective to be *the maximisation of energy sustainability*.

As we saw in the review of the state of the art, most of the existing models only provide results about aspects such as the system's costs, quantity and type of the energy carriers used, infrastructure capacities and investments, or emissions. But they do not include explicit metrics on energy sustainability. We think that a useful sustainable energy policy analysis methodology should incorporate quantitative metrics on energy sustainability. Once these metrics are introduced in a model, we can formulate it so that its objective function, which represents the overall policy aim, consists in maximizing energy sustainability. This allows us to understand how each precise policy affects this overall objective of evolving towards a sustainable energy model, the purpose of sustainable energy policymaking.

Here, however, two significant complexities arise:

- **Measurement:** how to measure many of the (sometimes very complex) energy sustainability aspects reviewed in Chapter 2? A first step could be the use of values reported in the literature, such as the social cost of carbon (Tol, 2009) for CO₂ emissions, or the estimated values of NO_x, SO₂ or particulate matter externalities as those from the ExternE project (European Commission, 2011a). This has been our approach in the

economic Sankey diagram of the Spanish energy sector with discounted environmental externalities (refer to Chapter 2), described in detail in (López-Peña, Linares, Pérez-Arriaga, et al., 2013). However, there are still many aspects of energy sustainability which need further research. Just to cite a few, which are the externalities associated with energy dependence? Which is the burden that inequity in energy access imposes on a society? How to quantify the implications of the depletion of energy resources?

- Aggregation: even if we manage to measure all the relevant aspects of energy sustainability, the partial indicators may be in different units. In that case, how to aggregate them into a single indicator? And even if they were all in uniform units (e.g. in terms of an economic costs), should they be aggregated? Aggregation brings the advantage of easy comparison between policy scenarios (because each scenario is characterised through a single number), but at a cost: the single process of aggregation implies a loss of information. Should it maybe be better to keep different indicators and to optimise them in some sort of multi-criteria optimization? If we decide to go for aggregation, which is the weight that should be given to each individual indicator in the aggregation? Equal weights? Should a poll be conducted to see which aspects are the most valued ones for society? In this case, should this poll be carried with a representative group of the complete society or only with experts, stakeholders and policymakers, for instance?

A proper treatment of all these issues is beyond the scope of this thesis.. Therefore we will get back to this in the chapter where future research lines are described, and we will propose there some of the possible lines that we consider could be interesting to follow. Within this PhD thesis, we have only considered two aspects of energy sustainability: energy supply private¹²⁰ economic costs, and the social cost of CO₂ emissions. This is because of three main reasons. First, these are two of the most worrisome aspects of energy sustainability in Spain, as pointed out in chapter 2. Second, there are significant research gaps in quantifying other aspects of energy sustainability, so including more would mean using weak sources of information, which could undermine the credibility and trustworthiness of our methodology (which we claim to be based on contrasted and public data). Third, we consider this thesis just a first step in this research line: going deeply into such a research effort was out of our scope. Hence we have only included these two crucial aspects where significant/solid data availability existed: private economic costs of energy supply, and social costs of CO₂ emissions. In the first case, economic costs are widely described in many energy reports. For the second case (i.e. the social cost of carbon), although methodological uncertainties remain (e.g. the discount rates to be used), significant consensus on the orders of magnitude seems to exist in the literature (Tol, 2009), and it is already being used by some governments for policy evaluation (United States Government, 2013).

¹²⁰ By this we refer to the usual economic costs of energy infrastructure, imports, etc. Following economic terminology, they are called *private* as opposed to *public*, which would include external costs to society.

IV.3.5. Our proposal: modelling framework

IV.3.5.a. Main ideas

As already stated, our modelling framework should be as transparent as possible, with simple but sound mathematical techniques, so that all its underlying calculations are intuitive and easy to understand for any user, even if she does not have a very advanced mathematical training. Very complex mathematical formulations can be counterproductive for our purpose. We believe that simple optimization or simulation techniques, which in general yield intuitive results and present understandable behaviours, are enough to represent energy systems with an adequate level of detail for policy applications. The required level of technical detail has been given by the experience of the PhD advisors and candidate, by extensive consultations with experts and colleagues, and by a thorough literature review. Modularity can help in achieving this transparency, if the user can see and understand the information that, within the model, is available to different agents (represented as separated modules interconnected by information flows) and the decisions that they take based on it.

Our modelling framework should also take into account that the energy sector is a very policy-driven one. By this, we mean that it is subject to significant regulatory intervention and many of its developments are consequences of these regulations. They affect issues such as the quantity and type of installed electricity generation capacity (e.g. renewables support schemes or nuclear policy largely affect investment decisions in these technologies), the fuels used by cars (e.g. the large dieselization of car fleet in some European countries is due mainly to tax reasons) or the energy efficiency of buildings (e.g. building codes or refurbishing programs can be very influential on the energy demand for space heating). The precise way these regulations affect the decisions of the different agents can be complex to understand and model, but one can be confident in the fact that, if policymakers want some developments to take place, they will pursue the objective until they do. For instance, if a premium on wind energy is established, it can be difficult to model the way wind power investors make their investment decisions, but if wind power is not coming into the system, the regulator will act (increasing the premium) until it happens¹²¹. A useful energy policy assessment model (in the context of this thesis, of course), should represent if an effect is desirable, without explicitly representing how to achieve it, since this can be much more complex to model, introducing new internal parameters and hypothesis, and reducing transparency. This is what in this PhD thesis we refer to as “direct policy effect modelling”. Using the example of wind power, in the context of this thesis we want to model if achieving 60 GW of installed wind is desirable (which will be assessed looking at the used sustainability indicators), but not how to achieve it (which would imply representing the investors’ decision making process, also a very interesting research line). We think that the

¹²¹ The reductions on renewable energy premiums that we are currently seeing in countries such as Spain are mainly the result of declining technological costs or other influencing aspects (e.g. economic constraints). Our affirmation applies to hypothetical case where the wind energy policy was the top priority and there were no other constraints. In any case, this is just an illustrative example.

policymaker would use our model to see the effects of having 60GW of wind, how it affects costs, emissions, prices, sustainability indicators, etc. and decide whether it is desirable. Then, she would use other models (i.e. of agents' investment processes) to analyse how to achieve that objective. Our model has more of a long-term indicative energy planning approach, which then should be complemented by specific models for regulatory design, which are not within the scope of this thesis. For example, in the case of auctions being used to promote a certain renewable technology, our model would inform the amount of auctioned capacity (i.e. GW), but then another specific model, which considers the decisions and behaviours of specific agents, would be needed to design the details of the auction, or to estimate its outcomes (e.g. resulting premium).

Our modelling framework should also have the possibility of reflecting energy markets' imperfections and their influences on the effectiveness, costs and outcomes of energy policies. Many externalities are present in the energy sector and most of them are not correctly priced (climate change, resources depletion or pollution, amongst others). Furthermore, there may be information asymmetries and competition problems. Strategic and market-positioning behaviors are common within energy utilities. Risk aversion and uncertainties play very important roles in agents' decisions, sometimes making implicit discount rates to take unusually high values and causing myopia in decisions. In many cases, other non-economic or qualitative aspects may play important roles in the decisions of energy consumers, aspects hard to quantify in the type of utility functions that are normally used in existing models. In other words, energy markets are not perfect. This can cause energy policies to have unexpected results and costs. This may seem slightly incoherent with the previous paragraph (i.e. direct policy effect modelling), because in this second case (i.e. representing realistic behaviours) we may need to model more of the agents' internal decision processes. This slight incoherence is indeed the case, and this is precisely why our methodology is based on two models, a static optimization and a dynamic simulation one, each one allowing us to represent each aspect (respectively). More detail on this will be given in the next paragraphs.

Taking this into account, the modeling framework that we propose, as mentioned above, makes use of two complementary models, one with a static optimization approach (MASTER_SO) and the other one with a dynamic simulation one (MASTER_DS). From the perspective of the characteristics that have been analysed for the mainstream models in Chapter 3, our MASTER models can be classified as follows.

*Figure 50: introductory table containing the main features of the MASTER models.
Source: own elaboration.*

	MASTER
Economic representation	Partial Equilibrium
Env. Feedbacks	No
Modelling technique	Optim (MASTER_SO) and Simul (MASTER_DS)
Technological detail	Bottom-up
Geographic perspective	National
Time representation	Static (MASTER_SO) and Dynamic (MASTER_DS)
Future foresight	Perfect (MASTER_SO) and Perfect/Myopic (MASTER_DS)
Technological change	Exogenous
Internat. energy mkts.	Exogenous

They are, in essence, two bottom-up, partial equilibrium, models of national energy systems. Within this PhD thesis, we have applied them to the specific case of Spain, but they could be adapted to other countries. They both have a technology-rich (i.e. bottom-up) representation, which allows us to represent realistic features of energy technologies. This is, in our opinion, a necessary condition for an energy policy evaluation methodology to be able to capture the fact that many policies have a technological orientation (e.g. support for certain types of power generation such as wind power, or for specific energy-use devices such as electric cars).

Even if a more complete economic representation (some sort of general equilibrium) is a very relevant research area and could have been an interesting (and extremely demanding) approach, it is out of the scope of this thesis. In our opinion, this would have made the models more complex to understand (even more if a bottom-up approach is to be used). In any case, some degree of reaction to energy prices from the rest of the economy could be included in our models through price elasticities of energy demand (both short term and long term elasticities), although the models may become non-linear, hence some degree of linearization would be needed and the interpretation of constraints shadow prices (needed to understand policy trade-offs, as will be explained below) may not be straightforward. Environmental feedbacks on the economy (e.g. due to the impacts of climate change or local pollution) have not been included, given that their inclusion makes sense, mainly, within general equilibrium frameworks (where the economy is modeled), and doing this was out of our scope.

Provided that our methodology is intended to be used at a national level, and mainly for small and medium sized countries which do not significantly affect global variables such technology evolution or global energy markets, exogenous modeling of these issues has been used. This means that the costs and availability of technologies and internationally-traded energy commodities (e.g. electric cars, nuclear power technologies, crude oil or biodiesel) are given as external data.

Figure 51 places our proposed models within the (above introduced) table in which the mainstream models reviewed in this thesis' review of the state of the art on energy modeling. We have already commented on the characteristics of all the models. Concerning the numerical classification of features, given that our methodology is composed of two models, to be fair in

the comparison we have only included the features of MASTER_SO. Also, as we are reviewing our own model, we try to be neutral and critical.

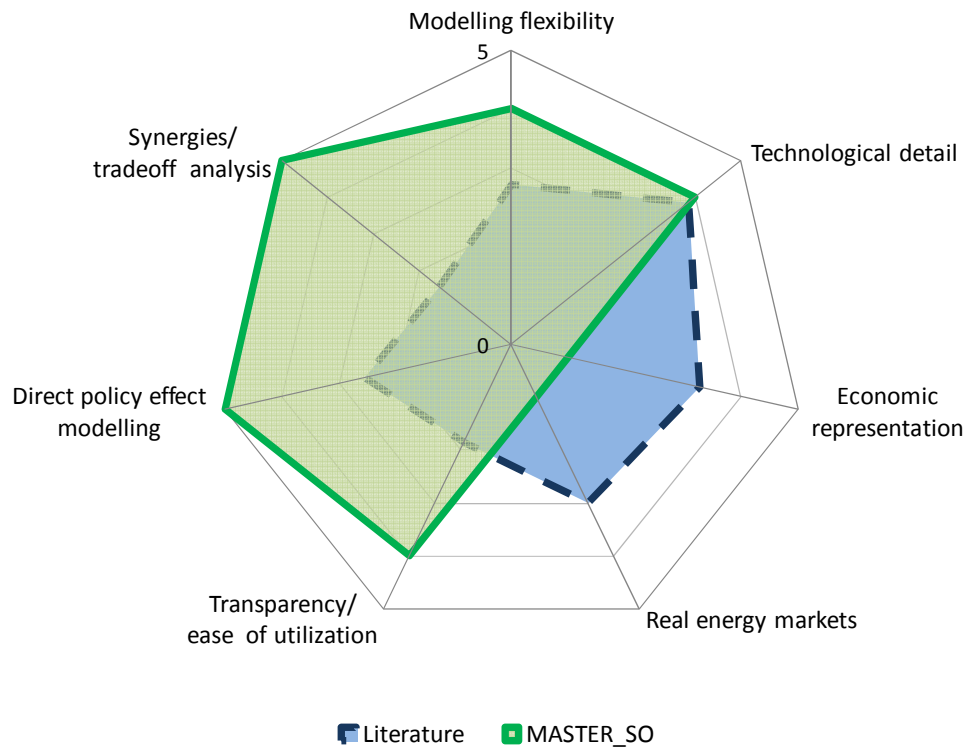
As can be seen in Figure 52, we think that one of the best features in MASTER_SO, is the easy evaluation of policy trade-offs/synergies, since it is a mathematically simple, LP, static model, as will be seen. This also plays in favor of its transparency/easy of understanding, and in directly policy effect modeling (it can be done simply by introducing a new constraint). Modeling flexibility and technological detail are also good (new processes can be easily introduced, and if they need specific constraints, they can also be introduced, as long as they keep the model linear and feasible). Its representation of real energy markets is not good (it is a static optimization model). In any case we have provided a modeling framework (MASTER_DS) where this could be improved by further research. Lastly, we believe that the main drawback of our methodology is our economic representation, since we use a strictly bottom-up partial equilibrium approach with inelastic demands for energy services.

Figure 51: table placing the MASTER models within the family of mainstream models reviewed.
 Source: own elaboration.

	MARKAL/TIMES	POLES	WEM	PRIMES	NEMS	EPPA	WITCH	MASTER
Economic representation	Partial Equilibrium	Partial Equilibrium	Partial Equilibrium	Partial Equilibrium	General Equilibrium	General Equilibrium	General Equilibrium	Partial Equilibrium
Env. Feedbacks	No	No	No	No	No	Mainstream EPPA no. Yes, if coupled with IGSM or EPPA-HE.	Yes, IAM	No
Modelling technique	Optimization	Simulation	Simulation	Optimization	Simulation	Optimization	Optimization	Optim (MASTER_SO) and Simul (MASTER_DS)
Technological detail	Bottom-up	Bottom-up	Bottom-up	Bottom-up	Bottom-up	Top-Down	Top-Down	Bottom-up
Geographic perspective	Customizable	World (46 regions)	World (25 regions)	Extended Europe	USA (sub divisions)	World (16 regions)	World (12 regions)	National
Time representation	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic	Static (MASTER_SO) and Dynamic (MASTER_DS)
Future foresight	Perfect	Myopic (recursive dynamic)	Myopic (recursive dynamic)	Myopic or perfect	Myopic or perfect	Myopic or perfect	Perfect	Perfect (MASTER_SO) and Perfect/Myopic (MASTER_DS)
Technological change	Exogenous	Endogenous (both learning by doing and research)	Endogenous (only learning by doing)	Endogenous (only learning by doing)	Endogenous (only learning by doing)	Endogenous	Endogenous (both learning by doing and research)	Exogenous
Internat. energy mkt.	Exogenous	Endogenous	Exogenous	Exogenous	Endogenous	Endogenous	Endogenous	Exogenous
Modelling flexibility	5	2	2	3	3	2	2	(ONLY MASTER_SO) 4
Technological detail	5	3	4	5	5	2	3	4
Economic representation	2	3	3	2	4	5	4	1
Real energy markets	1	3	2	5	5	3	2	1
Transparency/ ease of utilization	2	2	2	1	1	2	3	4
Direct policy effect modelling	3	2	2	3	2	3	3	5
Synergies/ tradeoff analysis	3	1	1	1	1	2	2	5

Figure 52: level of treatment of each assessed features in this thesis's main model (MASTER_SO) versus the reviewed models in the literature.

Source: own elaboration.



The reasons for proposing two complementary models are explained next. MASTER_SO has a static optimization approach, it represents only one period in the future (in our case, the year 2030), whereas MASTER_DS (dynamic simulation) is able to represent an evolution for a number of years (in our case, from the present time until 2030). MASTER_SO assumes perfect foresight, whereas MASTER_DS tries to replicate myopia to some extent, also being able to model some aspects of perfect foresight if deemed adequate.

The use of two models has a reason: we propose to use them in a specific, sequential process where both models are complementary. The main idea is the following: in a first step, the policymaker would use the static optimization model to assess different alternatives for the energy system in a given year in the future (e.g. 2030), what would allow her to decide the main energy policy objectives for that year (e.g. installed capacities in each technology, share of energies in the energy matrix, penetration of electric vehicles and smart appliances, etc.). Afterwards, in the second step, she will use the dynamic model to assess which would be the more suitable combination of policies in order to, starting with the current energy model (e.g. in 2010), reach the objectives that have been established in the first step for that year in the future. The first model (MASTER_SO) would allow her to decide how the energy system in the future should look like, understanding the main policy synergies/trade-offs, representing direct policy effects (i.e. the fact that energy is a very policy-driven sector), and understanding its resulting sustainability. The second model (MASTER_DS) would allow her to see if those objectives are achievable and how to achieve them, which trajectories should be followed by the energy system in its evolution. Three additional aspects about this second model should be made clear: (i.) it should try to model realistic features of energy markets, including market imperfections, myopia, etc. because this would allow her to obtain realistic trajectories of the energy system

and hence assess if the long term objectives (decided with the static model) are realistically achievable; (ii.) it could have been proposed as an optimization-based model, however, for reasons that are given below, we propose it to be simulation-based; and (iii.) this implies that the obtained trajectories are possible trajectories, none of them being necessarily the optimal one, which (for any given set of hypothesis) would only be obtained by an optimization-based model, which is not the case here.

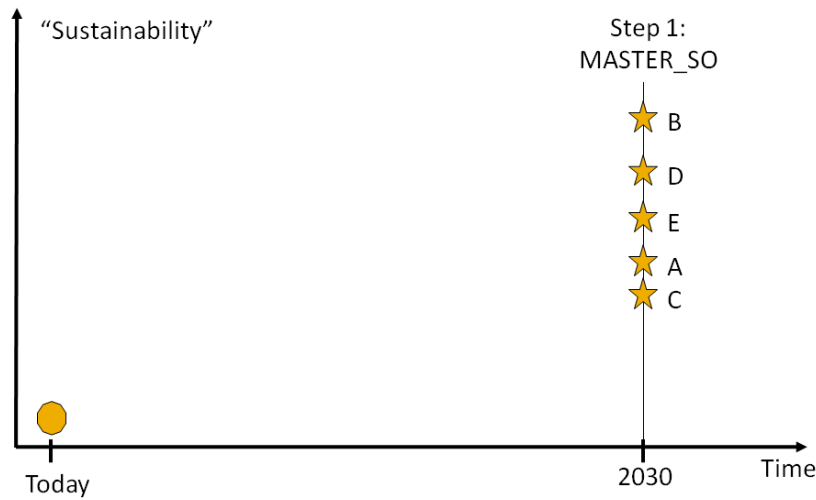
Other interesting modeling approaches for the dynamic model, which have not been explored within this thesis, but could also be useful for this second step, are those more directly based on *backcasting* (Höjer & Mattson, 1999), or in optimization techniques. This optimization could either try to include features of realistic energy markets (e.g. uncertainties, bounded rationalities, etc. as does SAGE) or assume perfect foresight, perfect rationality, etc. (as does TIMES). It could try to obtain the optimal trajectory for a given future, or optimise over a set of possible futures. Also, some type of multi-objective optimization could have been done, aiming to obtain dominant trajectories looking at the different objectives. In any of these cases, other useful insights could be extracted. For example, by simply using a deterministic intertemporal optimization model with a single objective function, we could assess the following: if we know (from the static model) that, in 2030, a certain capacity of certain technologies (e.g. coal-fired CCS or offshore wind plants) is needed, such a dynamic optimization model would tell us when it would be optimal to start installing this capacity and which would be the optimal installation path, according to the underlying optimization hypothesis and to dynamic issues such as their learning curves or the evolutions of prices of fuels or CO₂. These optimal installation paths could then be useful to inform lower-level policies, such as the demanded capacity in each year in the case of auctions being used to support the installation of these technologies. What is more, once the optimization-based static model (MASTER_SO) is programmed, building such a model (deterministic intertemporal optimization) could have been relatively simple, as it only needs to be adapted to consider the different years (intertemporal constraints, adapted objective function, intertemporal discounting, etc.).

Finally, it should be noted that our models could be also used separately and in different ways, as we will explain below. But first, we will detail the proposed two-steps utilization process, as could be carried out by a hypothetical policymaker using our models.

IV.3.5.b. First step of the proposed sequential process: MASTER_SO

Let's assume (as shown in Figure 53) that we could represent in one axis the time and, in the other one, the energy sustainability indicator that is to be maximized. Even if, as argued in the previous pages, the development of such an indicator is a complex issue, this assumption has the purpose of illustrating our methodology. Let's assume that our energy model today is represented as the orange circle, and let's apply our proposed sequential process to the 2030 horizon.

Figure 53: proposed sequential use of the two models. Step 1 out of 2.
 Source: own elaboration.



The main purpose in this first step is to choose the best *static* energy system (i.e. the static picture of the energy system in a year) for the last year in our study horizon (i.e. 2030), by using the MASTER_SO model. The different possible “future points” are represented as orange stars in the figure (each of them is the optimal energy system under a given combination of policies). We propose to do this through a certain use of the mathematical properties of linear programming (LP) optimization models, as explained in the next paragraphs. We propose MASTER_SO to be a LP model (mathematically quite simple) because it allows us to represent enough technical detail while keeping the model easy to compute and conceptually simple to understand, which is especially useful concerning the interpretation of the constraints’ shadow prices.

In a first analysis step, the main international policy obligations (e.g. those derived from a future European 2030 framework), or other long-term considerations such as a smooth transition towards the European objectives in the Energy Roadmap 2050 should be included as constraints and kept fixed (e.g. maximum emissions or minimum share of renewables).

Second, with the remaining degrees of freedom (e.g. distribution of those emissions among the energy subsectors, relative shares of different renewables), the user would assess different policy combinations (e.g. A, B, C... in the figure) and how they affect the objective function to be maximized, that is, our energy sustainability indicator. The fact of energy being a very policy-driven sector would be considered here through direct policy effect modeling, which is introducing policies as constraints which have *already* created the desired policy effect. For example, instead of adding a premium on wind generation (e.g. a value increasing its income or reducing its costs), a constraint on the established amount of installed wind power (e.g. 40GW) would be included (with an *equals* formulation, i.e. *wind capacity equals 40GW*). The shadow price of this constraint provides important information¹²² about how this policy (e.g. 40GW of wind) is improving / worsening the objective function (depending on the sign of the shadow

¹²² Which is relatively easy to understand because our formulation, as will be seen, consists on a mathematically simple Linear Programming problem.

price). The sign allow allows us to see whether from the perspective of the objective function (e.g. sustainability) it would be preferable to increase or decrease this policy's level of ambition (this is illustrated in the case study in the next chapter). However, using an *equals* formulation also has a mathematical drawback: it limits the feasible region of the problem. In other cases it may be better to just impose a *larger than* or a *smaller than* constraint, or to use the *equals* constraint in an ulterior stage once the policymaker understands if the specific policy is improving/worsening energy sustainability.

In a next step, once the policy constraint on wind has been assessed, if another one is included (e.g. penetration of electric cars) keeping constant the first constraint (on wind power), the shadow price of that first constraint will probably change (with respect to their previous value without this second policy constraint). The sign and magnitude of this change would allow us to see if the second policy is being synergic or counter-productive with the first one, in order to maximize energy sustainability.

Therefore, by an intelligent use of constraints (adding/removing them in a certain sequence) and their shadow prices, important insights can be extracted about policy synergies/interactions/trade-offs or which is their relative contribution to maximising the sustainability of the energy system (i.e. in improving the optimization problem). It should be noted however than from a mathematical perspective, policy conclusions should not be drawn only from shadow prices, because these are by definition only relevant in the neighbouring area of the optimal solution to the problem. Other quantitative results (i.e. from other outputs of the model) and qualitative considerations (e.g. from relevant literature) should also been used to complement the information provided by the shadow prices.

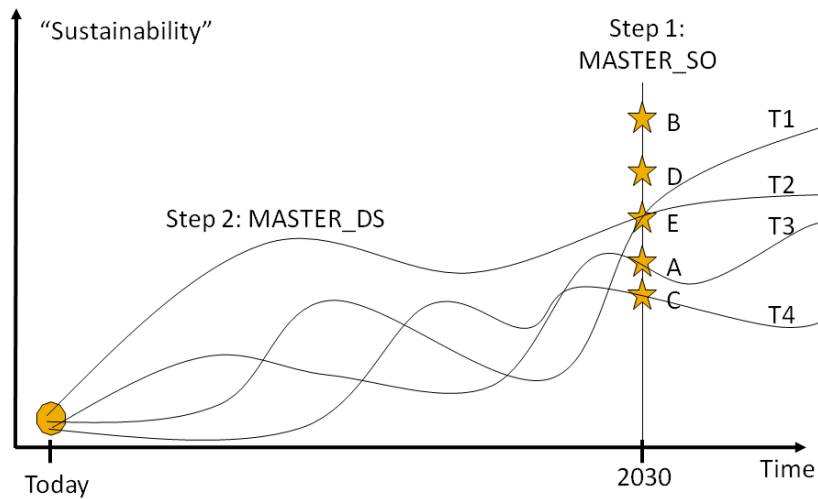
After this, and considering all the possible policies and their trade-offs/interactions/synergies, the policymaker would decide upon the above-mentioned degrees of freedom, and hence how she wants the system to be like in 2030. In a normal situation, and going back to our graphical example, this would probably be in the "B" point (i.e. maximum sustainability). However this may imply a very complex policy measure (e.g. totally forbidding cars in cities), so she may decide to aim for the second-best option: the "D" point. This choice (the set of applied policies and their ambition level, which completely determine the above-introduced degrees of freedom) would be the main output of this step. Along with it, all the other associated output information from the optimization model is also useful, which includes the needed capacity of each technology in that "D" situation, as well as all the associated energy flows, the costs, the retail energy prices, the emissions, the values of the used sustainability indicators, etc. This first step has allowed the user to decide *where she wants the energy system to be in 2030*. The second step will allow her to decide *how to reach that point from here the energy system is now*.

IV.3.5.c. Second step of the proposed sequential process: MASTER_DS

The main purpose of this step would be to obtain the best set of policies that take the energy system from its current state to the desired future situation, if it is possible to be reached (see Figure 54). This is somehow inspired in the *backcasting* techniques (Höjer & Mattson, 1999), although advancing forward in time. The first issue to be considered here is that, given

the current situation, not all possible situations may be reachable from the current one, in a limited number of years. This may happen for instance if investments are too high to be realistic or if any other hard (dynamic) constraint, which could not be considered in the static model, is violated during the studied period. The desired situation from the static model (i.e. “D”) may not be reachable from a dynamic perspective.

Figure 54: proposed sequential use of the two models. Step 2 out of 2.
Source: own elaboration.



As depicted in the example within Figure 54, four trajectories are identified (“T1” to “T4”), and none of them reaches the “D” point (the “B” point had already been discarded in the static analysis because it implied a very complex policy, e.g. totally forbidding cars in cities). As said above, these trajectories are just possible realistic trajectories (i.e. given the included realistic features of energy markets), they are not optimal trajectories. If these four were the only realistic trajectories, it could be concluded that the “D” point is not reachable, a fact that was not captured by the static model. Hence the final point to be reached (i.e. the 2030 energy system¹²³) should be changed to the “E” point (i.e. maximum sustainability within the reachable ones). Finally, the policymaker should decide which trajectory is preferable: “T1” or “T2”. In principle, (and this is just an illustrative and simplistic example) T2 would be preferable, because it is more stable and sustainability is higher throughout the study horizon, although this may not be the case further away in time, i.e. after 2030. The analysis of this issue is out of our scope, although it could be an interesting future research line (for instance using an approach similar to the *residual value*¹²⁴ one).

¹²³ We are aware of course that this is not a final point as such, but we will assume that the policymaker is only looking at the 2010-2030 period. In any case, the future after that year should of course also be considered.

¹²⁴ Inspired in the financial concept, we understand *residual value* to be a way of quantifying a certain situation (i.e. the sustainability of the energy system) in the future, after the study horizon (i.e.. how the energy system would be from 2030 on). This is used, for instance, in financial analysis, to compute the value of an investment using the net present value concept, in order to be able to account for the value of the asset after the discounting period.

IV.3.5.d. Addendum

Even if we have proposed the sequential use of both models, this does not need to be the case. Each model could be used separately. The static model alone could be used to provide insights about possible future energy systems, without worrying about how to reach them. Or it could also be used to evaluate the past (i.e. in ex-post analyses) to see how far from optimal a past policy has been, as done in (López-Peña, Pérez-Arriaga, et al., 2012a). Or the dynamic model could be used just with a *exploratory* rationale (Bankes, 1993), without necessarily caring about the destination point. Examples of some of these approaches are given later, in Chapters 6 and 8.

As said, we propose the “vertical axis in our methodology” to be a comprehensive energy sustainability indicator, which as it has been, seen can be complex to obtain. In any case, our methodology could be also used with this axis being much simpler, e.g. simply the private economic cost of energy supply, or this cost added to the social cost of carbon emissions, or even including the external costs of other pollutants, as mentioned above. In these cases, obviously, the objective would not be to maximize but to minimize the objective function. In any case, our main methodological approach remains the same.

IV.3.6. Our proposal: the static model

MASTER_SO is a partial equilibrium LP optimization model whose goal is to supply the externally-given demand for energy services in all demanding sectors, complying with all technical and policy constraints, and maximizing the objective function, which is a measurement of energy sustainability. It is programmed in GAMS and solved with CPLEX. It represents the complete energy system with our processes and flows approach. It is computed for each time slice of the year (month, day, group of hours, etc.) in which the model is represented, and one of its main outputs is the Sankey graphical representation of all flows in each time slice or for the complete year (in terms of power or in terms of energy). The power flows through each of these processes can be subject to capacity restrictions, hence the model can decide to invest in new capacity in some of these processes. To correctly account for investment costs, given that this is a static model representing one year, the annuities (i.e. yearly amortization) of each investment costs are considered. Therefore, another one of the main outputs of the model is the investments in new capacities in those processes. The precise mathematical formulation of the model is shown in the next chapter. Even if it may seem similar to TIMES, our static model has clear differences with it, which have been detailed above.

IV.3.7. Our proposal: the dynamic model

As said, once the optimization-based static model (MASTER_SO) was programmed, it could have been transformed into a dynamic deterministic intertemporal optimization model quite easily. The main needed adaptations needed would have been: (i.) adding a new temporal dimension for *years*, and modifying the input data accordingly, which could imply more data research; (ii.) adapting all the affected constraints and variables; (iii.) modifying the objective

function, including for instance a maximization of accumulated or discounted sustainability (in this case, the choice of the discount rate is a critical issue¹²⁵); (iv.) adding the needed intertemporal restrictions, such as capacity conservation (e.g. “capacity in year t + investments – retirements = capacity in year $t+1$ ”), energy conservation, etc.; (v.) including a suitable condition for the end of the study horizon (e.g. some kind of residual value¹²⁶). The fact of it being an LP model makes this approach acceptable from a computational perspective. If, however, solution times grow too much, a possible solution would be to implement some temporal aggregation (e.g. solving one out of every 5 years), which would reduce the size of the problem. Keeping it as an optimization-based dynamic model would be definitely in line with the “energy calculator” metaphor mentioned above, and would allow the user to answer relevant questions (such as the optimal year to start installing CCS capacity) which cannot be answered with the static model, because it does not consider the dynamic nature of external parameters such as energy prices or technology costs.

However, answering these dynamic questions with such an optimization model would imply assuming perfect foresight and perfect rationality, unless specific techniques are used, such as dynamic or stochastic programming (to account for uncertainties), recursive optimization or high discount rates (to represent myopia), game theory-oriented approaches (to model imperfect competition), etc. If not, if simple deterministic intertemporal optimisation is done (as does TIMES), the model would not represent realistic aspects of energy systems (as seen). In addition, we believe that this (just adding the temporal component to our previously-developed optimisation static model) did not add much value to other optimization-based models in the literature, such as TIMES. Hence we have decided to propose a completely new dynamic model, which is simulation-based, inspired in the System Dynamics technique, and which is able to deal with some of the imperfections of real energy markets. This connects with previous experience from the PhD candidate in working with System Dynamics models (Centeno et al., 2008; González-Blanch et al., 2010; López-Peña et al., 2009; Sánchez et al., 2007a, 2007b, 2008). In any case, developing the some type of dynamic optimisation model remains an interesting line for future research.

Furthermore, as said, simulation models can sometimes have a significant number of internal parameters, which play against their transparency and trustworthiness (and hence against the methodological perspective defended in this thesis). This can be especially true if realistic aspects of energy markets want to be modeled, what normally requires an even larger number of parameters (e.g. an extra value may be needed to represent the degree of myopia of each agent, which would not be required if perfect foresight was assumed). These parameters can greatly influence the behavior of the model, hence such a model should be designed with great care, avoiding hard-to-understand or arbitrary internal parameters as much as possible.

¹²⁵ In many studies “private” discount rates (e.g. around 9%) are used, because they are inspired on how private agents make their investment decisions using for instance the net present value concept. However, for studies concerning a broader view of societal welfare in the long term, such as ours, it may be more adequate to use “social” discount rates, around 2-3%. This topic is very complex and out of our scope.

¹²⁶ A “sustainability” residual value is a concept that has not been seen in the literature and could be interesting in our framework. It could be further research.

What is more, correctly obtaining the required ones may require significant work, using techniques such as econometrics, sensitivity analyses, surveys, interviews with experts or detailed reviews of other energy simulation models in order to know the parameters used in them and their justification, which in many cases are not available in the documentation.

The trust of the user of our models in these parameters is critical, hence the model should be built in close collaboration with her, in order to obtain familiar/expected behaviours and to match historical data (if a calibration is deemed necessary). Ideally, this can be done modularly, in separate modules, so that once each one is validated, they can be put together. If the modeller is unsure about the value given to a parameter, this should be made explicit and very visible in the documentation, so that a future user is well aware of it and, if desired, can easily change it and perform new simulations (this also applies to the rest of our methodology, of course). We believe that such a model would gain much trustworthiness if it is, from the very beginning, developed and tested in close collaboration with the user, following the “collaborative modeling” ideas as supported by the System Dynamics community (Forrester, 1989, 1991; Morecroft, 2007; Sterman, 2000).

Doing such an intensive and time-consuming work was out of the scope of this PhD thesis, hence it remains a clear line for future research. In any case, we have indeed implemented a prototype (MASTER_DS) that works correctly and which could be enriched by future research with the aim of building such a complete simulation model.

MASTER_DS is hence a prototype which sets the basis for a modular dynamic simulation model where realistic aspects of energy markets could be represented. By *modular* we imply that it leaves open to future research the possibility of improving specific sectoral models (electricity, transport, specific industries, etc.). It allows for the representation of trajectories/evolutions of the energy system under study under a set of policies, for example, between 2010 and 2030. These trajectories will gain in realism with future research, once aspects of realistic and/or imperfect energy markets are included. In any case, this PhD thesis presents a model which is already implemented with acceptable hypothesis (refer to Chapter 7), and which already produces useful results (refer to Chapter 8).

IV.3.8. Our proposal: output

Finally, we also have a proposal concerning the outputs of our models. As anticipated, we believe that the results should be presented in a way which allow for a quick and simple understanding of the *big picture* of the effects of studied policies, in order to allow the user to easily obtain conclusions and insights.

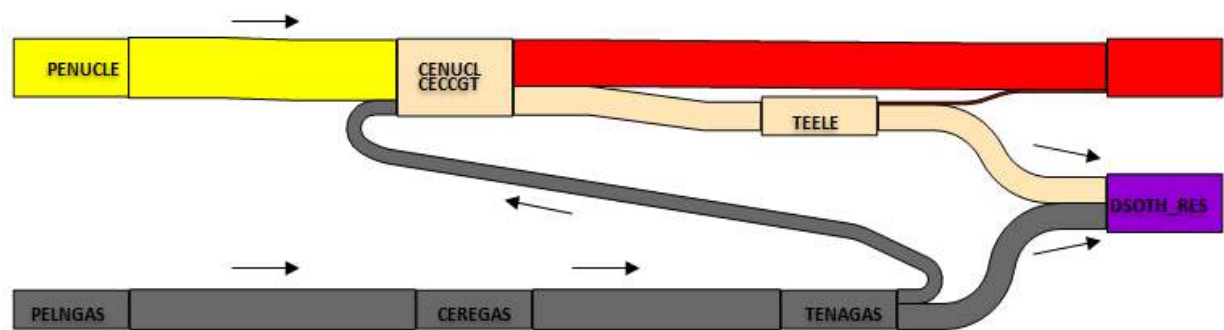
With this in mind, the Sankey diagram representation is proposed, also because (as described above) we have found it to effectively combine with our modelling paradigm based on processes and flows (even if it does not include the policy synergies/trade-offs, also very important). Once the model is solved for each year under each policy scenario, Sankey diagrams provide an intuitive and schematic way of representing the model's output, showing all the energy flows within the country and the relative magnitudes of all flows and processes (which are not always well understood even by experts). In addition, all the other numerical outputs,

not included in the Sankey diagram (e.g. capacities, prices, costs, etc.) should be presented in coherent and uniform units where the different orders of magnitudes are easily understandable, as already mentioned above.

The use of Sankey diagrams to represent current energy flows is a common practice, for instance, in the U.S. Energy Information Administration (EIA U.S. Department of Energy, 2012c), in the Spanish Energy Ministry (Ministerio de Industria, Turismo y Comercio, 2011c) or in the BP Chair's Observatory on Energy and Sustainability in Spain (López-Peña, Linares, Pérez-Arriaga, et al., 2013). They can also be seen in a number of scientific papers on energy and linked resources such as water (Hu et al., 2013; Pardo et al., 2013). Using them to represent future energy situations (maybe as a result of different policies) is something that seems to be quite novel in the literature and hence, part of our added value. One of the sources who actually does it is the web page of the Energy Technology Perspectives report (International Energy Agency, 2012g).

A simplified example of the usefulness of such an approach is given next. We will continue with the same example from above, where a simplified energy system in which there was only one demanding sector (i.e. households) only consuming electricity and natural gas was used. A Sankey representation of such a system was provided above, which is also reproduced here (Figure 55) for the reader's convenience¹²⁷. We will assume this to be the reference policy scenario, where electricity is produced both from nuclear and CCGT power plants.

Figure 55: Sankey representation¹²⁸ of our example. Policy scenario: reference.
Source: own elaboration



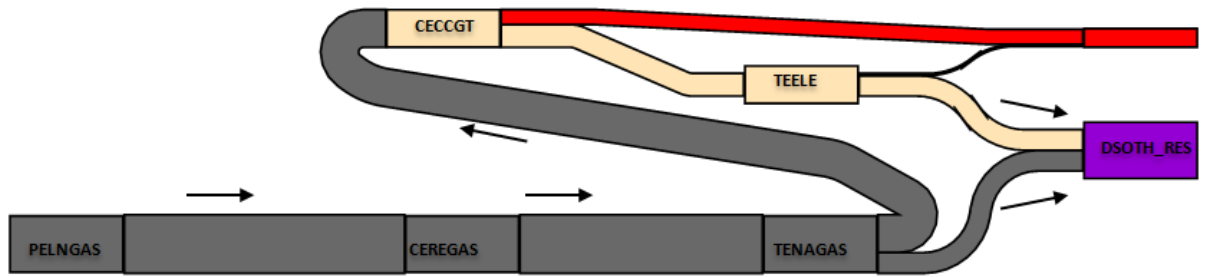
Then, we could make the hypothesis of the country deciding to phase-out all its nuclear power plants, hence a “no nuclear” scenario could be represented (Figure 56). In this case, the amount of electricity and gas served to the demand sector is the same, but the fact of not using nuclear energy creates the following effects: (i.) reduced losses in power generation (CCGTs

¹²⁷ In these first Sankey diagrams we will keep the arrows indicating the directions of energy flows, although this will not be done in the Sankey diagrams contained in next chapters.

¹²⁸ In this diagram, the same color codes used in the Sankey diagrams for the BP Observatory on Energy and Sustainability in Spain are kept (refer to Chapter 2). Mainly: yellow for nuclear energy; grey for LNG and natural gas; light beige for electricity generation, electricity flows and electricity grid; red for losses; and purple for the Other Uses demand sector.

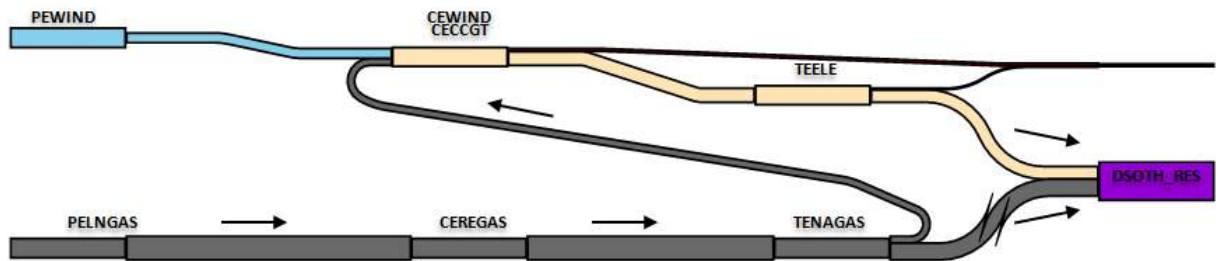
have 60% efficiency vs. 33% of nuclear plants¹²⁹); (ii.) increased gas demand for power generation (going into the “CECCGT” process); (iii.) increased transported gas (going into the “TENAGAS” process); (iv.) increased LNG imported and regasified. The impact of the no-nuclear policy upon the energy flows throughout the complete energy system can be easily understood just by comparing both Sankey diagrams. Of course, other numerical outputs (on costs, emissions, etc.) are required to understand the complete impact.

*Figure 56: Sankey representation of our example. Policy scenario: no nuclear.
 Source: own elaboration*



A third case is represented in Figure 57, corresponding to a policy scenario in which energy efficiency in final uses is strongly pursued in the households sector (achieving a 20% reduction in the demand for natural gas and an 40% reduction in electricity demand), and in which power generation with wind power is strongly supported¹³⁰. It can be seen how energy flows towards the demanding sector are smaller. Also, losses are largely reduced (due to the null losses from wind power generation, following International Energy Agency’s convention). The use, transportation, regasification and import of gas is also reduced on a large proportion.

*Figure 57: Sankey representation of our example. Policy scenario: efficiency and wind.
 Source: own elaboration*



These three simple examples have allowed us to show the potential of representing policy outputs through Sankey diagrams. More of this will be showed on Chapter 6, in that case applied to a realistic case based on Spain.

¹²⁹ As mentioned above we are aware that, from a physical perspective, the thermal losses from a CCGT are not completely equivalent to the lost energy in a nuclear reactor. The same will happen with mechanical losses from wind power, as we will see below. We consider them as equivalent just for the sake of simplicity, and because these distinctions are largely irrelevant from a policy perspective.

¹³⁰ Just as a remainder, in this example we are considering to be the reference case the one with nuclear power

Chapter V.

MASTER_SO: A STATIC OPTIMISATION MODEL FOR SUSTAINABLE ENERGY POLICY ASSESSMENT.

V.1	Outline of this Chapter	181
V.2	Model overview	181
V.3	Previous explanations, conventions and notation	182
V.4	Sets	183
V.5	Parameters	193
V.6	Decision variables	205
V.7	Constraints	209
V.8	Objective function	230
V.9	Utilization modes, other options and computer implementation	240
V.10	Main outputs	242

V.1. OUTLINE OF THIS CHAPTER

In this chapter we describe the mathematical formulation of MASTER_SO, a model that achieves the objectives established in Chapter 1 and has the modelling philosophy described in Chapter 4. Prior to this mathematical description, a brief overview of the model is presented, and some important issues regarding conventions and notation are explained, which are key to the correct understanding of our formulation. Afterwards, the mathematical formulation is described. Given that it is an optimization model implemented in GAMS, we will describe it following a logical structure based on the definition of mathematical programming models in this language: sets, parameters, variables, constraints and objective function, mainly. We will use GAMS terminology, hence a basic knowledge of it is advisable; see (Rosenthal, 2010) for reference¹³¹. From another point of view, MASTER_SO is a partial equilibrium model with exogenously-fixed demand (so it could be understood to be demand-driven), where the complete upstream energy sector is optimised to supply the demand. Hence we will follow the same logical order in explaining the mathematical formulation: we will start from the demanding sectors (“DS”), then the energy transportation processes (“TE”), the energy conversions (“CE”), primary energy (“PE”) and lastly, the issues regarding energy exports and imports (“EI”). This is somehow equivalent to going from right to left in our Sankey diagrams (i.e. starting from the *fifth column* as identified above, then the *fourth*, the *third* and so on). Other issues are explained after the mathematical formulation: main execution modes and options, computer implementation, and some of the main outputs. This chapter is inspired in a working paper (López-Peña, Linares, & Pérez-Arriaga, 2013) which was originally published in September 2011.

V.2. MODEL OVERVIEW

As said previously, MASTER_SO is a bottom-up, static, partial equilibrium, linear programming (LP) model for sustainable energy policy analysis. Its main aim is to supply the externally-given demand for energy services in all demanding sectors, complying with all technical and policy constraints, and maximizing an objective function, which could represent a measurement of energy sustainability, but for now is implemented as the minimisation of the total private economic costs of energy supply, plus the social cost of CO₂ emissions. It is programmed in GAMS and solved with CPLEX.

With the current data structure it represents the Spanish energy system (with the level of detail described above in Chapter 4 Section IV.3.2.b.), but it can be adapted to any other energy

¹³¹ For the reader’s convenience, we include here the relevant information on the relation between GAMS terminology and the one used in general in mathematical programming. Citing from (Rosenthal, 2010): “In GAMS, the terminology adopted is as follows: indices are called *sets*, given data are called *parameters*, decision variables are called *variables*, and constraints and the objective function are called *equations*.”

sector, and it could even include non-energy commodities such as water. It does so using our *processes and flows* approach, inspired in the MARKAL/TIMES models (Loulou et al., 2005) and described in Chapter 4. In any case, MASTER_SO presents some clear differences with MARKAL/TIMES: (i.) we have a much smaller (but sufficient) level of technical complexity, which allows us to greatly reduce the use of hard-to-understand parameters and which greatly increases the transparency in our models; (ii.) the code of the model has been completely developed and maintained by the PhD candidate, putting a clear emphasis on transparency and easy interpretation, whereas TIMES is a model-generator with closed code and a proprietary graphical interface; (iii.) our structure of processes is clearly conceived to be able to easily represent the output of the model in the form of Sankey diagrams (which could also be possible in TIMES, although not as straightforward as here); (iv.) as will be seen below, our objective function is conceived as a measurement of energy sustainability, which is not necessarily the case in TIMES, and allows us to more easily represent policy trade-offs and synergies; (v.) our model is based upon a database built from scratch based on public and contrasted data, and which will be made open, which is not the case for TIMES-Spain, the existing TIMES model of the Spanish energy sector (Caldés et al., 2008). Also, when compared specifically to TIMES-Spain, our model achieves a larger level of technical detail in end-use technologies.

The model represents a year by means of time slices (month, day, group of hours, etc.), and one of its main outputs is the Sankey graphical representation of all flows in each time slice or for the complete year (in terms of power or in terms of energy). The power flows through each of the processes can be subject to capacity restrictions, hence the model can decide to invest in new capacity in some of these processes. Therefore, another of the main outputs of the model are the corresponding investments in new capacities.

V.3. PREVIOUS EXPLANATIONS, CONVENTIONS AND NOTATION

This section includes some previous information that will be useful to understand the rest of this chapter. The reader should not worry if this seems slightly confusing now: it will become clear later, once the actual variables, equations, etc. are explained. This section is intended only as a general overview of the notation that we shall use, and as a previous explanation of our main hypotheses.

For the sake of simplicity and in order to increase transparency in our model, all sets, parameters, variables, constraints, etc. have been given clear names that allow the reader to easily remember what they mean, once it has been explained (e.g. “GENAMORTRATE” represents the general amortization rate). The units of all parameters and equations are provided, using the most convenient ones in each case. Of course, internally in the code of the model there are unit conversion parameters to make them all coherent; we have not included them here for simplicity.

The mathematical explanation of the model will not be a usual (compact) mathematical explanation, but a more detailed one, including verbal descriptions, useful explanations, hypothesis or even some numerical examples (in the case of parameters). This is done with the final aim of enhancing model's transparency and ease of understanding for readers not-very-familiarised with the mathematical description of optimization models. This is inspired in some recent examples of the literature (Howells et al., 2011).

Throughout this PhD thesis, we have used two capital letters to identify each family of processes, which are, also, the five *columns* explained above (e.g. PE for primary energy, CE for energy conversions, and so on). In this chapter, we will continue using capitals to refer to those processes or columns, or to name variables or parameters associated to them (see below). However, when referring to these processes as sets (which are normally used for subscripting) we will use small case letters (e.g. *pe* is the set containing all PE processes). The individual elements of those sets will, again, be referred to using capital letters (e.g. PENUCLE is an element of the *pe* set).

In our model we consider two main types of energy: primary energy and final energy (the distinction has been done in the Introduction of this thesis). Primary energy and primary energy processes will be identified as PE, or using the "*pe*" set. Final energy will be identified as FE. However, it should be noted that this final energy is distributed through energy transportation and distribution processes "*TE*" (e.g. electricity grids, gas networks, pipelines for oil products, etc.), because we have made the modelling hypothesis that each transportation process "*TE*" carries one and only one type of final energy. Hence in some cases final energy will be identified through the "*te*" set, associated to energy transportation processes. In all the rest of this chapter we have been very careful in always making this very clear to avoid misunderstandings.

We will also use capital letters to refer to all external parameters (be them scalars, parameters or tables), and to variables and constraints. Small case letters will be used for the sets used in the subscripts.

Finally, and for the sake of a better understanding of the following sections, it should be made clear that the current MASTER_SO version is implemented as a pure cost minimization problem. Our objective function represents the total economic private costs of energy supply in the country in a year, as will be seen below. We have also included the possibility of accounting for the social cost of carbon emissions, as a first step towards a more comprehensive energy sustainability indicator. The development of a more comprehensive sustainability indicator (to be included as the objective function) remains a key line for future research.

V.4. SETS

V.4.1. Time definition

As said, MASTER_SO is a static model representing only one year. The time definition within a year is carried out in a flexible way using periods, sub-periods and load levels, in a

similar way to electricity market models. Even if in complete energy models (where not only the electricity sector is represented) this level of detail may not be strictly needed, it is used here in order to be able to model the electricity sector within the energy system with enough precision, and it is in any case useful to increase the accuracy of the representation in other energy vectors. It is also useful for reflecting the less critical (but existing) temporary variations of other energy carriers' demand and supply conditions.

- Time periods of the year (elements of the “*p*” set). These represent the periods in which a year is divided. Several levels of disaggregation can be used, such as months or seasons (spring and autumn could be aggregated in the same period if only three seasons are wanted). Example: monthly periods are currently used: January (JN), February (FB), March (MR), April (AP), May (MY), June (JN), July (JL), August (AG), September (SP), October (OC), November (NV), and December (DC).
- Time sub-periods of each period (elements of the “*s*” set): In each of the periods there can be several subdivisions. Example: two divisions: weekdays (WD) and weekends (WE).
- Load levels of the sub-period (elements of the “*l*” set): In each of the sub-periods there can be several load levels. Example: four load levels: super-peak (SP), peak (PK), medium (MD) and off-peak (OP).

The model minimizes the objective function for the entire year, subject to the constraints, and accounting for all the considered time slices. It produces the energy flows for all the slices and the annual (or per slice, if required) Sankey diagrams. The examples provided here correspond to 96 time slices (i.e. 12 periods x 2 sub-periods x 4 load levels). The Sankey diagrams for individual time slices can be expressed in terms of power (e.g. GW), considering them as a fixed picture of the power flows throughout the complete time slice or, just by multiplying by the duration of the time slice and adapting the units (e.g. from GWh to PJ) in terms of energy, being a picture of all the energy that flows during the complete time slice. The yearly energy Sankey is simply the addition of all the 96 energy Sankeys.

V.4.2. Processes

Within our model, the *processes* can be either final energy use devices, which we called *energy services supply technologies* (“*esst*”), energy transportation processes (“*te*”), energy conversion processes (“*ce*”), primary energy processes (“*pe*”), regions with which energy is traded (“*rg*”), or a domestic region (“*dr*”) to model domestic energy resources. They all belong to the set of processes (“*proc*”) set, which is then composed of all these different subsets, as follows: $proc = \{esst, te, ce, pe, rg, dr\}$.

- Energy services supply technologies (elements of the “*esst (proc)*” subset): they model the final energy use devices, which consume final energy to provide energy services, as described in Chapter 4. Some examples would be lamps (consume electricity to supply illumination), cars (consume gasoline to produce mobility) or boilers (consume natural gas to provide heating). They all belong to a demand sector (DS, elements of the auxiliary

set “ds”, as will be see below). In the latest version of the model we use around 260 energy use technologies, as was described in Chapter 4. An interesting line of future research would be to model the energy losses in these end use technologies. Given that the energy services they provide are measured in different units (almost none being energy magnitudes, e.g. passengers-kilometres for mobility), this is not trivial, since it cannot be done with a single subtraction. It could be done through further research by including, through data, the *ideal ESSTs*, which represent the minimum needed energy to provide a unit of energy service (taking into account the physical principles of each technology, thermodynamic limitations, mechanic losses, etc.). All the energy consumed in excess of the one that the ideal ESST would consume could be considered to be lost energy (of course, considering a broad interpretation of energy losses from the physical perspective, as has been explained in previous chapters).

- Energy transportation processes (elements of the “*te (proc)*” subset): these represent the energy transportation and distribution networks that deliver final energy to end use technologies (energy services supply technologies, ESSTs). Each process transports one and only one final energy type (hence this subset also represents the list of final energy types considered, e.g. gasoline, electricity, natural gas, biomass). They have associated average cost and loss factors. An important convention must be explained here, which concerns the centralised and distributed TE types. The process “TE Electricity Centralised”, for instance, represents the complete electricity grid (corresponding to the electricity flow from large power plants sited at transmission network nodes to end consumers connected to the distribution network), while “TE Electricity Distributed, in Industry” represents the electricity networks in industrial areas that transport the electricity produced in distributed generation facilities, such as in cogeneration facilities. There may also exist a “TE Electricity Distributed, in Residential Areas” used to model distributed generation (e.g. from solar photovoltaic panels) in these areas. Therefore, the two latter processes, the distributed ones, may have a lower losses factor. Something similar would be applicable for heat distribution networks, when used. Distributed generation (e.g. industrial cogeneration) would in this case be connected to these distributed processes, while centralised power plants (e.g. a large nuclear power plant) would be connected to the centralised grid. This distinction is similar to the one between transportation and distribution grids, although not completely equivalent: what is important is to be consistent with how these centralised and distributed processes are used, which costs and losses are assigned to each, and which power flows are allowed to take place among them. A similar point could be done if single node representation wants to be improved: several TE processes can be used, each of them representing a different region, and amongst which only some physical flows are allowed. These flows could even be limited to consider interchange capacity limitations (further research). An example of the elements of this subset in a version of MASTER_SO can be seen in Figure 58.

Figure 58: example of elements in the “te” subset.

TEELECE	"TE Electricity Centralised"
TEELEDIIND	"TE Electricity Distributed, in Industry"
TEELEDIOTH	"TE Electricity Distributed, in Other Uses"
TEHEADIIND	"TE Heat Distributed, in Industry"
TEHEADIOTH	"TE Heat Distributed, in Other Uses"
TECOAL	"TE Coal"
TENAGAS	"TE Natural Gas"
TEOPGSN	"TE Oil Product Gasoline"
TEOPDIE	"TE Oil Product Diesel"
TEOPFOI	"TE Oil Product Fuel Oil"
TEOPLPG	"TE Oil Product Liquefied Petroleum Gas"
TEOPKER	"TE Oil Product Kerosene"
TEOPOTH	"TE Oil Product Other"
TEBIOETH	"TE Bioethanol"
TEBIODIE	"TE Biodiesel"
TEBIOMA	"TE Biomass"

- Energy conversion processes (elements of the “*ce (proc)*” subset): they represent all the technologies used to transform primary energy into final energy that, through the TE processes, is transported and distributed for final uses. Among them, as said above, some special types should be described: centralised/distributed. Not only electricity generation can be modelled with CE processes, but also oil refineries, biofuel production or LNG regasification (which we consider to transform a primary energy, LNG, into a final energy, natural gas¹³²). An example of the elements of this subset in a version of MASTER_SO can be seen in Figure 59.

¹³² As was explained in Chapter 3, when describing the representation of the gas sector, we assume LNG to be primary energy and natural gas to be final energy.

Figure 59: example of elements in the “ce” subset.

CENUCLEAR	"CE Nuclear Power"
CENACOTRA	"CE National Coal Traditional"
CEIMCOTRA	"CE Imported Coal Traditional"
CEIMCOIGCC	"CE Imported Coal Integrated Gasification Combine Cycle"
CEIMCOSCPC	"CE Imported Coal Super-critical Pulverised Coal"
CEIMCOSCCCS	"CE Imported Coal Super-critical Pulverised Coal with CCS"
CECCGTTRA	"CE Combined Cycle Gas Turbine Traditional"
CECCGTCCS	"CE Combined Cycle Gas Turbine with CCS"
CEOCGTTRA	"CE Open Cycle Gas Turbine Traditional"
CEOCGTCCS	"CE Open Cycle Gas Turbine with CCS"
CEFUOITRA	"CE Fuel Oil Traditional"
CEHYRURIV	"CE Hydro Run off the River"
CEHYRSCAP	"CE Hydro with Reservoir Capacity"
CEHYPSTOR	"CE Hydro with Pumping Storage"
CEMINIHYDR	"CE Mini Hydro"
CECOGENIND	"CE Cogeneration in Industry"
CECOGENOTH	"CE Cogeneration in Other Uses"
CEWINDONS1	"CE Wind Onshore 1st class best sites high load factor"
CEWINDONS2	"CE Wind Onshore 2nd class medium sites medium load factor"
CEWINDONS3	"CE Wind Onshore 3rd class worst sites low load factor"
CEWINDOFF	"CE Wind Offshore"
CESOPHVCEWT	"CE Solar Photovoltaic Centralised with Tracking"
CESOPHVDIWOTIND	"CE Solar Photovoltaic Distributed without Tracking. In Industrial Sector"
CESOPHVDIWOTOTH	"CE Solar Photovoltaic Distributed without Tracking. In Other Uses Sector"
CESOTELCE	"CE Solar Thermoelectric Centralised"
CESOLTHDIIND	"CE Solar Thermal Distributed Industry"
CESOLTHDIOTH	"CE Solar Thermal Distributed Other Uses"
CEBIOMECCE	"CE Biomass Energy Crops Centralised"
CEBIOMAWCE	"CE Biomass Agriculture Waste Centralised"
CEBIOMFWCE	"CE Biomass Forestry Waste Centralised"
CESLDWAST	"CE Solid Waste "
CEREFINLOWC	"CE Refinery Low Complexity"
CEREFINHIGC	"CE Refinery High Complexity"
CEREFINVHIC	"CE Refinery Very High Complexity"
CEREGASIF	"CE Regasification Terminal"
CEBIOETHPP	"CE Bioethanol Production Plant"
CEBIODIEPP	"CE Biodiesel Production Plant"

- Primary energy sources (elements of the “*pe (proc)*” subset): these account for the total primary energy used in each moment, be it domestic or imported, renewable or non renewable. Each process considers one and only one primary energy type (hence this subset also represents the list of final primary energy types in the model). An example of the elements of this subset in a version of MASTER_SO can be seen in Figure 60.

Figure 60: example of elements in the “pe” subset.

PENUCLE	"PE Nuclear"
PENATCO	"PE National Coal"
PEIMPCO	"PE Imported Coal"
PENAGAS	"PE Natural Gas"
PELNGAS	"PE Liquefied Natural Gas"
PECROIL	"PE Crude Oil"
PEHYDRR	"PE Hydro Run off the River"
PEHYDRC	"PE Hydro with Reservoir Capacity"
PEMNHY	"PE Mihi Hydro"
PEWINON	"PE Wind Onshore"
PEWINOF	"PE Wind Offshore"
PESOLPV	"PE Solar Photovoltaic "
PESOLTE	"PE Solar Thermoelectric"
PESOLTH	"PE Solar Thermal"
PEBIOMECH	"PE Biomass Energy Crops"
PEBIOMAW	"PE Biomass Agriculture Waste"
PEBIOMFW	"PE Biomass Forestry Waste"
PESWAST	"PE Solid Waste"
PEBIOETHPI	"PE Bioethanol Production Inputs"
PEBIODIEPI	"PE Biodiesel Production Inputs"
PEBIOGAS	"PE Biogas"
PEHUMANE	"PE Human Energy"

- Energy trade regions (elements of the “rg (proc)” subset): they represent the regions in the world, with which the modelled energy system can exchange both primary and final energy, where each region has different prices and different exchange capacities. These prices are given parameters (as we said, our representation of international energy market is exogenous). Capacities are also given parameters, although the model could easily be prepared to decide investments in those capacities that are more limiting for the problem, as could be the interconnections in electricity and gas networks. As a first approach, a mainly geographical division has been done for these regions, although other divisions could be done, such as economic or political (e.g. OPEC, OECD). An example of the elements of this subset in a version of MASTER_SO can be seen in Figure 61.

Figure 61: example of elements in the “rg” subset.

EU15EX	"European Union 15 Extended with Iceland, Norway and Switzerland"
OTEURO	"Other European Countries"
MIDDEA	"Middle East"
OTASIA	"Other Asian Countries"
AFRICA	"African Countries"
NORAME	"North America: USA and Canada"
CASAME	"Central and South America"
OCEANI	"Oceania"

- Domestic region (element of the “dr (proc)” subset). For modelling purposes, the domestic region, which represents autochthonous energy supply, has also been created. It

is the only element in the “*dr*” subset. More domestic regions could have been created if different energy production costs/availabilities were to be modelled, although the added value of this approach, if a single node representation is used for TE processes, is unclear.

V.4.3. Main demand characterization sets

This section contains the main sets used for demand characterization.

- Demand sectors (elements of the “*ds*” set): represent the sectors in the economy that are demanding energy, and they are composed of ESSTs. In our case (this could be defined differently), demand sectors are divided into Industry (IND), Transportation (TRA) and other uses (OTH), this final one including primary sector, tertiary sector (services) and residential sector. Each of these sectors is at the same time divided into sub-sectors or, in the transportation sector case, in modes, as shown in Figure 62.

Figure 62: example of elements in the “*ds*” set.

DSIND_MCM	"DS Industry Mining, Constructions and Materials"
DSIND_CHE	"DS Industry Chemical"
DSIND_OTH	"DS Industry Other "
DSOTH_PRI	"DS Other Uses Primary Sector"
DSOTH_RES	"DS Other Uses Residential Sector"
DSOTH_SRV	"DS Other Uses Services sector "
DSTRA_AIR	"DS Transportation Air"
DSTRA_SEA	"DS Transportation Sea"
DSTRA_LND	"DS Transportation Land"

- Energy services (elements of the “*es*” set): they represent all the possible energy services demanded in the modelled economy. Three associated double sets are relevant: (i.) the “*esbds (es, ds)*” one represents if an energy service belongs to a specific demand sector (e.g. the *washing machines* energy service belongs to the residential sector but not to the air transportation one); (ii.) the “*esstses (esst, es)*” one, which defines which ESSTs supply each energy service (e.g. the *space cooling* energy service can only be provided by air conditioning ESSTs); and (iii.) the combination of both, “*esstbds (esst,ds)*”, which represents if an ESST belongs to a DS. An example of the elements of this set in a version of MASTER_SO can be seen in Figure 63.

Figure 63: example of elements in the “es” set.

ES_DSIND_MCM_ELEDCD	"Industry, Mining, Constructions and Materials. Electricity with Load Curve Demand"
ES_DSIND_MCM_OTNRGD	"Industry, Mining, Constructions and Materials. Other Energy Demand"
ES_DSIND_CHE_ELEDCD	"Industry, Chemical. Electricity with Load Curve Demand"
ES_DSIND_CHE_OTNRGD	"Industry, Chemical. Other Energy Demand"
ES_DSIND_OTH_ELEDCD	"Industry, Other. Electricity with Load Curve Demand"
ES_DSIND_OTH_OTNRGD	"Industry, Other. Other Energy Demand"
ES_DSOTH_PRI_ELEDCD	"Primary Sector. Electricity with Load Curve Demand"
ES_DSOTH_PRI_OTNRGD	"Primary Sector. Other Energy Demand"
ES_DSTRA_LNP_URBN	"Transportation, Land, Passengers. Urban (less than 10km)"
ES_DSTRA_LNP_L50	"Transportation, Land, Passengers. Metropolitan not urban (between 10 and 50km)"
ES_DSTRA_LNP_G50	"Transportation, Land, Passengers. Interurban longer than 50"
ES_DSTRA_LNP_G100	"Transportation, Land, Passengers. Interurban longer than 100"
ES_DSTRA_LNP_G500	"Transportation, Land, Passengers. Interurban longer than 500"
ES_DSTRA_AIP	"Transportation, Air, Passengers"
ES_DSTRA_SEP	"Transportation, Sea, Passengers"
ES_DSTRA_SEF	"Transportation, Sea, Freight"
ES_DSTRA_AIF	"Transportation, Air, Freight"
ES_DSTRA_LNF_URBN	"Transportation, Land, Freight. Urban (less than 10km)"
ES_DSTRA_LNF_L50	"Transportation, Land, Freight. Metropolitan not urban (between 10 and 50km)"
ES_DSTRA_LNF_G50	"Transportation, Land, Freight. Interurban longer than 50"
ES_DSTRA_LNF_G100	"Transportation, Land, Freight. Interurban longer than 100"
ES_DSTRA_LNF_G500	"Transportation, Land, Freight. Interurban longer than 500"
ES_DSOTH_RES_HEAT	"Residential Buildings. Space Heating"
ES_DSOTH_RES_COOL	"Residential Buildings. Space Cooling"
ES_DSOTH_RES_HTWA	"Residential Buildings. Hot water"
ES_DSOTH_RES_LIGH	"Residential Buildings. Lighting"
ES_DSOTH_RES_FRID	"Residential Buildings. Fridge"
ES_DSOTH_RES_OVEN	"Residential Buildings. Oven"
ES_DSOTH_RES_WAMA	"Residential Buildings. Washing machine"
ES_DSOTH_RES_DIWA	"Residential Buildings. Dish washer"
ES_DSOTH_RES_COOK	"Residential Buildings. Cooking"
ES_DSOTH_RES_OEAP	"Residential Buildings. Other Electric Appliances"
ES_DSOTH_SRV_HEAT	"Services Buildings. Space Heating"
ES_DSOTH_SRV_COOL	"Services Buildings. Space Cooling"
ES_DSOTH_SRV_HTWA	"Services Buildings. Hot water"
ES_DSOTH_SRV_LIGH	"Services Buildings. Lighting"
ES_DSOTH_SRV_OEAP	"Services Buildings. Other Electric Appliances"

- Energy services variation measures (elements of the “esvm” set): a possible energy efficiency policy may consist not in improving the efficiency with which final energy is transformed into energy services (e.g. improving the efficiency of cars or heating systems), but actually reducing the demand for energy services (e.g. reducing mobility or improving the insulation of buildings). We have modelled these through this set, whose name comes from the fact that they *vary* the demand energy services. We say “vary” and not “reduce” because a policy can reduce the demand for one energy service but increase the demand for other one. For instance, the promotion of teleconferences as a means to reduce mobility for business reasons may increase the demand for electricity from appliances in offices (probably in a slight way). Hence the ESVM “teleconference promotion” *varies* the demand for energy services in two ways: reduces the demand for mobility, and increases the demand for electricity from appliances in offices). In other words, in some cases it would not be correct to call it just “reduction”. An example of the elements of this set in a version of MASTER_SO can be seen in Figure 64. The relation of which ES are varied by each ESVM is given through the “esvmves (esvm,es)” double set.

Figure 64: example of elements in the “esvm” set.

ESVARM_DSTRA_LNP_TeleconfProm	"Teleconference promotion for businesses"
ESVARM_DSOTH_RES_InsOpaqDtchdUCTE0p8	"Improve insulation of opaque elements in detached dwellings built prior to 2011 to a U value of 0.8W/m2K (CTE standar)"
ESVARM_DSOTH_RES_InsOpaqDtchdUPsvH0p2	"Improve insulation of opaque elements in detached dwellings built prior to 2011 to a U value of 0.2W/m2K (almost Passive House)"
ESVARM_DSOTH_RES_WindowsDtchdUCTE0p8	"Improve windows in detached dwellings built prior to 2011 to a U value of 0.8W/m2K (CTE standar)"
ESVARM_DSOTH_RES_WindowsDtchdUPsvH0p2	"Improve windows in detached dwellings built prior to 2011 to a U value of 0.2W/m2K (almost Passive House)"
ESVARM_DSOTH_RES_InsOpaqBlockUCTE0p8	"Improve insulation of opaque elements in block dwellings built prior to 2011 to a U value of 0.8W/m2K (CTE standar)"
ESVARM_DSOTH_RES_InsOpaqBlockUPsvH0p2	"Improve insulation of opaque elements in block dwellings built prior to 2011 to a U value of 0.2W/m2K (almost Passive House)"
ESVARM_DSOTH_RES_WindowsBlockUCTE0p8	"Improve windows in block dwellings built prior to 2011 to a U value of 0.8W/m2K (CTE standar)"
ESVARM_DSOTH_RES_WindowsBlockUPsvH0p2	"Improve windows in block dwellings built prior to 2011 to a U value of 0.2W/m2K (almost Passive House)"
ESVARM_DSOTH_RES_ImprInsNewBUCTE0p8toUPsvH0p2	"Improve insulation of dwellings built between 2011 and 2030 from CTE Estándar (U=0.8W/m2k) to almost Passive House Estándar (U=0.2W/m2k)"
ESVARM_DSOTH_RES_ThermostaticValves	"Install thermostatic valves in dwellings in roughest climatic areas (in 600k dwellings in 2030)"
ESVARM_DSOTH_SRV_InsUPsvH0p8	"Improve insulation of commercial buildings built prior to 2011 to a U value of 0.8W/m2K (CTE standar)"
ESVARM_DSOTH_SRV_InsUCTE0p2	"Improve insulation of commercial buildings built prior to 2011 to a U value of 0.2W/m2K (almost Passive House)"
ESVARM_DSOTH_SRV_ImprInsNewBUCTE0p8toUPsvH0p2	"Improve insulation of commercial buildings built between 2011 and 2030 from CTE Estándar (U=0.8W/m2k) to almost Passive House Estándar (U=0.2W/m2k)"

V.4.4. Auxiliary sets

In this section we describe the auxiliary sets, created for an easier definition of some parameters, variables or constraints which only make sense over specific processes.

To begin with, the exclusion of energy services variation measures (ESVMs, defined in the previous section) must be modelled. By this we mean that if an ESVM is implemented, another one may be excluded, e.g. if we improve the windows of a house to the CTE standard (Spanish recent Building Code “Código Técnico de Edificación”) we cannot improve them to a Passive House¹³³ standard *at the same time*. We have done this through an ESMV exclusion constraint, as will be seen later. For it, the multiple set “*esvmexcl*” is used, which contains all the groups of ESVMs that are mutually exclusive.

In addition, as part the “*ce (proc)*” subset, there are the following two subsets. First “*celoadf (ce)*”, which contains all of the CE processes modelled with load factors (i.e. the group of

¹³³ An ambitious standard for building’s efficiency.

intermittent or non-manageable CE technologies whose average yearly production is given through a yearly load factor). It would be more precise to give a monthly or even more disaggregated load factor if variability wants to be better represented, but due to data availability we have only used the yearly load factor (although, in the case of mini-hydro power plants, this yearly factor is internally modified to obtain a monthly load factor depending of each month's water availability but maintaining the yearly load factor as the average). Second, "*ceececentral (ce)*", contains all the electricity generation processes connected to the centralised electricity grid and to which the generation reliability constraints (i.e. adequacy and reserves constraints, defined in Chapter 4 and detailed later) are applied. This implies the modelling hypothesis that distributed generation does not affect the centralised electricity grid's reliability, which may not hold in a future of higher penetration of these technologies. Hence, improving this could be a future research line.

Finally, as part of the "*pe (proc)*" subset, we have defined the "*pelimey (pe)*" one, which stands for "PE processes with limited energy in the year", and contains the elements of the "*pe*" subset where the total amount of disposable energy in the year is limited. This is the case for example for biomass, biogas or solid waste. The case of hydropower has been modelled in a slightly different way (imposing energy limitations per month instead of per year), as will be seen later.

V.4.5. Possible energy flows

As defined in Chapter 4, the energy system's definition, once the processes have been defined, is completed allowing energy to flow among them. This is done via the definition of energy flows, which are the possible flows that energy can follow with a prescribed direction (i.e. from A to B, but not from B to A). These flows determine the topology of the energy system in all the time slices within the studied year, and given that this topology is something that may need to be changed (e.g. in order to include a new technology), the flows are given to the model in a flexible way. This is done using GAMS's double sets: each flow starts in one element of the set "*proc*" and ends in another element of the set "*proc*". These double sets are grouped in the following groups: "*peceflows*" (flows from a PE to a CE), "*peteflows*" (flows from a PE to a TE), "*ceteflows*" (flows from a CE to a TE), "*tefeflows*" (flows from a TE to final energy use, i.e. to ESSTs), "*pefeflows*" (flows from a PE to final energy use, i.e. to ESSTs), "*teceflows*" (flows from a TE to a CE), "*teteflows*" (flows from a TE to another TE, which can be useful, for example, to represent electricity flowing from the high voltage network to the medium voltage one, both being TE processes).

In our current implementation we have made some hypotheses concerning energy flows, mainly based in the Sankey diagrams at the BP Observatory on Energy and Sustainability (López-Peña, Linares, Pérez-Arriaga, et al., 2013). These hypotheses are:

- Natural gas has to pass through the gas network before electricity generation in any of the gas-based technologies (combined cycle and open cycle gas turbines, and cogeneration) in order to account for its transportation losses and costs.

- Liquefied natural gas passes through the regasification process before entering the natural gas network, which is equivalent to assuming LNG to be a primary energy, regasification a CE, and natural gas a final energy.

V.5. PARAMETERS

In this *Parameters* section, all the numerical data exogenous to the model are described, no matter the number of dimensions of sets that the data is dependent on. In GAMS language, simple *scalars* (0 dimension dependence), *parameters* (1 dimension dependence) or *tables* (2+ dimension dependence) are treated separately, as can be seen in (Rosenthal, 2010). Here, instead of this differentiation (which can, however, be inferred from the number of dependence sets), we have grouped them in general parameters (affecting the complete energy system), or those affecting demand sectors, TE processes, CE processes, PE processes or EI (i.e. Export/Import) processes. The parameters appear in the same order as in the Excel data book for MASTER_SO, for the convenience of future model users.

V.5.1. General parameters

- CO2PRICE: carbon price in €/tCO₂ used for valuing the social cost of carbon emissions (the value of the externality) in the objective function, which allows us to have an objective function which is closer to an energy sustainability indicator. This is not a carbon price from the ETS market, since different sectors are covered in each case: here, all emissions from every process in Spain are affected by this value, whereas the ETS only covers some sectors and for the entire European Union.
- YEAR: year of the study expressed in 4 digits (e.g. "2030") and stored by GAMS as a number.
- GDP: Gross Domestic Product of the country in the year of study, in M€. Used to compare the energy system costs, that is, to express them as a share of GDP if needed (e.g. the total cost of the energy system in a year may for instance be around 10% of the GDP).
- GENAMORTRATE: (GENeral AMORTization RATE), general interest rate used for investments amortization. It represents the rate of return on capital that companies demand from their investments in energy assets, which normally is equivalent to the weighted average cost of capital, WACC, which includes both debt and equity. A usual value for this parameter, in the case of Spain, could be 9%.
- CEHYPSTORCYEF: (CE HYdro Pumping STORage Cycle EFFiciency), efficiency of the pumping storage cycle in the CEHYPSTOR process (i.e. hydro pumping storage power plants). A usual value for this parameter, in the case of Spain, could be 70%.
- CERESMRG4ADEQ: (CE REServe MaRGin For ADEQuacy), required firm capacity reserve margin over yearly peak electricity demand, for the *adequacy* constraint applied to the

elements of the “*ceelectra*” set. A usual value for this parameter in Spain could be 10%. We will comment on *firm* capacity below.

- CEDEMAVGPRERR4RSRV: (CE DEMand Average Prediction ERRor For ReSeRVes), average prediction error in demand, for the *reserves* constraint applied to the elements of the *ceelectra* set. A usual value for this parameter in Spain could be 4%.
- CELOADFAVGPRERR4RSRV: (CE LOAD Factor AVeraGe PRediction ERRor For ReSeRVe), average forecast error in the electricity produced by intermittent power plants (the ones in the set “*celoadf*”), for the *reserves* constraint. It is expressed as a percentage of their total yearly average production (expressed by their load factor). A usual value for this parameter in Spain could be 20%.
- CELARGCECAP4RSRV: (CE LARGE CE CAPacity For Reserve), size of the largest electricity generation plant that could fail suddenly, to be used in the *reserves* constraint. A usual value for this parameter in Spain could be 1000 MW, corresponding to a large nuclear power plant.
- $D_{p,s,l}$: duration in hours of each load level. The values should be chosen so that the SuperPeak load levels are just 1% of the hours (approx.) in each period and sub period, in order to have an adequate representation of the peaking situations in the electricity dispatch.
- MINREGAS: (MINimum REGASification level), contains the technical minimum of regasification terminals, as explained below. To see how this minimum level has been calculated, refer to the Data Documentation Annex.

V.5.2. DS Parameters

These parameters are the basis for our comprehensive representation of final energy use technologies, mainly based in energy services (ES) and energy service supply technologies (ESST), as seen in Chapter 4.

- ESVMCOSTYEAR_{esvm}: (Energy Service Variation Measure COST per YEAR), cost per year of fully implementing (up to 100%) each ESVM, measured in million €. In the case of an ESVM that can be considered to be an investment for several years (e.g. new windows for residential buildings), the annuity of this investment should be included here..
- ESSTCOSTPACTUY_{esst}: (Energy Service Supply Technology COST Per ACTivity Unit in each Year), represents the non-energy costs of each unit of activity in each ESST for each year, in million €. They are calculated as the annualised investment costs as well as all (non-energy) operational costs of each ESST, divided by an average (expected) value for its activity in a year (e.g. in the case of a car they are the annual costs of the car, excluding gasoline, divided by an average yearly mileage, because activity is measured in vehicle-kilometres). Infrastructure costs (e.g. of network transportation modes such as metro or train) should as well be included. As said in Chapter 4, these non-energy costs allow the optimization to consider the trade-off between: (i.) older, energy inefficient and

- (economically) less costly; and (ii.) modern, more efficient and (presumably) expensive technologies. If these non-energy usage costs were not included, the model would only choose the most energy efficient technologies, without considering their costs (e.g. we would only have electric cars in the streets).
- $ESSTLSCOST_{esst}$: (ESST Load Shifting COST in each ESST), represents the cost in €/MWh of shifting energy demand by users. Shifting demand may have a cost for users, because of the losses in utility derived from it. These costs should depend on how much energy is displaced and how far (for how many hours) it is displaced. In our model, we do not have enough chronological detail to accurately represent this second factor, so we will estimate load shifting costs only through the total amount of energy displaced.
 - $ESDEMY_{es,ds}$: (Energy Service DEMand per Year), measures the total yearly demand of each energy service in each demand sector. It is measured in different units, depending on the ES. These values are fixed, implying that these demands are price-inelastic. An interesting line for future research would be to include some sort of price elasticity here, as a means for a better representation of the response of the rest of the economy to what is happening in the energy sector (it should be reminded that MASTER_SO is a partial equilibrium model). However this could make the problem non-linear, as said in Chapter 4.
 - $NSFECOST_{esst,ds}$: (Non-Supplied Final Energy COST), in each ESST in each demand sector DS, measured in €/MWh. Importantly, it does not measure the utility of unserved energy demand. For electricity, for instance, this utility of unserved demand is considered to be somewhere between 200 and 5000 €/MWh, with very low consensus among the literature due, in part, to the very difficult estimation of these values and to the very variable values that correspond to users in different sectors or countries. For other types of final energy such as gasoline or natural gas, the situation is similar. Therefore, in this model this value is set at a very high value for all types of final energy in all demand sectors. The idea behind this is that the model never chooses to leave unserved demand. In other words, estimations of the real values are to be used if the modeler wants the model to be able to choose to not serve all demand (in the case where the cost of satisfying it is greater than the utility given to it by demand sectors). In this model, the unserved demand is only considered as a slack variable used for avoiding infeasibilities in the optimization problem, but highly penalized in the objective function (through this parameter) so that the model tries to keep it null in all circumstances. We are currently using a 10000 €/MWh value. It is defined over the ESSTs for a reason that will be seen later, when defining the energy balance in ESSTs.
 - $FEUEMISSFTE_{esst,te}$: (Final Energy Use EMISSIONS Factor per unit of consumed TE), represents the per-unit emissions of CO₂, expressed in tCO₂/MWh, which are produced in each ESST when it consumes a unit of each final energy (TE). These factors are applied to the actual energy consumed by the technology, not to the produced energy service, i.e. the energy lost in these energy use technologies also produces emissions because it is

indeed consumed. For the moment we have only modelled CO₂ emissions, but other gasses or pollutants could be included by creating analogous input parameters.

- FEUEMISSFPE_{esst,pe}: (Final Energy Use EMISSIONS Factor per unit of consumed PE), similarly to the previous parameter, it represents the unitary emissions of CO₂, expressed in tCO₂/MWh, which are produced in each ESST when it consumes a unit of each primary energy (PE).
- ESVMEFFECT_{esvm,es}: (Energy Service Variation Measure EFFECT), represents the effect that a full application of each ESVM would have on each ES, in percentage. As said, some ESVMs can reduce the demand for some energy services, while increasing others. Hence, this parameter can have both negative and positive values. These effects should not be confused with the inclusion of price elasticity of demand in our model, which, as said, is price-inelastic for now. Price elasticity represents when the consumers decide to reduce their consumption due to high prices. On the contrary, the implementation of ESVMs is decided by the policymaker (represented by the model) if profitable from the point of view of the optimization of the defined objective function.
- ESDEMLoadC_{es,p,s,l}: (Energy Services DEMand LOAD Curve), represents the load curve of the demand for each ES within the time slices of the year (p,s,l). It is expressed in %. When applied to the ESDEMY, it yields the amount of energy service (measured in its own units) that is demanded in each time slice. If uniform demand wants to be used, these values should simply be the proportion of each time slice's duration in the complete year's duration.
- ESVMLOADC_{esvm,p,s,l}: (Energy Service Variation Measure LOAD Curve), represents the load curve of the effects of each ESVM in the different time slices of the year (p,s,l). It is expressed in %. When applied to the ESVM, it allows us to obtain how the effects of each ESVM are distributed among the time slices of the year. If uniform effects are assumed, these values should simply be the proportion of each time slice's duration in the complete year's duration.
- QACTESST2ES_{esst,es}: (Quantity of ACTivity in each ESST To Energy Service), represents the fixed relation between the activity level in each ESST (a variable called QACTESST, as will be seen below) and the amount of each ES that this activity is producing. These parameters are measured in units of ES divided by units of ESST activity (units "es" / units activity "esst"). For instance, in the case of a car, where the ES units are passenger-kilometre and the ESST activity units are vehicles-kilometre, this parameter is measured in pkm/vkm, which is p/v, which is the occupation factor of the car (persons per vehicle). The fact of these factors being fixed (and not a variable in the problem) impedes us from being able to model interesting policies such as those improving the occupation factors in vehicles. But it allows us to keep the model linear: if these parameters were variables, we would have the product of two variables (QACTESST·QACTESST2ES), hence not a LP model anymore. In any case, we can model improved QACTESST2ES factors by duplicating the ESST, each one representing a different QACTESST2ES factor. Improving this remains, however, an interesting future research line.

- $TE2QACTESST_{esst,te}$: (TE To Quantity of ACTivity in each ESST), represents the amount of final energy (not power) needed to create a unit of activity level in each ESST (i.e. in the QACTESST variable). Its units are “units activity ESST / GWh”. Something similar as in the paragraph describing QACTESST2ES applies here: by making these values fixed, we keep the model LP, but we lose the possibility of representing some energy efficiency policies (e.g. improving air pressure in cars’ wheels, which allow cars to use less gasoline to drive for the same kilometres) or to consider flexi-fuel processes (those which can modify the shares of energies they use, e.g. a biomass furnace which can use several biomass types). In any case, these processes with improved efficiency or different energy use share can be modelled by duplicating the corresponding ESST.
- $PE2QACTESST_{esst,pe}$: (TE To Quantity of ACTivity in each ESST), represents the amount of primary energy (not power) needed to create a unit of activity level in each ESST (i.e. in the QACTESST variable). Its units are “units activity ESST / GWh”. It is the equivalent to $TE2QACTESST$ for ESSTs that use primary energy (e.g. bikes, which consume “human energy”, or solar thermal panels). Something similar as in the paragraphs describing QACTESST2ES and $TE2QACTESST$ applies here about the pros and cons of defining these values as fixed. Importantly, it should be noted that the combination (product) of two factors provide an indication of the energy efficiency of each energy services supply technology: QACTESST2ES and (depending on the case) $TE2QACTESST$ or $PE2QACTESST$. The first one measured in “units ES / units activity ESST” and the second ones in “units activity ESST / GWh”, hence their product has magnitudes of final energy use efficiency (“units ES / GWh”). When doing this product, care must be put in correctly considering the units, and that some ESSTs consume more than one type of final and/or primary energy (i.e. having different values in $TE2QACTESST$ and/or $PE2QACTESST$) and that some produce more than one type of energy service (i.e. having different values in QACTESST2ES).
- $ESSTLSPOSTE_{esst,te}$: (ESST Load Shifting POSSibility for TE), represents if each ESST has the possibility of load shifting for each TE. This parameter is defined as an adimensional natural number taking values 0, 1 or 2, meaning respectively no load shifting allowed, intradaily or intraweekly. This will be better understood later, when the energy balance in each ESST are described.
- $ESSTLSPOSPE_{esst,pe}$: (ESST Load Shifting POSSibility for PE), represents if each ESST has the possibility of load shifting for each PE. This parameter is also defined as an adimensional natural number taking values 0, 1 or 2, meaning respectively no load shifting allowed, intradaily or intraweekly. This will be better understood later, when the energy balance in each ESST are described.
- $MAXDEMYR_{te}$: (MAXimum DEMand in the YeaR), represents the maximum demand for each type of final energy in each year. For now, it is only used for the power generation adequacy constraint, where it represents the peak demand in the system (for centralised electricity). This value is given as an external parameter and not calculated internally, which we believe is more transparent and easier to understand. Indeed, peak demand is

a concept commonly used and well understood by policymakers and energy professionals. On the contrary, its internal calculation is complex, because it depends on the complete configuration of energy services' demands (also considering ESVMs), on how it is supplied by end use technologies (also considering issues such as load shifting) or even on how allowed energy flows are configured to allow energy to flow from the centralised electricity TE process to other (decentralised) electricity TE processes.

V.5.3. TE Parameters

- $TECAP_{te}$: (TE CAPacity), represents the capacity of each transportation process, that is, the maximum energy that, in each time instant, a transportation process can deliver, and it is therefore represented in power units (GW). It is measured as a limitation in the process's input. For the moment, given the difficulty of calculating these values in a single node model (as this one is), these values have been set at very high levels so that they do not become active limitations, but this possibility is prepared if needed.
- $TELF_{te}$: (TE Losses Factor), represents the total energy losses¹³⁴ in each transportation process, measured as a percentage of the incoming energy. For instance, if the electricity grid has a losses factor of 9%, in order to deliver 100 MW the amount of electricity generated (input to the electricity grid) must be 109.9MW, so that $(100\%-9\%)*109.9MW=100MW$.
- $ECOVCTE_{te}$: (ECONomic Variable Cost of TE), representing the variable costs (only economic private costs, no externalities or other public costs considered) of delivering each unit of energy-transportation in the process. It is measured in €/MWh, and applied to the incoming energy, considering that lost energy imposes a transportation cost as well. This cost is especially relevant for the electricity and gas networks, where it stands for both the physical infrastructure investment costs and its operation costs (O&M, system operator allowances, etc.). It can also be a relevant cost for biomass delivery, given its low energy content per volume unit. For the centralised electricity network, as said in Chapter 4, this cost factor has been calculated through an econometric approach (detailed in the Data Documentation Annex) to account not only for the amount of energy transported (energy term) but also for the installed capacity, notably intermittent (capacity term), because we believe that the latter plays an important role in total costs. For the other TEs, only a constant value of cost per unit of delivered energy (i.e. energy term) is used.
- $CO2EFTE_{te}$: (CO2 Emission Factor of each TE), represents the unitary CO₂ emissions produced per unit of transported energy, measured in tCO₂/MWh. Contrary to the cases of PE or CE, it is applied to the incoming energy of the process (i.e. its input). At the moment, the emissions produced in the gas network are not considered because they are methane emissions, not CO₂, and methane is not considered in this model. The emissions

¹³⁴ Once again, using a broad understanding of the word *losses*, as said above.

produced by the trains and trucks used to transport biomass, oil products, coal and biofuels are accounted for in the transportation demand sector. Electricity and heat grids do not produce any emissions. Therefore, for the moment, these factors are null for all TEs. Including methane emissions from the gas network could be an interesting line for future research, given that gas is expected to play a large role in the medium term and that these emissions can be important for global warming.

V.5.4. CE Parameters

- $CEPREVCAP_{ce}$: (CE PREVIOUS CAPacity), represents each process's previous capacity, that is, the capacity already installed prior to the model's execution, expressed in GW. These capacities are measured in the process's total output, i.e. for the total output of useful TE produced by the process (be it only one TE like in electricity generation plants or several as in oil refineries). The model decides whether to invest or not on top of this capacity. This capacity is assumed to be fully paid already, so the annuity of its investment costs is not considered in the objective function. This may underestimate the energy system's costs. However, given that we use a partial equilibrium approach (where sunk costs are less relevant, which is not the case in a general equilibrium approach), this is not a problem from the point of view of the mathematical optimization (they are just a constant in the objective function). But they are of course very relevant (and should be added) if the absolute system cost is needed, for instance to obtain economic and financial indicators of the studied energy system. Incorporating them is an interesting line for further research.
- $CECAPTOTINVSTCOST_{ce}$: (CE CAPacity TOTal INVeSTment COST), measures the total investment cost per unit of new capacity (measured over the process's useful output as explained above) of a CE process. It is measured in €/kW. The word *total* implies that it is the complete cost that must be paid over the investment's amortization period. In other words, it is not the annualised investment cost but the total overnight one: the annuities are calculated internally within the model, given the amortization years and interest rate, as will be seen next.
- $CECAPAMORTYEARS_{ce}$: (CE CAPacity AMORTization YEARS), it represents the amortization years of a new investment in CE capacity, that is, the number of years over which the annuity must be paid. This should normally be the *technical life* of the process (for taxing purposes the private companies sometimes amortize the investment in fewer years, which is sometimes called *economic life*, although these values are not always publicly disclosed so using them within our model would go against our claim for public and transparent data). Given that the model is a static one (represents only one year), the different technical lives of different technologies (and thus, different amortization periods) could significantly affect the calculation of each technology's annuity and therefore, the investment decisions made for that year. This problem would not be present in a dynamic model (representing several years), where the complete cash flow associated to an investment over its complete life is considered. In our case, and as a first

approach where we tried to limit these effects, we have assumed 20 years life for all technologies.

- $CECAPRISKPREM_{ce}$: (CE CAPacity RISK PREMium), aims at representing the incremented cost of capital that a certain CE technology (e.g. nuclear) may suffer from its increased risk as compared to other technologies (i.e. a sort of risk premium). It is added to the WACC mentioned above (the general market amortization rate parameter), in order to calculate the interest rate with which a particular investment in a CE process is amortized. It is also measured in %. In the current version of MASTER_SO we are using 0% for all CEs except for nuclear, which has a 6% risk premium, i.e. all CEs are amortised at GENAMORTRATE (9%) except for nuclear, amortised at 15%.
- $ACECAPFIXDCOSTYEAR_{ce}$: (Active CE CAPacity FIXeD COST per YEAR), represents the yearly fixed costs of keeping active a unit of CE capacity (only operation and maintenance costs). This *active* notation implies that the model may decide to not use some capacity that was already installed and paid (CEPREVCAP), and thus to not have it active in the studied year, saving its fixed O&M costs. The fixed costs are paid only for active capacity. For instance, the fixed costs of an old power plant can be saved if the model decides to not use that power plant in the year (i.e. hibernation or *mothballing*), which in this model's terminology, means to not activate that power plant. Of course, the total output of the plant cannot be greater than the active capacity (i.e. if a plant is not active it cannot produce), and the active capacity cannot be greater than the installed capacity (previous + new, as will be seen below).
- $CELF_{ce}$: (CE Losses Factor), aims to represent the efficiency of the conversion process. More precisely, it represents the total energy losses¹³⁵ (i.e. opposite to the efficiency) in each CE, measured as a percentage of the incoming energy. It accounts for both energy losses and self-consumption (although these are not exactly losses, we consider them as so for simplicity). For example, in a modern combined cycle gas turbine with 60% efficiency, this parameter should be 40%.
- $CEMAXACTIVECAP_{ce}$: (CE MAXimum ACTIVE CAPacity), represents the maximum active capacity possible in a CE, measured in GW. This is especially useful in order to limit the amount of capacity installed by the model in certain technologies with physical limitations (e.g. some renewables such as hydro or wind, which have a limited potential).
- $CELOADFACTOR_{celoadf}$: (CE LOAD FACTOR), this value is the yearly average load factor needed to characterise the production of the CE processes modelled with load factors (i.e. the elements of the "*celoadf*" set, such as wind and solar power). This is equivalent to the % of hours in the year functioning at nominal power that would produce the same energy as the one actually produced in an actual average year. As said, it would be more detailed to have monthly or even daily load factors. This is somehow done (internally in the model) for minihydro, where its yearly load factor is modified with the monthly

¹³⁵ Once again, using a broad understanding of the word *losses*, as said above.

water availability (HYDRONRGMONTH, as will be seen below). Therefore, in months with more water availability the load factor is bigger, but always keeping the given annual factor (the data in CELOADFACTOR) as the average throughout all the periods in a year. For wind power we have used three decreasing load factors (24%, 22.5% y 22%) for each of the three levels of resource quality, each having a limited potential (by using the CEMAXACTIVECAP parameter).

- CEFIRMNESS4ADEQ_{ceelecentral}: (CE FIRMNESS For ADEQuacy), represents the amount of *firm* capacity that each unit of this CE's capacity contributes to the centralised electricity system, with regard to calculating the adequacy constraint of the system (refer to Chapter 4 and to the "Constraints" section below). As previously mentioned, this constraint establishes that the (centralised) electricity system needs a reserve margin of firm capacity over the yearly peak demand. By *firm*, we understand the amount of power that, with a high degree of certainty, is provided by the technology in a critical moment of the system (this is also called *capacity credit* in the literature). For instance, in this model, wind power is assumed to have a capacity credit of 7.5%: each GW of installed capacity provides the system with 75MW of firm capacity. These values are very difficult to estimate, especially for the case of wind, solar and hydro power: the values we have used, as said in Chapter 3, come from the literature and from consultation to experts at the PhD candidate's research centre¹³⁶ and at the Spanish Transmission System Operator, Red Eléctrica de España.
- CEFLEXIBILITY4RSRV_{ceelecentral}: (CE FLEXIBILITY For ReSeRVes), represents the measure of how flexible this CE is, for the reserves constraint in the centralised electricity system (refer to Chapter 4 and to the "Constraints" section below). This constraint must ensure that the amount of idle (but active) and flexible capacity in the system is enough to cover the need for reserves. By *flexibility*, we understand the ability to quickly increase or decrease its output. In our model, for example, an old nuclear power plant with no output flexibility has a value of 0%, whereas a very modern open cycle gas turbine has a factor of 95%.
- CEINSHARETE_{ce,te}: (CE INput SHARE of each TE). In order to be able to represent CE processes in a flexible way, with the inspiration of the MARKAL/TIMES philosophy, the CE processes must consume primary energy (PE) or final energy (TE) in order to produce each unit of output. This parameter is used to introduce the share (in %) of each type of final energy TE that each CE must consume when producing a unit of output. For instance, a fuel-oil electricity generation plant does not consume any primary energy. However, it consumes a type of final energy (TE), which is fuel oil. Therefore, this parameter takes 100% value for the "TE fuel oil" in the "CE fuel oil" electricity power plant. As another example, if the electricity consumption of an oil refinery wants to be modelled (and assuming it represents 2% of its input), it could be established that the input in a refinery is in a 98% the primary energy "crude oil", and in a 2%, the "TE

¹³⁶ IIT, Comillas University, Madrid

electricity”. Thus, this parameter for the refinery would take the value 2% for “TE electricity”. For more information, see the energy balance constraint in the CEs, below in this chapter. For each CE, the values of $CEINSHARETE_{ce,te}$ and $CEINSHAREPE_{ce,pe}$ for all TEs and PEs must add 100%.

- $CEINSHAREPE_{ce,pe}$: (CE INput SHARE of each PE). This parameter is complementary to the previous one, and establishes the share of each primary energy PE that is consumed by each CE when producing a unit of output. In the example of the oil refinery used in the previous paragraph, this parameter for the refinery would take the value 98% for “PE crude oil”. For more information, see the energy balance constraint in the CEs, below in this document. For each CE, the values of $CEINSHARETE_{ce,te}$ and $CEINSHAREPE_{ce,pe}$ for all TEs and PEs must add 100%. As a line for future research, if other non-energy commodities want to be modelled (e.g. water¹³⁷), a similar approach (i.e. a parameter relating the inputs needed to create a unit of output) could be followed, although taking into account that the units are different, so no percentages can be used. In the literature, TIMES solves this by also using activity variables, as the ones we use for ESSTs, in conversion processes.
- $CEMAXTEOUTSHARE_{ce,te}$ and $CEMINTEOUTSHARE_{ce,te}$: (CE MAXimum TE OUTput SHARE and CE MINimum TE OUTput SHARE). In a CE process, not only the share in inputs can be limited or established through parameters (as explained in the two previous paragraphs), but also the shares in output. If a CE process produces more than one flow of final energy TE, the total output is the total added power of all the useful output flows (losses not considered). The maximum and minimum allowed shares of each flow in the total output are restricted through these parameters, which are measured in %. This is particularly useful in order to model oil refineries, where a more modern and flexible refinery will have wider limits on the shares, or where a refinery with a *coker*¹³⁸ would reduce the shares of heavy products and increase the shares of light ones.
- $ECOVCC_{ce,te}$: (ECONomic Variable Costs of CE), represents the variable O&M costs (only economic private costs, no externalities or other public costs considered) of producing each unit of output TE in each conversion process CE. They are therefore measured in €/MWh. It should be reminded that the variable fuel costs of electricity generation (or oil refining) are not considered within the CE itself, but at a national level when accounting for imports or domestic energy production, which in any case yields an equivalent result when looked from a broad national perspective, which is the one adopted in this thesis (of course it is not the same from the perspective of the electric utility).

¹³⁷ Water is very relevant, for instance, in thermal power plants where it is used for refrigeration.

¹³⁸ A *coker* is a special unit/process that, when installed in a refinery, allows for a deeper transformation of heavy products into lighter ones.

- $CO2EFCE_{ce,te}$: (CO₂ Emissions Factor in this CE), represents the per unit CO₂ emissions of producing each unit of output TE in each conversion process CE. They are measured in tCO₂/MWh. It is applied to the output of the process. For the moment we have only modelled CO₂ emissions, but other gasses or pollutants could be included by creating analogous input parameters.
- $CEFIXEDPROD_{ce,te,p,s,l}$ and $CEFIXEDTECONS_{ce,te,p,s,l}$: (CE FIXED PRODUCTION or CE FIXED CONSUMPTION). The model gives the opportunity to establish, through these parameters, a fixed production of a type of final energy TE in a CE or a fixed consumption of a TE in a CE. However, these parameters must be used with great care because if not correctly coordinated with other model's parameters (such as possible energy flows, CE capacity constraints, CE's efficiencies or CE input and output share limitations) they may make the optimization problem infeasible. This could have also been implemented as minimums and maximums.

V.5.5. PE Parameters

- $PEDOMCONSCAP_{pe}$: (PE DOMESTIC CONSUMPTION CAPACITY). Used in order to model the maximum capacity of domestic primary energy production, measured in GW. This can be used for limiting, for instance, the amount of domestic coal used by the model if it needs to be constrained through power and not through energy (for example, to establish that the maximum domestic coal mining capacity is 4GW). In order to limit it through energy, the next parameter should be used.
- $PEMAXECONSYEAR_{pelimey}$: (PE MAXIMUM ENERGY CONSUMPTION per YEAR). Represents the maximum amount of this type of primary energy that can be consumed by the energy system in a year, measured in GWh. It is only applied to the elements of the "*pelimey*" subset. It can be useful, for example, to limit the total amount of biomass consumed by the energy system, trying to model the maximum biomass availability in the country in a year. For hydro, a monthly limitation is done, as seen below.
- $ECOVCPEDOM_{pe}$: (ECONOMIC VARIABLE COST of PE DOMESTIC), represents the private economic costs (no externalities or other social costs are considered here) of producing each unit of domestic primary energy within the country. Measured in €/MWh. It can, for example, model the cost of domestic coal mining or of biomass production. This value should be null for hydro, wind and solar energies.
- $CO2PEDOMEF_{pe}$: (CO₂ PE DOMESTIC EMISSIONS FACTOR), represents the unitary CO₂ emissions from the domestic production of primary energy, measured in tCO₂/MWh. It is applied to the output of the process. This parameter is especially useful for modelling emissions from activities such as gas flaring in oil and gas production (not applicable for now in the case of Spain, but this could be useful to model other countries). As an interesting line for future research, methane emissions could be included in the model through an analogous parameter, which could be relevant for coal mining and gas drilling, for instance when hydraulic fracturing (i.e. *fracking*) is used.

- $PEID_{pe}$: (PE Import Dependence), determines how much of this PE consumption within the country is imported, expressed in %. For example, in the case of Spain, this parameter would be 100% for oil, natural gas, or imported coal but 0% for wind energy or domestic coal. The imported share will be treated as imports, with the limitations and prices that will be explained below under the EI (i.e. Exports/Imports) sections. To the remaining share (i.e. domestic), the above parameters are used to impose production limitations (PEDOMCONSCAP and/or PEMAXECONSYEAR), associated costs (ECOVCPEDOM) or produced emissions (CO2PEDOMEF).
- $HYDRONRGMONTH_p$: (HYDRO eNeRGy per MONTH), represents the water availability (i.e. total hydro energy available for electricity generation) in each period of the year (in this case, in each month). It is measured in GWh, and this energy is used in those plants that the Spanish Transmission System Operator (Red Eléctrica de España, REE) considers “Régimen Ordinario”, which mainly include large hydro plants, some of them being run-off-the-river and the rest having some reservoir capacity (each share is defined by the next parameter). The amount of hydro energy used by mini-hydro power plants (“Régimen Especial”) is not included in this parameter (they are modelled with a yearly load factor which is internally modified to account to the monthly variation implied in this water availability parameter). Normally this parameter is set to the values reported by REE for the studied year, or if it is a year in the future, a reasonable hypothesis is that it will follow the average hydraulic year.
- $RURIVNRGSHARE_p$: (RUN-off-the-RIVER eNeRGy SHARE). As mentioned in the previous paragraph, available hydro energy is used by the model for the run-off-the-river and for the reservoir (large) power plants. This parameter establishes the share of energy that, each month, is used in run-off-the-river plants. The currently-used value (42% in the case of Spain) has been calculated with historic data, and represents that in each month, 42% of the total hydro energy available for electricity generation is used in run-off-the-river plants, whereas the rest is used in plants with reservoir capacity.

V.5.6. EI Parameters

The acronym EI stands for Exports/Imports, denoting that these parameters are used for modelling the energy system’s energy trade with external regions.

- $TEIMPCAP_{rg,te}$: (TE IMPort CAPacity), represents the maximum imported energy of final energy TE from region “*rg*”. It is implemented as a capacity limitation, measured in GW, because it makes more sense in order to model electricity and gas interconnections, which are (in the Spanish case) the most relevant ones. However, this could also be applied for instance to imports of oil products. If data is only available in energy terms, this parameter can be obtained dividing by the duration of the corresponding period of time.
- $TEIMPCOST_{rg,te}$: (TE IMPort COST), the import cost of each unit of final energy TE from region “*rg*”, measured in €/MWh. It will probably be the wholesale price of each type of energy in each region, adding the transport costs to Spain (use CIF terms instead of

FOB¹³⁹). As said, the modelling of international energy markets done in our MASTER models is exogenous, and this is why these parameters are given as data.

- $TEEXPCAP_{te,rg}$: (TE EXPort CAPacity), represents the export capacity of final energy TE measured in GW to region “*rg*”. Once again, it is implemented as a capacity limitation because it makes more sense in order to model electricity and gas interconnections.
- $TEEXPVE_{te,rg}$: (TE EXPort REVENue), the export revenue of each unit of final energy TE to region “*rg*”, measured in €/MWh. In this case, the wholesale price of this energy type in the region should be used, but here without considering transportation costs (FOB terms instead of CIF).
- $PEIMPCAP_{rg,pe}$: (PE IMPort CAPacity), contains the import capacity of primary energy measured in GW from region “*rg*”. As said, our modeling hypothesis is that liquefied natural gas (LNG) is considered as a PE, and natural gas (not liquefied) is considered as TE so that the regasified LNG can be exported/imported from/to the gas network, which is where LNG regasification terminals (a type of CE process) deliver their output.
- $PEIMPCOST_{rg,pe}$: (PE IMPort COST), the import cost of each unit of PE from region “*rg*”, measured in €/MWh. The same issues explained above (i.e. CIF terms vs. FOB terms) apply.
- $PEEXPCAP_{pe,rg}$: (PE EXPort CAPacity), the export capacity of PE measured in GW to region “*rg*”.
- $PEEXPVE_{pe,rg}$: (PE EXPort REVENue), the export revenue of each unit of PE to region “*rg*”, measured in €/MWh. The same issues explained above (i.e. CIF terms vs. FOB terms) apply.

V.6. DECISION VARIABLES

The main decision (i.e. independent) variables in MASTER_SO belong to the seven groups detailed next:

- The capacities in the CE processes, both the new installed capacity decided by the model (independent variable “ $NEWINSTALLCAP_{proc}$ ”), and the previously installed active capacity (independent variable “ $PREVACTIVECAP_{proc}$ ”) that it decides to use (as said, it can choose not to have some of the previously installed capacity active, saving its fixed O&M costs). These variables are measured in GW and defined as positive and not mathematically bounded by any upper limitation in their algebraic definition (which in

¹³⁹ These acronyms, frequently used in the maritime transport sector, mean “Cargo, Insurance and Freight” and “Free On Board”, and represent two ways of measuring the value (price) of a cargo, either including the cargo, the insurance and the shipping costs, or only the cargo costs. The former can be seen as the cost for the importer, and the latter as the revenue for the exporter.

GAMS is done through the “.up” statement). Of course, once the complete model is solved, these variables will be bounded in some way or another by the applied constraints (e.g. maximum potentials, possible financial or industrial limitations, etc.).

- The amount of reserves (variable “CEELERSRVPWR_{proc,p,s,l}”, standing for CE ELEctricity ReSeRve PoWeR) that each CE is providing in each time slice of the year. Given the definition of the optimization problem, this variable will only take positive values for the centralized electricity generation technologies (i.e. those affected by the reliability constraints). These variables are measured in GW and defined as positive and not mathematically bounded by any upper limitation in their algebraic definition (but will of course be bounded by the constraints of the problem).
- The level of application of Energy Service Variation Measures (“ESVMLVL_{esvm}”, standing for ESVM LeVeL), which for each ESVM can vary from 0% to 100% (i.e. from not applied to fully applied). As said, if fully applied, the full cost of the ESVM will be accounted for in the objective function and its full effects on energy services (either increasing or decreasing them) will be considered. These variables are adimensional and can take values from 0 to 1, to represent in per-unit terms the percentages said above (i.e. they are defined as positive and bounded to an upper value of 1).
- The activity level in each ESST (i.e. Energy Service Supply Technology) in each time slice of the year (independent variable “QACTESST_{esst,p,s,l}”, standing for Quantity of ACTivity in this ESST). As said, each ESST must consume final or primary energy to have a non-null activity level, and through that activity, the ESST produces one or more energy services, also creating some usage costs (non energy-related) in the objective function. These activity variables are measured for each ESST in its own activity units, and are defined as positive and not mathematically bounded by any upper limitation in their algebraic definition.
- As said, we have also modelled the possibility of shifting energy demand between different time slices within the year (without involving any reduction/increment in the total demand for energy services in the year, or any change in the type of energy used or in the total energy demanded in the complete year). Each ESST can operate in three modes: no load shifting allowed, intradaily or intraweekly shifting. Instead of an actual load shifting, we have modeled this as if the ESST was accumulating/releasing energy, because it was more convenient from our modeling perspective and it produced equivalent results. It is as if a washing machine whose load is shifted from 8pm (peak time) to 3am (off-peak time), instead of actually being turned on at 3am, still works at 8pm but with electricity accumulated at 3am the previous day (this will be better understood later, when the energy balances in ESSTs are presented). There are two independent variables which, for each ESST and in each time slice of the year, represent the accumulated and the released energy (“ESSTLS_ACC_{proc,esst,p,s,l}” and “ESSTLS_RLS_{proc,esst,p,s,l}”, standing for ESST Load Shifting ACCumulation and ESST Load Shifting ReLeaSe). They are defined for each time slice of the year (hence the use of the “p”, “s” and “l” indexes) and for all types of primary/final energies (hence the use of the

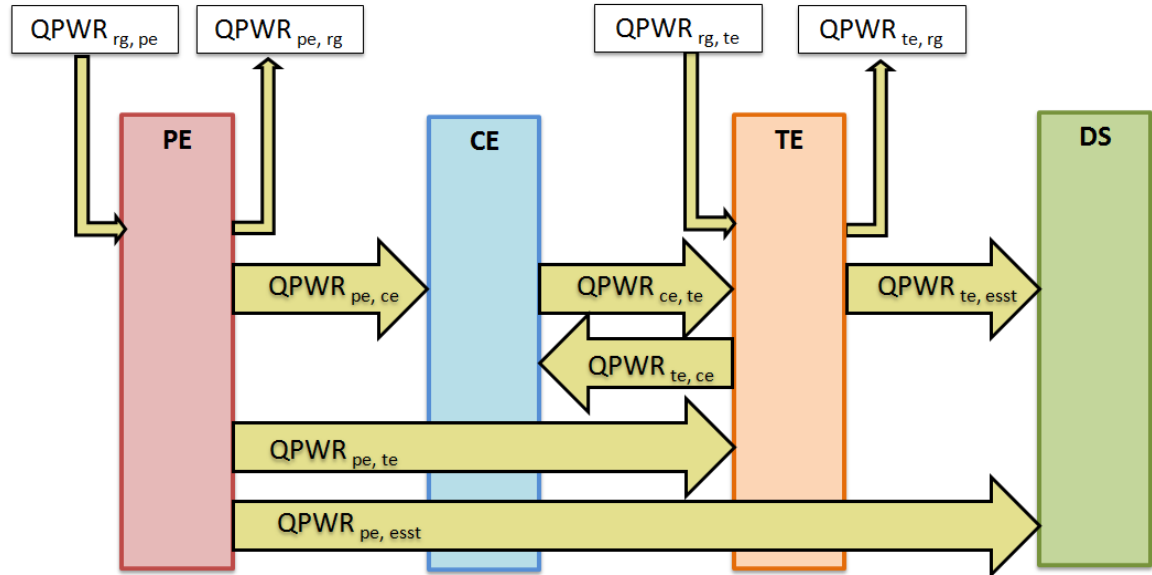
“*proc*” indexes), which will then be limited to the actual consumed energy types by the TE2QACTESST and TE2QACTESST parameters of each ESST. These variables are measured in GW and defined as positive and not mathematically bounded by any upper limitation in their algebraic definition. When they take positive values, an intradaily or intraweekly (depending on each ESST’s working mode) energy balance is imposed (see below), and the (possible) cost of load shifting (i.e. the loss of utility) is accounted for in the objective function.

- As said, the model can decide to use unsupplied energy, but it is highly penalized in the objective function (i.e. it does not represent the lost utility due to non served demand, but it is rather a slack variable to avoid infeasibilities). The level of unsupplied final energy in each ESST (expressed in power terms) is another independent variable of the model (“QPWRNS_{proc,esst,p,s,l}”, standing for Quantity of PoWeR Non Supplied). These variables are also calculated for every time slice of the year (i.e. for every period, subperiod and load level). They are measured in GW and defined as positive and not mathematically bounded by any upper limitation in their algebraic definition.
- Finally, and very importantly, the useful energy flows expressed in power terms (“QPWR_{proc,proc,p,s,l}”, standing for Quantity of PoWeR) from one process to another in the energy supply chain (i.e. the Sankey diagram). They can be interpreted both as energy or power flows because, as they are defined for each individual time slice, the conversion from one to another is simply done by dividing/multiplying by the duration of the time slice. It should be remembered that the order in the two first subscripts “*proc, proc*” represents the sense of the energy flow, because these variables are defined as positive. These variables are measured in GW, calculated for every time slice of the year (i.e. for every period, subperiod and load level), and are defined as positive and not mathematically bounded by any upper limitation in their algebraic definition. As said, these variables are only allowed to be defined (e.g. have a non-null value) for the possible energy flows introduced to the model through the double sets mentioned in section V.4.5. The graphical representation of the allowed energy flows including imports and exports (of both primary energy PE and final energy TE), which was already introduced in Chapter 4, is reproduced again¹⁴⁰ for the reader’s convenience in Figure 65. A list of the flows represented in the figure follows, where the subsets “*p*”, “*s*” and “*l*” have been omitted for greater simplicity. It should be reminded that these energy flows, in the mathematical definition of the model are expressed in power terms (i.e. GW) for each individual time slice.

¹⁴⁰ With a minor modification with respect to the one in Chapter 4: the flows reaching final energy use do not really go to the demand sectors “*ds*”, which are not actual processes, but to the ESSTs, which are the processes that are actually consuming the energy. The subscripts of two arrows have been changed accordingly. This was not done in the original figure for clarity in the explanation in Chapter 4.

- a) $QPWR_{rg,pe}$: quantity of primary energy “pe” from region “rg”. This is used both for imported energy and for domestic energy production (in this case the region is the domestic region “dr”).
- b) $QPWR_{pe,rg}$: quantity of exported primary energy “pe” to region “rg”.
- c) $QPWR_{pe,ce}$: quantity of primary energy “pe” used in conversion process “ce”. Only defined over the “peceflows” double set.
- d) $QPWR_{pe,te}$: quantity of primary energy “pe” directly transported to final uses through “te”. Only defined over the “peteflows” double set.
- e) $QPWR_{ce,te}$: quantity of final energy flowing from “ce” to “te”. Only defined over the “ceteflows” double set.
- f) $QPWR_{te,ce}$: quantity of final energy of type “te” used in conversion “ce”. Only defined over the “teceflows” double set.
- g) $QPWR_{rg,te}$: quantity of imported final energy “te” from region “rg”.
- h) $QPWR_{te,rg}$: quantity of exported final energy “te” to region “rg”.
- i) $QPWR_{te,esst}$: quantity of final energy “te” used in end use technology “esst”. Only defined over the “tefeflows” double set.
- j) $QPWR_{pe,esst}$: quantity of primary energy “pe” used in end use technology “esst”. Only defined over the “pefeflows” double set.
- k) $QWPR_{te,te}$: even if this flow is not represented in the figure, it represents the quantity of final energy flowing between two “te” processes. Only defined over the “teteflows” double set.

Figure 65: generalized representation of the allowed power flows within our modeling framework.
 Source: own elaboration



V.7. CONSTRAINTS

V.7.1. Constraints in DS

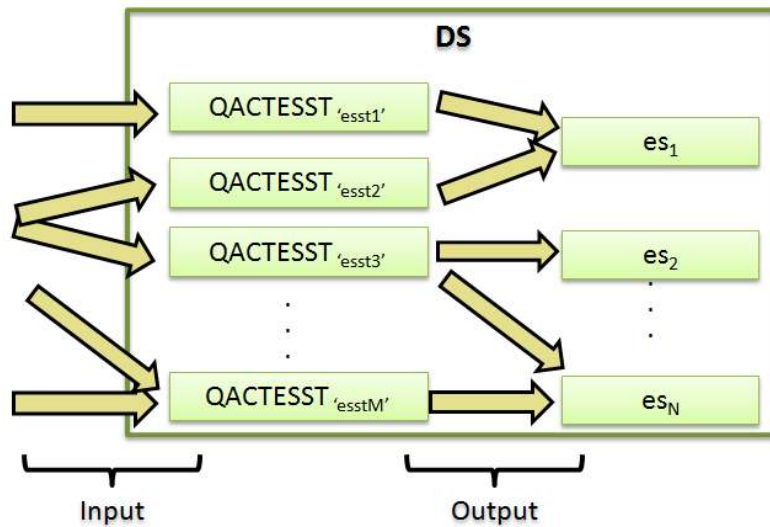
In this section, the constraints in demand sectors are presented. It should be reminded that, as can be seen in Figure 66, each demand sector DS (e.g. land transportation, residential, commercial, etc.) is composed of a number of demanded energy services ("es1", "es2", ... "esN"), and a number of Energy Services Supply Technologies ("esst1", "esst2", "esst3", ... "esstM"). For example, the road transportation demand sector has several energy services (e.g. urban passenger mobility, interurban passenger mobility, international freight mobility, etc.) and it is composed of several ESSTs (e.g. diesel cars, gasoline cars, plug-in-hybrid cars, bikes, motorcycles, vans, trucks, etc.).

Each ESST has an input and an output side. In the input, it consumes energy (final or primary) to have some internal activity level ($QACTESST$) which then is converted into some supply of energy services in its output. The $TE2QACTESST$ and $PE2QACTESST$ parameters establish how much of each type of final or primary energy (TE or PE) is needed to create a unit of activity in each ESST, hence these parameters affect its input side. Then, the $QACTESST2ES$ parameter establishes how much of each energy service (ES) is produced in the output of an ESST per each unit of activity. Of course, the (internal) activity level is what links the input and the output.

As can be seen in the figure, each ESST can consume one or more types of final or primary energy, and can produce one or more energy services. For instance, a plug-in-hybrid car can consume either gasoline or electricity, and it can produce both urban and interurban passenger mobility, of course with different conversion factors (more efficiently in the interurban case).

What matters is that the balances both in the input and the output sides are respected. These balances, and other constraints used to model the demand sectors in MASTER_SO, are explained in the next sections.

Figure 66: example of how a demand sector *DS* is composed of a number of *ESs* and *ESSTs*.
 Source: own elaboration



V.7.1.a. Energy services supply in each Demand Sector

This constraint models that, in each demand sector *DS*, the demand for every energy service (net of energy service variation measures, *ESVMs*, which can reduce or increment it) must be *completely* supplied (we say *completely* because the possibility of leaving unsupplied demand has been modelled on the *input* side of the *ESSTs*, as will be explained in the next section). This demand will be supplied by the sum of all *ESSTs* (within the *DS*) that are able to provide that energy service through their internal activity. Each *ESST* supplies an energy service (*ES*) if two conditions are met: (i.) the *ESST* has a positive activity level, and (ii.) it has a positive value in the $QACTESST2ES_{esst,es}$ parameter (which relates the activity in each *ESST* to each *ES*). These constraints can be seen as the balances in the *output* of *all* the *ESSTs* within each *DS*, and they are expressed in each energy service's units. For instance, the complete demand for the energy service *residential hot water* must be totally supplied, by the addition of the activities (multiplied by the corresponding $QACTESST2ES$ factors) in all technologies supplying residential hot water (e.g. solar thermal panels, diesel boilers, gas boilers, electric boilers, etc.). If for instance one of those technologies is not used (e.g. diesel boilers, due for instance to a limit on residential emissions), the other three technologies will have to increase their activity until the full demand is supplied (because the $QACTESST2ES$ are externally fixed hence they cannot modify their value).

$\forall ds, esbds (es, ds), p, s, l :$

$$\sum_{essts(esst, es)} QACTESST_{esst, p, s, l} \cdot QACTESST2ES_{esst, es} > \\
ESDEMY_{es, ds} \cdot ESDEMLOADC_{es, p, s, l} + \\
\sum_{esvmves(esst, es)} ESVMVLV_{esvm} \cdot ESVMEFFECT_{esvm, es} \cdot ESVMLOADC_{esvm, p, s, l} \cdot ESDEMY_{es, ds}$$

[each ES units]

For every demand sector ds , for each energy service es belonging to this ds (as defined by “ $esbds$ ”) and for every time slice (all combinations of p , s and l):
sum of ES units given by all ESSTs supplying it (activity · $QACTESST2ES$) must be greater than the demand for this energy service in this time slice ($ESDEMY \cdot ESDEMLOADC$) plus the increments (or decrements) in the demand for this energy service caused by all applied ESVMs which modify this ES (as given by “ $esvmves$ ”): their application level (0 to 1) · its effect (positive or negative, as a % of the yearly demand for the ES) · the load curve of the effects of each ESVM (representing how much is the effect in each time slice) · $ESDEMY$ (to convert this whole term from % to ES units, such as the rest of the equation).

[Eq. 1]

NOTE: the “greater” formulation (instead of “equal”) is used to avoid infeasibilities, which would be produced in the case of an ESST supplying two ESs (with fixed proportions because $QACTESST2ES$ are fixed parameters) and the problem being tight on both: let’s assume for example the case where, in order to provide an energy service “ES1” it needs to increase the activity level in the ESSTs supplying it, but one of those ESSTs also produces a second energy service “ES2” which is already completely provided. If we used an “equals” formulation in this constraint, the model would be infeasible in this case. In this (unlikely) case the “greater” formulation allows for some spillover on one of the ESs, avoiding the infeasibility. These effects are very small and they tend not to happen, because they represents a worsening of the objective function (i.e. the model tends to make them “equal” instead of “greater”).

V.7.1.b. Balances energy – activity, in each ESST

As opposed to the previous constraint (which was formulated for all ESSTs providing each energy service), this constraint is formulated for each individual ESST. It represents that each ESST must consume enough final or primary energy (TE or PE) in order to have the activity level required to produce the energy services that it is supplying (as said, the internal activity links the input to the output of each ESST). This constraint has the same units as the activity in each ESST (e.g. vehicles-kilometre in the case of cars), and not energy service units (e.g. passengers-kilometre in the case of cars), as the previous constraint did. If an ESST has several TE or PE inputs, it uses each of them in the proportion defined through data parameters ($TE2QACTESST$ and $PE2QACTESST$). As seen before, this does not allow us to represent flexi-fuel end-use technologies or efficiency improvements but it allows us to avoid the product of two variables (in order to maintain the linear programming nature of our model). As said above, if the global energy efficiency of an ESST in providing each energy service needs to be calculated, it is given by the combination (through the *activity* variable) of this and the previous constraint. More precisely it can be obtained by multiplying the $QACTESST2ES$ and $TE2QACTESST$ or

PE2QACTESST parameters, carefully considering the units and taking into account when more than one energy type is consumed or when more than one energy service is produced.

Two more issues are represented in the constraint described in this section. First, non-served demand has been represented here (instead of in the previous constraint) for a simple reason: to have all non-served demand in uniform energy units (instead of in the units of each energy service e.g. passenger-kilometers, liters of hot water, units of space heating, etc.). We assume that the energy services are *fully* provided by ESSTs (no unserved energy services, as seen in the previous section), hence the used ESST's all have enough activity levels. But these activity levels can be produced through consuming energy, or through consuming a "non-supplied energy" commodity, which is very highly penalized in the objective function, using the NSFECOST parameter. This non-supplied energy has energy units, and hence we can easily assign it a familiar penalisation value (in €/MWh), or we can compare non-served energies among different demand sectors (all of them in energy units such as GWh), which would be harder if they were expressed in energy services units (e.g. non-served passengers-kilometres vs. non-served litres of hot water). This representation would also allow, in further research, to include realistic (i.e. lower) values for non served demand in different sectors and/or ESSTs (e.g. between 200 and 5000 €/MWh in the electricity sector) and for different energy vectors, trying to actually represent the utility produced given to it by energy consumers. This would give the model the possibility of leaving unserved demand if the costs of supplying it are larger than the utility given to it by demand, and using different values for different sectors and/or energy types would allow the model to prioritise between them.

The second issue represented in this constraint is load shifting which (as said) is modelled as if the ESST was accumulating/releasing energy, because it was more convenient from our modeling perspective and it produced equivalent results. Instead of modelling a shift in the energy service demand itself, we model it through a shift in the energy that the ESST consumes for supplying that demand, which is equivalent. It is as if a washing machine whose load is shifted from 8 pm (peak time) to 3 am (off-peak time), instead of actually being turned on at 3am, still works at 8 pm but with electricity accumulated at 3am the previous night. As can be seen in the equation below, there are two independent positive variables that, for each ESST, for each energy type it is consuming, and in each time slice of the year, represent the accumulated and the released energy ("ESSTLS_ACC" and "ESSTLS_RLS"), in GW. As defined in the equation, an ESST can decide to consume more power at an off-peak time slice than the one needed to produce its internal activity (and through it, energy services), and hence accumulate that extra power (ESSTLS_ACC being positive). Even if the activity is null (i.e. in this time slice there is no need to supply any energy service by this ESST), the process could consume power and accumulate it all. The accumulated power can then be released in a peak-period when it is needed to supply an energy service and hence consume less (or even none) actual power (QPWR being reduced). Of course, an energy accumulation-release balance must be imposed, which is explained in the next section. From the upstream energy system perspective, this is equivalent to the demand for energy service being actually shifted from peak to off-peak, which was not the case. This is only allowed to happen in ESSTs where the ESSTLSPOSTE or ESSTLSPOSPE parameters are non-null.

Lastly, as it will be seen next, for modeling reasons this constraint is actually split into two complementary constraints, one for the final energies (TE) and one for primary energies (PE). It is the application of both at the same time that produces the desired mathematical relation.

$\forall ds, esstbds(esst, ds), teesstflows(te, esst), p, s, l:$

$$\begin{aligned} QACTESST_{esst,p,s,l} &= TE2QACTESST_{esst,te} \cdot D_{p,s,l} \\ &\cdot [QPWR_{te,esst,p,s,l} + QPWRNS_{te,esst,p,s,l} \\ &+ (ESSTLS\_RLS_{te,esst,p,s,l} - ESSTLS\_ACC_{te,esst,p,s,l})] \quad [ESST \text{ activ. units}] \end{aligned}$$

$\forall ds, esstbds(esst, ds), peesstflows(pe, esst), p, s, l:$

$$\begin{aligned} QACTESST_{esst,p,s,l} &= PE2QACTESST_{esst,pe} \cdot D_{p,s,l} \\ &\cdot [QPWR_{pe,esst,p,s,l} + QPWRNS_{pe,esst,p,s,l} \\ &+ (ESSTLS\_RLS_{pe,esst,p,s,l} - ESSTLS\_ACC_{pe,esst,p,s,l})] \quad [ESST \text{ activ. units}] \end{aligned} \quad [Eq. 2]$$

For all demand sectors, all ESSTs belonging to each DS, all TEs supplying this ESST, and for all time slices:

The level of activity in this ESST (measured in ESST's activity units) must be equal to: the conversion parameter from TE energy (not power in this case) to this ESST's activity (units activ. ESST/GWh) multiplied by the duration (hours), multiplied by the total power creating activity in this ESST (GW). This total power is the sum of the actual power flowing to the ESST (QPWR) plus the "non-supplied energy" commodity (in GW terms), plus the net energy being released (released - accumulated), which models load shifting. Load shifting is only allowed in each ESST if its ESSTLSPOSTE or ESSTLSPOSPE parameters are non-null, as will be seen next.

The same analogous constraint applies to primary energies.

V.7.1.c. Load shifting limitations in each ESST

This constraint establishes, for each ESST, if load shifting can take place (with its consumption of primary or final energy). This is established respectively by the ESSTLSPOSTE or ESSTLSPOSPE parameters, which can take values 0, 1 or 2, meaning respectively no load shifting allowed, intradaily load shifting or intraweekly load shifting. The energy accumulation-release balance will be different in each case, as seen next. Also, as happened in the previous section, two separate constraints are imposed, one for final energies and one for primary energies. Each load shifting will have an associated cost (utility losses) accounted for in the objective function through the ESSTLSCOST parameter. A non-null cost should be applied to *all* ESSTs where load shifting is allowed to take place. This value should be the actual utility losses

due to demand shifting, or if no utility losses are implied, a very small penalisation, which would prevent the model from accumulating and releasing energy at the same time in a same ESST, which would not make sense. This small penalisation would create a (small) cost and not bring any benefit to the system (because its net energy effect is null), so the optimisation would not choose to do it.

$\forall \text{ esst}, \text{teesstflows}(te, \text{esst}), p, s, l :$ $D_{p,s,l} \cdot \text{ESSTLS\_ACC}_{te, \text{esst}, p, s, l} = 0 \quad \text{if } \text{ESSTLSPOSTE}_{\text{esst}} = 0$ $\sum_l D_{p,s,l} \cdot (\text{ESSTLS\_ACC}_{te, \text{esst}, p, s, l} - \text{ESSTLS\_RLS}_{te, \text{esst}, p, s, l}) = 0 \quad \text{if } \text{ESSTLSPOSTE}_{\text{esst}} = 1$ $\sum_{s,l} D_{p,s,l} \cdot (\text{ESSTLS\_ACC}_{te, \text{esst}, p, s, l} - \text{ESSTLS\_RLS}_{te, \text{esst}, p, s, l}) = 0 \quad \text{if } \text{ESSTLSPOSTE}_{\text{esst}} = 2$ [GWh] $\forall \text{ esst}, \text{peesstflows}(pe, \text{esst}), p, s, l :$ $D_{p,s,l} \cdot \text{ESSTLS\_ACC}_{pe, \text{esst}, p, s, l} = 0 \quad \text{if } \text{ESSTLSPOSPE}_{\text{esst}} = 0$ $\sum_l D_{p,s,l} \cdot (\text{ESSTLS\_ACC}_{pe, \text{esst}, p, s, l} - \text{ESSTLS\_RLS}_{pe, \text{esst}, p, s, l}) = 0 \quad \text{if } \text{ESSTLSPOSPE}_{\text{esst}} = 1$ $\sum_{s,l} D_{p,s,l} \cdot (\text{ESSTLS\_ACC}_{pe, \text{esst}, p, s, l} - \text{ESSTLS\_RLS}_{pe, \text{esst}, p, s, l}) = 0 \quad \text{if } \text{ESSTLSPOSPE}_{\text{esst}} = 2$ [GWh] <i>For each ESST processes, for each final energy type consumed by it, in all time slices: If the ESSTLSPOSTE parameter in the ESST is null, no load shifting is allowed so the accumulation variable is null (this makes the release variable to be automatically null as well, because it is the one with the cost associated); if the parameter is 1, a intradaily energy balance must be met; if it is 2 an intraweekly daily balance must be met. The same applies to load shifting of primary energies. These constraints have energy units.</i>	[Eq. 3]

V.7.1.d. Exclusion of Energy Services Variation Measures

As introduced above, some ESVMs are mutually exclusive. By this we mean that if an ESVM is implemented, another one may be excluded, e.g. if we improve the windows of a house to the CTE standard (Spanish recent Building Code “Código Técnico de Edificación”) we cannot improve them to a Passive House standard *at the same time*. We have done this through an ESMV exclusion constraint, explained here. Mutually-exclusive ESVMs are grouped in exclusion groups (the multiple set “*esvmexcl*”). The sum of the levels of application of all the ESVMs within each group cannot be greater than 100%. This represents that, for instance, 60% of the windows in Spain can be improved to the CTE standard while the other 40% to the Passive House one, or 70% and 30%, but both ESVMs must add 100% as maximum. Of course, less is also allowed (e.g. 20% and 10%), if the measures are not convenient from an optimization perspective.

$\forall esvmexcl(esvm) :$

$$\sum_{esvmexcl(esvm)} ESVMLVL_{esvm} < 1 \quad [p.u.]$$

[Eq. 4]

For all ESVM exclusion groups, the sum of all the application levels of all ESVMs within each group cannot be greater than 100%.

V.7.2. Constraints in TE

V.7.2.a. Energy balance in each transport process

Energy balances must be correctly met in every transport process in all time slices. These balances are expressed in power (e.g. GW) terms, which is equivalent because they are imposed on every time slice. A related hypothesis has to be explained here: energy exports are also considered for calculating losses, i.e. they do not cancel imports. If in a moment there is the same value of export as imports, it is assumed that this amount of energy travels through the whole grid and thus, produces lost energy.

$\forall te, p, s, l :$

$$TOTQTEIN_{te,p,s,l} - QLTE_{te,p,s,l} = TOTQTEOUT_{te,p,s,l} \quad [GW] \quad \text{where:}$$

$$\begin{aligned} TOTQTEIN_{te,p,s,l} &= \sum_{peteflows(pe,te)} QPWR_{pe,te,p,s,l} + \sum_{ceteflows(ce,te)} QPWR_{ce,te,p,s,l} \\ &+ \sum_{tete flows(te',te)} QPWR_{te',te,p,s,l} + \sum_{rg} QPWR_{rg,te,p,s,l} \end{aligned}$$

$$QLTE_{te,p,s,l} = TELF_{te} \cdot TOTQTEIN_{te,p,s,l}$$

$$\begin{aligned} TOTQTEOUT_{te,p,s,l} &= \sum_{teceflows(te,ce)} QPWR_{te,ce,p,s,l} \\ &+ \sum_{teflows(te,esst)} QPWR_{te,esst,p,s,l} \\ &+ \sum_{tete flows(te,te')} QPWR_{te,te',p,s,l} + \sum_{rg} QPWR_{te,rg,p,s,l} \end{aligned}$$

[Eq. 5]

For all transportation processes in all time slices:

Total incoming power – losses = total outgoing power, measured in GW, where:

Total incoming power is the sum of power from all PE, CE and TE processes, plus imports,

losses is the losses factor applied to the total incoming power, and

total outgoing power is the sum of power to all CE, ESST and TE processes, plus exports

V.7.2.b. Capacity constraint in each transport process

The total incoming power to a transportation process cannot be greater than its capacity. This is an important convention in our model: the capacity limitation in TE processes is applied to the input flows to the process, as opposed to the capacity limitation in CE processes, applied to the output (as will be seen later).

$\forall te, p, s, l :$ $TOTQTEIN_{te,p,s,l} < TECAP_{te} \quad [GW]$ <i>For all transportation processes in all periods of time: Total incoming power < TE process's capacity (Total incoming power is described in the previous constraint)</i>	[Eq. 6]

V.7.3. Constraints in CE**V.7.3.a. Power balance in each conversion process**

Power balances must be correctly met in every conversion process in all time slices. The only exception is in the pumping storage power plant process, which accumulates energy in some time slices to release it in others, and therefore does not comply with this condition. Its specific constraint is shown later.

$\forall ce, p, s, l \ / \ ce \neq "CE \text{ Pumping Storage}" :$ $TOTQCEIN_{ce,p,s,l} - QLCE_{ce,p,s,l} = TOTQCEOUT_{ce,p,s,l} \quad [GW] \quad \text{where:}$ $TOTQCEIN_{ce,p,s,l} = \sum_{pe \in flows(pe,ce)} QPWR_{pe,ce,p,s,l} + \sum_{te \in flows(te,ce)} QPWR_{te,ce,p,s,l}$ $QLCE_{ce,p,s,l} = CELF_{ce} \cdot TOTQCEIN_{ce,p,s,l}$ $TOTQCEOUT_{ce,p,s,l} = \sum_{te \in flows(ce,te)} QPWR_{ce,te,p,s,l}$ <i>For all conversion processes except pumping storage, in all time slices: Total incoming power – losses = total outgoing power, where: Total incoming power is the sum of power from all PE and TE processes, losses is the losses factor applied to the total incoming power, and total outgoing power is the sum of power to all TE processes.</i>	[Eq. 7]

V.7.3.b. Share limitations in power flows outgoing from CE processes

As previously mentioned, one CE process can produce more than one flow of final energy TE. This is typical of oil refineries, which produce gasoline, diesel, kerosene, fuel oil or LPGs, among others. In this case, the total output TOTQCEOUT is defined as the sum of all of them. These next constraints limit the maximum and minimum shares that each individual outgoing

flow can represent in the total output. This is done through the above-mentioned CEMAXTEOUTSHARE and CEMINTEOUTSHARE parameters. These constraints are only defined over the allowed *ceflows*, in order to reduce the size of the problem¹⁴¹.

As defined above:

$$\forall ce, p, s, l: \quad TOTQCEOUT_{ce,p,s,l} \\ = \sum_{ceflows(ce,te)} QPWR_{ce,te,p,s,l}$$

$\forall ceflows(ce, te), p, s, l :$

Maximum share limitation:

$$QPWR_{ce,te,p,s,l} < TOTQCEOUT_{ce,p,s,l} \cdot CEMAXTEOUTSHARE_{ce,te} \quad [GW]$$

Minimum share limitation:

$$QPWR_{ce,te,p,s,l} > TOTQCEOUT_{ce,p,s,l} \cdot CEMINTEOUTSHARE_{ce,te} \quad [GW]$$

For all CEs and TEs linked by an allowed energy flow, in all time slices:

Each TE flow coming out of the CE must be smaller than the maximum allowed by the maximum share limit, and bigger than the minimum allowed by the minimum share limit.

[Eq. 8]

V.7.3.c. Share specifications in power flows incoming to CE processes

As previously mentioned, in producing each unit of output, a CE process can use more than one flow of incoming energy, be it primary energy (PE) or final energy (TE). The shares of each PE or TE that a process must use in order to produce each unit of output are specified with the above-mentioned CEINSHAREPE and CEINSHARETE parameters, which are used in these constraints. These constraints are only defined over the allowed relevant flows.

¹⁴¹ This would not be strictly necessary because GAMS pre-solver eliminates the irrelevant equations. However, we have done it.

As defined above:

$$TOTQCEIN_{ce,p,s,l} = \sum_{pe \in flows(pe,ce)} QPWR_{pe,ce,p,s,l} + \sum_{te \in flows(te,ce)} QPWR_{te,ce,p,s,l}$$

PE share definition:

$\forall pe \in flows(pe,ce), p, s, l$:

$$QPWR_{pe,ce,p,s,l} = TOTQCEIN_{ce,p,s,l} \cdot CEINSHAREPE_{ce,pe} \quad [GW]$$

[Eq. 9]

TE share definition:

$\forall te \in flows(te,ce), p, s, l$:

$$QPWR_{te,ce,p,s,l} = TOTQCEIN_{ce,p,s,l} \cdot CEINSHARETE_{ce,te} \quad [GW]$$

PE share: for all PEs linked by an allowed energy flow to each CE, in all periods of time: the power from each PE must be equal to the share in total input defined by CEINSHAREPE.

TE share: for all TEs linked by an allowed energy flow to each CE, in all periods of time: the power from each TE must be equal to the share in total input defined by CEINSHARETE.

V.7.3.d. Energy conservation in the pumping storage power generation process

The pumping storage electricity generation process ("CE Pumping Storage") is assumed to be pure pumping storage, i.e. no natural hydro inflows. Therefore, the amount of generated electricity in each day must be equal to the amount of consumed electricity for pumping water in that same day, considering the efficiency of the pumping storage – power generation process. In other words, as said before, daily pumping storage regime has been assumed, which is a reasonable hypothesis for the Spanish case in a future with higher penetration of intermittent generation (this has been contrasted with experts from the Spanish Transmission System Operator, Red Eléctrica de España). Additionally, it has been assumed that these power plants are connected to the centralised electricity grid, that is, to "TE Electricity Centralised".

$\forall p, s$:

$$\begin{aligned} \sum_l (QPWR_{"CE Pumping Storage", "TE Elec Centr", p, s, l} \cdot D_{p, s, l}) \\ = \sum_l (QPWR_{"TE Elec Centr", "CE Pumping Storage", p, s, l} \cdot D_{p, s, l} \\ \cdot CEHYPSTORCYEF) \quad [GWh] \end{aligned}$$

[Eq. 10]

For all days of the year (for all periods and subperiods):

Total energy (power · duration) generation flowing to the centralised electricity grid during the day (all load levels) =

Total energy (power · duration) absorption from to the centralised electricity grid during the day (all load levels), multiplied by the efficiency of the pumping storage cycle (normally 70%)

V.7.3.e. Energy conservation in hydro power plants with reservoir capacity

In the hydro power plants with reservoir capacity, the amount of generated electricity in each month must be equal to the availability of hydro energy in that same month, as given for each month through the above-described external parameter HYDRONRGMONTH, which directly corresponds to the monthly values reported by the Spanish Transmission System Operator (Red Eléctrica de España). This implies the hypothesis that no water is kept from one month to another. This may be a hard hypothesis, which prevents our model to be able to use, for instance, water from mild and humid spring months where electricity demand is not very high due to mild temperatures (e.g. april) to generate electricity in hot and dry summer months where electricity demand for air conditioning is very high (e.g. july). This is open for improvement by further research. Within each month, however, the model freely decides when to generate electricity, which typically will be in high demand periods, where the most expensive power plants would have to produce otherwise. As explained in detail above (when the external parameters for hydro characterisation were introduced), the amount of hydro energy available each month is calculated from the HYDRONRGMONTH parameter. It includes the total hydro energy used in both the reservoir capacity and the run-off-the river power plants. Hence to calculate the monthly water availability for reservoir capacity ones, the amount of hydro energy used by run-off-the-river power plants must be subtracted first, as done below with the RURIVNRGSHARE parameter. As was the case with pumping storage, it is assumed that these power plants are connected to the centralised power grid.

$\forall p :$

$$\sum_{s,l} (QPWR_{"CE Hydro Reservoir Capacity", "TE Elec Centr", p, s, l} \cdot D_{p, s, l}) =$$

$$HYDRONRGMONTH_p \cdot (1 - RURIVNRGSHARE_p) \quad [GWh]$$

[Eq. 11]

For all months of the year (for all periods):

Total energy (power · duration) generation flowing to the centralised electricity grid during the month=

Total hydro energy available for reservoir capacity power plants (subtracting the share of hydro energy used by run-off-the-river power plants)

V.7.3.f. Energy conservation in run-off-the-river hydro power plants

Run-off-the-river hydro power plants produce a constant amount of electricity all the time, which only depends on how much water is flowing down the river. In this model, the hypothesis is that this water flow variations are only from month to month, and are given with the water availability parameter explained above. Of all this available hydro energy in each month, the share of run-off-the-river energy is expressed by RURIVNRGSHARE. Afterwards this monthly run-off-the-river energy is divided within the month's time slices so that the produced power is constant in all of them. As done with pumping storage and reservoir capacity hydro power plants, it is assumed that these power plants are connected to the centralised power grid.

$\forall p, s, l :$ $QPWR_{"CE Hydro Run-off-the-river", "TE Elec Centr", p, s, l} = \frac{HYDRONRGMONTH_p \cdot RURIVNRGSHARE_p}{\sum_{s, l} D_{p, s, l}} \quad [GW]$ <i>For all months of the year (for all periods), in each time slice (subperiod and level):</i> <i>Power generated in run-off-the-river plants (in GW) =</i> <i>Total hydro energy available for run-off-the-river power plants in the month (considering only the share of hydro energy used by run-off-the-river power plants), in GWh</i> <i>divided by the duration of the month, in hours.</i>	[Eq. 12]

V.7.3.g. CE processes' capacity limitations

Each CE process must comply with a main capacity limitation: its outgoing power flow (of all types of final energy produced) cannot be bigger than its total active capacity. The term *total* means that it can be either previous capacity or new investments decided by the model. The term *active* implies that it must be capacity that is activated by the model in order to be used, and therefore, its fixed O&M costs are accounted for in the total costs of the system. If the model decides to not activate some old capacity, in order to save its fixed O&M costs (i.e. hibernation or mothballing), this capacity cannot produce any output. It is assumed that all newly installed capacity is active (otherwise it would not make sense, from the optimization perspective, to invest in it). From another perspective, the electricity generation processes affected by the reliability constraints (*reserves* and *adequacy*) may have to have some idle capacity (active but not producing electricity) providing reserves to the system (for more detail on these reliability constraints see below). Therefore, as shown next, the addition of total output power plus idle capacity providing reserves cannot be greater than the total active capacity of the process. Finally, it is important to insist that in CE processes the capacity limitation is applied to the output (contrary to TE processes, where it was in the input).

As defined above: $\forall ce, p, s, l: \quad TOTQCEOUT_{ce,p,s,l} = \sum_{ce \in flows(ce,te)} QPWR_{ce,te,p,s,l}$ $\forall ce, p, s, l :$ $TOTQCEOUT_{ce,p,s,l} + CEELERSRVPWR_{ce,p,s,l} < TOTACTIVECAP_{ce} \quad [GW]$ $TOTACTIVECAP_{ce} = PREVACTIVECAP_{ce} + NEWINSTALLCAP_{ce} \quad [GW]$ $PREVACTIVECAP_{ce} < CEPREVCAP_{ce} \quad [GW]$ $TOTACTIVECAP_{ce} < CEMAXACTIVECAP_{ce} \quad [GW]$ For all conversion processes, in all time slices of the year: Total output of power + idle capacity providing reserves (GW) < Total active capacity (GW) Total active capacity (GW) = Previous capacity activated + new installed capacity (GW) Previous capacity activated by the model (GW) < Previous capacity given through data (GW) Total active capacity (GW) < Maximum active capacity given through data (GW)	[Eq. 13]

V.7.3.h. Reserves constraint for electricity generation CEs

In the operation of large power systems, some reliability conditions must be met at all times for their smooth and secure functioning. For a good explanation on the subject see (Batlle et al., 2007). In this model, as anticipated, these conditions are summarised in two constraints: an *adequacy* constraint (models the *adequacy* and *firmness* elements from the referred paper) and a *reserves* constraint (equivalent to their *security* element). These are explained in this section and the next one. Let's start with the reserves constraints. In power systems, there is always a degree of uncertainty in the load that generators have to provide. This is mainly due to the lack of precision in demand forecasting, the possibility of failure in power plants, or the uncertainty of power generation from intermittent sources such as wind. The physics of power systems imply that load and generation must be in balance all the time, so if there is a sudden imbalance (for example because of a coal power plant's failure or an unforeseen increase in demand or decrease in wind production), some power plants must be able to increase their output instantly. The same happens in the opposite sense: if, for example, wind production ramps up or demand drops suddenly, the output of other power plants must be decreased immediately. The first case is called "upwards reserve" (capacity ready for increasing its output), while the second is "downwards reserve". The first is normally bigger because, in addition to the uncertainty in demand or intermittent generation, it must account for the possibility of failure in a large power plant. In this model, only upwards reserve is considered, which implies the hypothesis that all power plants generating at every moment are able to decrease their output instantly and therefore provide enough downwards reserve at all times. This is also a conservative hypothesis given that, as said, upwards reserve is normally larger. In conclusion, the constraint modelled here establishes the need for flexible, active and idle capacity to provide upward reserve in the power system. The term *flexible* means that this capacity must be able to increase its output very fast. At the same time, this capacity must be *active* (therefore its fixed O&M costs are computed in the system's costs) but *idle*, that is not producing energy at full

capacity, so that it can increase its output. This capacity must be, in all instants, greater than the need for upward reserves in the system, which is calculated adding the uncertainty in demand, the uncertainty in intermittent power generation technologies (i.e. those belonging to the “*celoadf*” subset, such as wind), and the capacity of the largest power plant that could fail. This constraint is only applied to the CE processes affected by the electricity reliability constraints, that is, the elements of the “*ceececentral*” set (i.e. the centralised power generation plants).

$\forall p, s, l :$

$$\sum_{ceececentral} (CEELERSRVPWR_{ce,p,s,l} \cdot CEFLEXIBILITY4RSRV_{ce}) > \\ CELARGCECAP4RS \\ + \\ \left(\sum_{teesstflows("TE Elec Centr", esst)} QPWR_{"TE Elec Centr", esst, p, s, l} \right) \cdot CEDEMAVGPRERR4RSRV \\ + \\ \left(\sum_{celoadf} (TOTACTIVECAP_{ce} \cdot CELOADFACTORP_{ce,p}) \right) \cdot CELOADFAVGPRERR4RSRV \\ [GW]$$

[Eq. 14]

For all time slices:

Total reserve of the system (idle capacity of *ceececentral* processes providing reserves, multiplied by their flexibility factors) >

Possibility of large plant failure (largest power plant capacity) +

Demand prediction uncertainty (centralised electricity demand · average prediction error) +

Uncertainty in intermittent power production (total production of intermittent sources, the ones modelled with load factors · average prediction error)

Note: CELOADFACTORP is the load factor in each period. For all technologies excepting minihydro it equals the yearly data CELOADFACTOR. For minihydro, as said, it is modified with the monthly water availability parameter, but keeping as average the yearly value given through data.

V.7.3.i. Adequacy constraint for electricity generation CEs

The second reliability constraint (the *adequacy* one) is explained now. In large power systems, there is the need for enough capacity to be installed in order to cover peak demand. Indeed, there is normally some excess capacity called *reserve margin*, for the system's capacity not to be too tight at any moment. The percentage of the installed capacity of a technology that can be considered with high probability (e.g. 90%) to be available to produce electricity when the system needs it is called *capacity credit* (we also call it *firmness factor*, even if some authors may consider it as a different issue). By multiplying this factor and the installed capacity of a technology, the *firm capacity* is obtained. For instance, in this model, wind power is assumed to have a capacity credit (i.e. firmness factor, in our terminology) of 7.5%: each 1000 MW of

installed capacity provides the system with 75MW of firm capacity. This means that of each GW of wind power, the system can only count (with a high probability of, for instance, 90%) on 75MW of production at critical times. This adequacy constraint imposes that the firm capacity in the system must be greater than the maximum yearly demand (peak demand) multiplied by the required reserve margin (for instance 10% excess capacity over peak demand).

$\sum_{ce \in ceelecentral} (TOTACTIVECAP_{ce} \cdot CEFIRMNESS4ADEQ_{ce}) >$ $(1 + CERESMRG4ADEQ) \cdot MAXDEMYR_{TE Elec Centr} \quad [GW]$ <i>The total firm capacity (total active capacity · capacity credit) of technologies affected (elements of the ceelecentral set) > Peak demand of central electricity increased by the reserve margin (CERESMRG4ADEQ).</i> <i>The peak demand is the maximum yearly value of the total demand of centralised electricity in all demand sectors (fixed as an external parameter).</i>	[Eq. 15]

V.7.3.j. Production in CE processes modelled with load factors

Some CE elements are modelled with load factors, as stated above (e.g, wind or solar power generators). These elements belong to the “celoadf” subset. This constraint, using the CELOADFACTOR parameter, establishes the production of each of these processes.

$\forall celoadf, p, s, l :$ $TOTQCEOUT_{ce,p,s,l} = TOTACTIVECAP_{ce} \cdot CELOADFACTORP_{ce,p} \quad [GW]$ <i>For all CE processes modelled with load factors, in all time slices:</i> <i>Total outgoing power = CE process's total active capacity · monthly load factor.</i> <i>Note: CELOADFACTORP is the load factor in each period (month). For all technologies except for minihydro it equals the yearly data CELOADFACTOR. For minihydro, as said, it is modified with the monthly water availability, but keeping as average the prescribed yearly value.</i>	[Eq. 16]

V.7.3.k. Minimal production of regasification terminals

As said, regasification terminals have a technical minimum value (expressed as a percentage of their capacity) below which they should not work. This value represents the minimum production level that allows the boil-off gas (i.e. BOG) to be recovered, while all installations are kept cold and 100% available in stable functioning conditions (ENAGAS, 2010). To see how this minimum level has been calculated, refer to the Data Documentation Annex.

$\forall p, s, l:$ $QPWR_{CE Regasification, TENatural Gas, p, s, l} > TOTACTIVECAP_{CE Regasification} \cdot MINREGAS \quad [GW]$ <i>For the benchmark regasification terminal, in all time slices:</i> <i>Total outgoing power > Regasification total active capacity * minimum level</i>	[Eq. 17]

V.7.4. Constraints in PE

V.7.4.a. Power balance in each primary energy process

Power balances must be correctly met in every primary energy process in all time slices. The main idea behind the primary energy process modelling is that all actually used (i.e. physical) primary energy used in the energy system (be it for conversion in CE processes, for delivery to TE processes, for direct final use in ESST processes, or for exports) must come either from domestic primary energy production or from primary energy imports (depending on level of import dependence established in the PEID parameter). No unserved energy is allowed here (contrary to the case of demand sectors). Primary energy exports will normally not take place in energy-importing countries such as Spain, but the modelling allows it in any case.

$\forall dr, pe, p, s, l$: $TOTQPEOUT_{pe,p,s,l} = QPWR_{dr,pe,p,s,l} + \sum_{rg} QPWR_{rg,pe,p,s,l} \quad [GW] \quad \text{where:}$ $TOTQPEOUT_{pe,p,s,l} = \sum_{peceflows(pe,ce)} QPWR_{pe,ce,p,s,l} + \sum_{peteflows(pe,te)} QPWR_{pe,te,p,s,l} + \sum_{peesstflows(pe,esst)} QPWR_{pe,esst,p,s,l} + \sum_{rg} QPWR_{pe,rg,p,s,l}$ $QPWR_{dr,pe,p,s,l} = (1 - PEID_{pe}) \cdot TOTQPEOUT_{pe,p,s,l}$ <i>For all primary energy processes in all periods of time (and in the domestic region dr): Total output power (i.e. the total primary energy used by the system in that moment) = Domestic primary energy (power flowing from the domestic region dr to the PE process) + Primary energy imports from all regions. These terms are defined as follows: The total output power is the addition of the power used in CE processes, the one delivered to TE processes, the one directly used in ESSTs, and the exported primary energy. The domestic primary energy is the share of outgoing PE power that is not imported, as established by the PEID (Primary Energy Import Dependence) factor.</i> <i>NOTE: having to define this restriction over the domestic region makes no difference because there is only one domestic region. It is only for coherent modelling.</i>	[Eq. 18]

V.7.4.b. Domestic PE production capacity limitation

The amount of primary energy production in the country can be limited, in power terms, through this constraint.

$\forall dr, pe, p, s, l :$ $QPWR_{dr,pe,p,s,l} < PEDOMCONSCAP_{pe} \quad [GW]$ <i>For all primary energy processes in all periods of time (and in the domestic region dr): The power produced domestically < domestic primary energy consumption capacity</i> <i>NOTE: having to define this restriction over the domestic region makes no difference because there is only one domestic region. It is only for coherent modelling.</i>	[Eq. 19]

V.7.4.c. PE consumption energy limitation

The total amount of primary energy consumption in the country can be limited through this constraint, which is only applied to the elements of the “*pelimey*” subset. It is important to understand the two differences between this restriction and the previous one: (i.) the previous one limits domestic energy, whereas this one limits all primary energy consumption, be it imported or domestic; and (ii.) the previous one is expressed in power terms for all time slices whereas this one is expressed as total yearly energy. These constraints are especially useful in order to limit the use of primary energies whose yearly availability is restricted, such as biomass or solid waste (hydro limitation is implemented in other constraints as explained before).

$\forall pelimey :$ $\sum_{p,s,l} (TOTQPEOUT_{pe,p,s,l} \cdot D_{p,s,l}) < PEMAXECONSYEAR_{pelimey} \quad [GWh]$ <i>For all PE processes with limited energy in the year (i.e. belong to the “pelimey” subset): The total consumed energy off this type throughout the complete year (power · duration) < yearly energy limitation.</i>	[Eq. 20]

V.7.5. Constraints in EI

These constraints establish that the amount of imported/exported energy, both primary and final (expressed in power terms) cannot exceed the interconnection capacities. This will be especially relevant for the cases of electricity and gas, but it could also be applied to any other commodity (e.g. limitations in ship change/discharge capacities). Since the administrative and political processes behind increasing interconnection capacities are quite complex, we have for the moment considered interconnections (both electric and gas) to be fixed at the levels forecasted by the latest infrastructure plans by the European Commission and the Spanish Government. In other words, the model cannot invest in increasing these capacities, which could be interesting from the optimization perspective if they are active constraints and the benefits of new investments exceed the costs. However, this would be an interesting future research line, especially if also associated with the enhanced capacity to integrate renewables (which would need an enhanced modeling of their variability) or the reliability provided to the system by

V.7. Constraints

increased interconnections (as should be if the recent European guidelines on the Internal Energy Market are implemented).

V.7.5.a. PE import capacity limitation

The imported PE power cannot be bigger than the import capacity.

$\forall pe, rg, p, s, l :$ $QPWR_{rg,pe,p,s,l} < PEIMPCAP_{pe,rg} \quad [GW]$ <i>For all regions, primary energy processes, and time slices in the year:</i> <i>Imported power < import capacity.</i>	[Eq. 21]

V.7.5.b. PE export capacity limitation

The exported PE power cannot be bigger than the export capacity.

$\forall pe, rg, p, s, l :$ $QPWR_{pe,rg,p,s,l} < PEEXPCAP_{pe,rg} \quad [GW]$ <i>For all regions, primary energy processes, and time slices in the year:</i> <i>Exported power < export capacity.</i>	[Eq. 22]

V.7.5.c. TE import capacity limitation

The imported TE power cannot be bigger than the import capacity.

$\forall te, rg, p, s, l :$ $QPWR_{rg,te,p,s,l} < TEIMPCAP_{te,rg} \quad [GW]$ <i>For all regions, energy transportation processes, and time slices in the year:</i> <i>Imported power < import capacity.</i>	[Eq. 23]

V.7.5.d. TE export capacity limitation

The exported TE power cannot be bigger than the export capacity.

$\forall te, rg, p, s, l :$ $QPWR_{te,rg,p,s,l} < TEEXPCAP_{te,rg} \quad [GW]$ <i>For all regions, energy transportation processes, and time slices in the year:</i> <i>Exported power < export capacity.</i>	[Eq. 24]

V.7.6. Constraints to avoid unrealistic solutions

Since MASTER_SO is a linear optimization model, it may result in extreme (i.e. knife-edge) solutions (as explained in Chapter 3, this refers to a situation when a certain technology happens to dominate all other alternatives and, because of the linear characteristics of the model, from an optimization perspective the model will use it far more of what would be realistic, since saturation cannot happen). This is because diverse nonlinear factors that play a substantial role in the decisions of the agents may not be correctly taken into account in the objective function (e.g. psychological, sociological, political, etc.) An example could be the fact that our model, under certain scenarios, tends to decide that all urban passenger mobility should be provided by bikes or motorbikes. This is because (as happens in reality) we have imposed an occupation factor of cars in these trips of 1.2 passengers/vehicle, which is quite close to the factors for motorcycles or bikes (1 passenger/vehicle), but the former use much more energy and are more expensive technologies (from the point of view of their non-energy utilization costs, i.e. ESSTCOSTPACTUY). Hence the model only uses bikes or motorbikes for urban trips. On the one hand, this is indeed quite logical. What is the point of using cars for short urban trips when a large share of the space within the car is empty? On the other hand, however, it is unrealistic, because in reality people do choose to behave like they do, for many other reasons such as comfort or security. Another tendency that we have observed is the overutilization of buses, much more than what is observed in reality. Again, their high capacity makes them more beneficial than cars from the optimization perspective, even if it may be unrealistic.

Trying to capture some of these effects within an objective function is an interesting line of research, which is currently being addressed (only for the transportation sector) in another PhD thesis within the BP Chair on Energy and Sustainability. Our approach has been, however, simpler: we have added some constraints that try to make the model use the affected technologies within reasonable limits (the inclusion of penetration curves could be a line for further research). However, we believe that it is key to be sure about these values, to be well aware of the effects that these constraints may have in the complete problem (for which sensitivity analyses may be crucial) and to be fully transparent about our doubts in using these values. Indeed, we think that further research in this aspect of our model would be needed.

We will not mathematically describe these constraints here, because they are all quite simple and similar to each other: they limit (either as a maximum or a minimum) the share of an energy service that can be supplied by some of these technologies ($\text{ActivityESST} * \text{QACTESST2ES} / \text{total ES demand}$). However, they are all enumerated here:

- Limit the share of urban mobility provided by bikes or motorbikes to 30%. This value has been obtained from (Greenpeace, 2011).
- Limit the share of metropolitan mobility provided by motorbikes to 30%.

- Limit the share of urban mobility provided by urban, metropolitan or interurban buses to 20%. This value has been obtained from (Ministerio de Medio Ambiente y Medio Rural y Marino et al., 2011).
- Establish a minimum use of metro in urban use of 10%. This value has been obtained from (Greenpeace, 2011).
- Limit the share of metropolitan, interurban and national mobility provided by trains to 10%. This value has been obtained from (Greenpeace, 2011).
- Establish a minimum use of high-speed train in long distance land mobility of 15%. This value has been obtained from (Fundación de los Ferrocarriles Españoles & Ministerio de Fomento, 2011).
- Limit the share of internal and international land freight mobility provided by trains to 5%. This value has been obtained from (Fundación de los Ferrocarriles Españoles & Ministerio de Fomento, 2011).
- Limit the share of long distance passenger mobility provided by planes to 40%. This value has been obtained from (Greenpeace, 2011).

V.7.7. Policy constraints

The current version of MASTER_SO has been prepared with data representing the year 2030. We have introduced all input parameters (e.g. demands for energy services, technological availabilities and costs, international primary and final energy prices, forecasted evolution of interconnections, etc.) using data for 2030 obtained from many different sources (refer to the Data Documentation Annex). But our 2030 scenario would not be complete without some representation of what we believe will be the policy scenario in that year. We have assumed some business-as-usual policy constraints, which are introduced in our reference scenario of the MASTER_SO model. These are the following:

V.7.7.a. Use of renewables in final energy

The European 2020 objectives establish a 20% share of renewables in final energy use. Currently, the European Commission is working on the European objectives for 2030 (European Commission, 2013), so we do not have yet a legally binding document about that year. However, we already have an indication of how 2050 would look: we have considered the “Diversified Supply Technologies” scenario of the European 2050 Energy Roadmap (European Commission, 2011b), which may imply a use of around 60% of renewables in final energy consumption. For 2030 we have assumed a 30% penetration level, which implies an acceleration of the adoption of renewables towards the end of the temporal horizon (we think this is reasonable because by then fossil fuels will be more expensive and renewables more cost competitive, as most reputed institutions are forecasting). In conclusion, with this constraint we impose that at least a 30% of total energy use in ESSTs must come from renewable sources (be it renewable-based electricity, biofuels, all types of biomass, or solar thermal).

Related to this policy, and to the next one, we have also considered the current Spanish Buildings Technical Code (“Código Técnico de Edificación”), which establishes the obligation of installing solar photovoltaic panels and solar thermal collectors for water heating in new buildings (PV only in commercial buildings, solar thermal in both commercial and residential). We have used these obligations and a projection of new building activity after the present crisis (Instituto para la Diversificación y Ahorro de la Energía, 2011b) to estimate the installed capacity (and, for solar thermal, the amount of produced hot water), which are then introduced to the model as another set of policy constraints.

V.7.7.b. Use of renewables in electricity generation

Concerning renewable electricity, for Spain, the 2020 objectives on renewables in final energy use translate into a 42% renewables in electricity generation (which is calculated by considering the share of electricity in final energy use). Using the same sources and hypothesis as before (European objectives for 2050, where the power sector will have to be fully decarbonised, although with some participation of nuclear and maybe carbon capture and storage), we have assumed a 75% penetration of renewables in power generation for 2050. With a linear interpolation we come to an approximate value of 52% in 2030, which is imposed through this constraint.

However, if only this constraint was introduced, the model would only use some renewable technologies (the least-costly ones, given our pure cost-minimisation problem). This is not the case in reality, where the Government normally establishes binding objectives per technology, in order to ensure a distributed effort amongst all technologies. Even if this may increase the cost of complying with the policy objectives of minimum renewables, it may (or not) make sense from a broader political viewpoint: it could ensure diversification and activity in different industrial sectors, but it could also bring some other undesirable effects. These objectives per technology are normally established in the national “Renewable Energy Plan” (Instituto para la Diversificación y Ahorro de la Energía, 2011a), which establishes the 2020 objectives for Spain. We have used it as a basis to calculate a scenario for objectives per technology in 2030 to be imposed as a set of constraints (one per technology). These objectives are: 2.5 GW of mini-hydro (of less than 10 MW per plant), 11.4 GW of solar photovoltaic (both on roofs and ground-based), 9.8 GW of solar thermoelectric, 52.1 GW of onshore wind, 1.65 GW of offshore wind, 2.33 GW of biomass, and 0.3 GW of solid waste. We have not modeled geothermal or biogas.

V.7.7.c. Emissions reduction

Another important policy objective that we have introduced is a limitation on the level of total CO₂ emissions produced in the complete Spanish energy system. Looking at forecasted values for Spain in 2020, which comply with our European commitment (Ministerio de Medio Ambiente y Medio Rural y Marino, 2011a), and establishing a trend for the 2050 objectives (80% reduction below 1990 levels, which we have assumed translated as such to Spain, although this may not be the case after the political negotiations and burden sharing), we have come to a total yearly value of around 180 million tonnes of CO₂ in 2030. Just for illustrative purposes, when

applied to the MASTER_SO model, this yields a CO₂ price (shadow price of this limiting constraint) of 47.4 €/tCO₂, in the same order of magnitude with expected values from latest official projections. This value would be significantly higher (around 107€/tCO₂) should the above-described constraints of minimum renewable use were not imposed: as known, renewable promotion puts downwards pressure on carbon prices.

V.8. OBJECTIVE FUNCTION

As stated, the objective function to be optimised should be a quantitative measurement of the sustainability of the energy system. Depending on what is considered as a *sustainable* energy supply for the country in a year, different objective functions could be defined. In this version of the model, we have implemented a minimisation of total private economic costs of energy supply plus the social cost of carbon emissions. We have also included a term in which the non-energy usage costs of final energy use technologies are accounted for, and also a penalisation for unsupplied energy.

The optimisation model minimises the full objective function (measured in million €¹⁴²), whose expression is presented next. Note that most of the terms are positive (i.e. costs), but there are two negative ones, which represent revenues gained via exports of either primary or final energy.

¹⁴² We actually use €'2010, to correctly account for the inflation between now and 2030.

$\min \{ \text{DOPECONSCOST} + \text{DOPECOEMCOST} + \text{PEIMPORTCOST} - \text{PEEXPORTREVE} + \\ \text{CECONVERCOST} + \text{CECONVEMCOST} + \text{CELERSRVCOST} + \text{ACAPFIXDCOST} + \\ \text{NCAPINVSCOST} + \text{TETRANSPCOST} + \text{TETRANEMCOST} + \text{TEIMPORTCOST} - \\ \text{TEEXPORTREVE} + \text{FEUEMISSCOST} + \text{ESVMPROMOCOST} + \text{ESSTLSTOTCOST} + \\ \text{ESSTACTTOTCOST} + \text{NONSUPFECOST} \quad [M\text{€}]$	[Eq. 25]

$\min \left\{ \begin{array}{l} \text{Domestic primary energy production cost} \\ + \text{Domestic primary energy production emissions social cost} \\ + \text{Primary energy imports cost} \\ - \text{Primary energy exports revenue} \\ + \text{Energy conversion variable cost} \\ + \text{Energy conversion emissions social cost} \\ + \text{Cost of the provision of electricity reserves by generators} \\ + \text{Active conversion capacity fixed cost} \\ + \text{New CE capacity investment cost (annuity)} \\ + \text{Energy transportation cost} \\ + \text{Energy transportation emissions social cost} \\ + \text{Final energy imports cost} \\ - \text{Final energy exports revenue} \\ + \text{Final energy use emissions social cost} \\ + \text{Energy service variation measures promotion costs} \\ + \text{Utility losses associated to load shifting in ESSTs} \\ + \text{Non energy usage costs of ESSTs (of their activity)} \\ + \text{Non supplied energy cost (penalisation)} \end{array} \right\} \quad [\text{in M€}]$	[in M€]

V.8.1. Domestic primary energy production cost

This term contains the cost of producing energy domestically, i.e. in the domestic region “rg”. This is useful to model for instance the costs of coal mining or biomass production. It is assumed to included all associated costs (i.e. investment, fixed, variable or others), accounted for as an average per-energy-unit value.

$\text{DOPECONSCOST} = \sum_{dr,pe,p,s,l} (QPWR_{dr,pe,p,s,l} \cdot D_{p,s,l} \cdot ECOVCPEDOM_{pe}) \quad [M\text{€}]$ <i>Domestic primary energy cost</i> =energy (power · duration) produced in the country in the year (flowing from the domestic region “dr”) multiplied by the per unit energy production cost	[Eq. 26]

V.8.2. Domestic primary energy production emissions social cost

This term represents the social cost of CO₂ emitted in domestic primary energy production. As said, the emissions factor is applied to the output of the process.

$DOPECOEMCOST = CO2PRICE \cdot \sum_{pe,p,s,l} (EMPE_{pe,p,s,l} \cdot D_{p,s,l}) \quad [M\text{€}]$ Where: $EMPE_{pe,p,s,l} = QPWR_{dr,pe,p,s,l} \cdot CO2PEDOMEF_{pe} \quad [tCO_2/h]$ Domestic primary energy production emissions social cost=Social cost of carbon, as represented by CO2PRICE multiplied by the total emissions produced in primary energy production.	[Eq. 27]

V.8.3. Primary energy imports cost

$PEIMPORTCOST = \sum_{rg,pe,p,s,l} (QPWR_{rg,pe,p,s,l} \cdot D_{p,s,l} \cdot PEIMPCOST_{pe,rg}) \quad [M\text{€}]$ Primary energy imports cost = imports from each region (power · duration) · import cost from that region	[Eq. 28]

V.8.4. Primary energy exports revenue

$PEEXPORTREVE = \sum_{pe,rg,p,s,l} (QPWR_{pe,rg,p,s,l} \cdot D_{p,s,l} \cdot PEEXPREVE_{pe,rg}) \quad [M\text{€}]$ Primary energy exports revenue = exports to each region (power · duration) · export revenue from that region	[Eq. 29]

V.8.5. Energy conversion variable cost

Energy conversion variable cost (considers only O&M variable costs, because the costs of fuel are accounted for as imports/domestic energy production costs).

$CECONVERCOST = \sum_{ceteflows(ce,te),p,s,l} (QPWR_{ce,te,p,s,l} \cdot D_{p,s,l} \cdot ECOVCCE_{ce,te}) \quad [M\text{€}]$ Energy conversion variable cost (only O&M costs) = Total amount of energy (power · duration) of each type of TE produced by the process · per unit variable O&M cost of the conversion process	[Eq. 30]

V.8.6. Energy conversion emissions social cost

As said, the emissions factor is applied to the output of the process.

$CECONVEMCOST = CO2PRICE \cdot \sum_{cete \text{ flows}(ce,te),p,s,l} (EMCE_{ce,te,p,s,l} \cdot D_{p,s,l}) \quad [M\text{€}]$ Where: $EMCE_{ce,te,p,s,l} = QPWR_{ce,te,p,s,l} \cdot CO2EFCE_{ce,te} \quad [tCO_2/h]$ Energy conversion emissions social cost=Social cost of carbon, as represented by CO2PRICE multiplied by the total emissions produced in energy conversion (all types of TE in every CE).	[Eq. 31]

V.8.7. Cost of the provision of electricity reserves by generators

This cost element accounts for the cost of having enough reserves in the system to comply with the reserves constraint, as explained above. The per unit cost of providing reserves by each generator is assumed to be equal to its variable O&M cost which, as stated above, does not consider fuel costs. In other words, it is assumed that generators providing reserves to the system are working (and therefore, must pay variable O&M costs) but do not burn any fuel. These generators also have to pay their fixed O&M and investment costs (if more capacity has been added in order to provide reserves), because capacity providing reserves is assumed to be *active* capacity, as will be seen later.

$CELERSRVCOST$ [M€] Where: $\forall ceelecentral: CEELERSRVCOST_{ceelecentral} = ECOVCCE_{ceelecentral, "TE Elec Centr"}$ Cost of the provision of electricity reserves by affected generators (elements of ceelecentral) = Reserves provided by affected generators · duration of those reserves · reserves per unit cost.	[Eq. 32]

V.8.8. Active conversion capacity fixed O&M cost

This term only considers the fixed O&M costs of conversion capacity. The fixed costs of domestic energy production are considered in the “Domestic energy production costs” term. Those of TE processes are considered within the “Energy transportation cost” term, and those of final energy use technologies (i.e. ESSTs) are included in the “Non-energy usage costs of ESSTs” term. Active CE capacity, as seen in the section explaining the “CE processes’ capacity limitations” constraint, contains both the CE capacity producing output energy and the idle capacity producing reserves (in the case of centralised electricity generators). Hence the latter also has to pay fixed O&M costs, as explained above.

$$ACAPFIXDCOST = \sum_{ce} (TOTACTIVECAP_{ce} \cdot ACECAPFIXDCOSTYEAR_{ce}) \quad [M\text{€}] \quad [Eq. 33]$$

Active capacity fixed cost = total active capacity in all affected processes (for the moment just CE) · yearly fixed O&M cost of each unit of active capacity

V.8.9. New CE capacity investment cost (annuity)

As happened in the previous section, this term only considers the investment costs of new conversion (i.e. CE) capacity. The investment costs of domestic energy production are considered in the “Domestic energy production costs” term. Those of TE processes are considered within the “Energy transportation cost” term, and those of final energy use technologies (i.e. ESSTs) are included in the “Non-energy usage costs of ESSTs” term. The CE capacity accounted for here is either used for actual energy production or for reserves’ provision. Given that MASTER_SO is a static model, these investment costs are considered through their annuity, which is computed using the linear amortization method, where the annual payments of investment depreciation are constant all over the asset’s life. As explained before, in the “CE Parameters” section, we have preliminarily used an equal amortization period of 20 years for all technologies. Finally, as also explained above, we have used a 6% risk premium for nuclear, which is then depreciated at a total rate of return of capital of 15%.

$$NCAPINVSCOST = \sum_{ce} (NEWINSTALLCAP_{ce} \cdot NEWICAPINVCOSTYEAR_{ce}) \quad [M\text{€}]$$

Where:

$$NEWICAPINVCOSTYEAR_{ce} = CEAPTOTINVSTCOST_{ce} \cdot \frac{AMORTRATE_{ce}}{\left(1 - \left(\frac{1}{1 + AMORTRATE_{ce}}\right)^{CECAPAMORTYEARS_{ce}}\right)} \quad \left[\frac{\text{€}}{\text{kW} \cdot \text{year}}\right] \quad [Eq. 34]$$

$$AMORTRATE_{ce} = GENAMORTRATE + CECAPRISKPREM_{ce} \quad [\%]$$

New capacity investment cost = new installed capacity in all affected processes · annuity of the investment cost of each unit of new capacity.

This annuity (measured in €/kW in each year) is the linear amortization of the total investment cost (CEAPTOTINVSTCOST), with an interest rate of AMORTRATE and an amortization period of CECAPAMORTYEARS. This AMORTRATE parameter is the addition of the general amortization rate of the market (GENAMORTRATE) and the technology’s specific risk premium (CECAPRISKPREM).

V.8.10. Energy transportation cost

This term is assumed to include all associated costs (i.e. investment, fixed, variable or others) of energy transportation processes (i.e. TEs), accounted for as an average per-energy-

unit value. As said, for the centralised electricity network, we have represented this cost factor through an econometric approach (detailed in the Data Documentation Annex) to account not only for the amount of energy transported (energy term) but also for the installed intermittent capacity, because we believe that the latter plays a non negligible role in total costs. In any case, we have done it only as a first approach to see that the model is able to consider such calculations. Indeed, more research is needed to determine which specific terms and factors should such an expression include, because different effects could take place in different cases: renewable capacity can also reduce total electricity networks costs, or reduce transportation costs while increasing distribution costs, or in some other cases all generation capacity (also non-renewable) may increase network costs, etc. This econometric approach has only been included as a first try. In any case, for future researchers continuing with this work, these econometric expressions should always be linear on the variables of the problem. For the other TEs, only a constant value of cost per unit of delivered energy (i.e. energy term) is used.

$TETRANSPCOST = \sum_{te,p,s,l} (TOTQEIN_{te,p,s,l} \cdot D_{p,s,l} \cdot ECOVCTE_{te}) \quad [M\text{€}]$ Where, as a first tentative: $ECOVCTE_{\text{"TE Ele Centralised"}} = \alpha \cdot TotEnergyTransported + \beta \cdot IntermittentCapacConnected$ Energy transportation costs = Total energy transported in all each processes (total incoming power · duration), multiplied by the per unit transport costs. For the centralised electricity we have for now used a linear econometric expression with an energy term and an intermittent capacity term.	[Eq. 35]

V.8.11. Energy transportation emissions social cost

As said, the emissions factor is applied to the input of the process, differently to the cases of PE and CE.

$TETRANEMCOST = CO2PRICE \cdot \sum_{te,p,s,l} (EMTE_{te,p,s,l} \cdot D_{p,s,l}) \quad [M\text{€}]$ Where: $EMTE_{te,p,s,l} = TOTQEIN_{te,p,s,l} \cdot CO2EFTE_{te} \quad [tCO_2/h]$ Energy transportation emissions social cost= Social cost of carbon, as represented by CO2PRICE multiplied by the total emissions produced in energy transportation (all TE processes).	[Eq. 36]

V.8.12. Final energy imports cost

$TEIMPORTCOST = \sum_{rg,te,p,s,l} (QPWR_{rg,te,p,s,l} \cdot D_{p,s,l} \cdot TEIMPCOST_{te,rg}) \quad [M\text{€}]$	[Eq. 37]
<i>Final energy imports cost = imports from each region (power · duration) · import cost from that region.</i>	

V.8.13. Final energy exports revenue

$TEEXPORTREVE = \sum_{te,rg,p,s,l} (QPWR_{te,rg,p,s,l} \cdot D_{p,s,l} \cdot TEEXPREVE_{te,rg}) \quad [M\text{€}]$	[Eq. 38]
<i>Final energy exports revenue = exports to each region (power · duration) · export revenue from that region.</i>	

V.8.14. Final energy use emissions social cost

This term includes the social cost associated to CO₂ emissions in final energy use (i.e. in energy consumption in ESSTs). The emissions factor is applied to the incoming energy to each ESST (not to the production of energy services), because it is what actually produces emissions (e.g. what creates emissions in a car is not the provision of a mobility service but the fact of burning gasoline), and where data is available.

$FEUEMISSCOST = CO2PRICE \cdot \sum_{ds,p,s,l} (EMFE_{ds,p,s,l} \cdot D_{p,s,l}) \quad [M\text{€}]$	[Eq. 39]	
<i>Where:</i>		
$EMFE_{ds,p,s,l} = \sum_{esstbds(esst,ds)} EMFE\_ESST_{esst,p,s,l} \quad [tCO_2/h]$		
$EMFE\_ESST_{esst,p,s,l} = \sum_{teesstflows(te,esst)} (QPWR_{te,esst,p,s,l} \cdot FEUEMISSFTE_{esst,te})$		
$+ \sum_{peesstflows(pe,esst)} (QPWR_{pe,esst,p,s,l} \cdot FEUEMISSFPE_{esst,pe}) \quad [tCO_2/h]$		
<i>Final energy use emissions social cost=</i> <i>Social cost of carbon, as represented by CO2PRICE, multiplied by the total emissions produced in energy use (all DS sectors), calculated as EMFE (tCO₂/h) multiplied by durations (h). The emission in each DS is the sum of the emissions in all ESST processes belonging to that sector. The emissions in each ESST are calculated as the sum of all the primary and final energies (in power terms, QPWR) used by that technology (measured in GW), multiplied by each energy type's emission factor (tCO₂/GWh).</i>		

V.8.15. Energy service variation measures promotion costs

$ESVMPROMOCOST = \sum_{esvm} ESVMLVL_{esvm} \cdot ESVMCOSTYEAR_{esvm} \quad [M\text{€}]$ <i>The total cost of implementing energy service variation measures (ESVMs) is the sum over all ESVMs of their implementation level (percentages) multiplied by their yearly cost, which is the cost of full (i.e. 100%) implementation in each year, as said above.</i>	[Eq. 40]

V.8.16. Utility losses associated to load shifting in ESSTs

In this term we account for the social costs of load shifting (i.e. energy use displacement). These try to capture the utility losses that load shifting causes to final energy users (e.g. having to put the dishwasher at 3am instead of 10pm). The aim is for the model to not decide to shift load if its costs (in terms of utility losses) are greater than its benefits for the energy system. In order to do this correctly, the crossed price elasticities of demand in different hours should be used, which would allow us to calculate the difference in utility from consuming energy in each hour. The data availability for that is quite limited, especially in our case when we consider many end use technologies (each may have different elasticities, e.g. dishwasher or washing machine) and several energy types (not only electricity). In addition, a more detailed temporal representation is needed (ideally chronological hourly detail), to account not only for the amount of displaced energy but also for how far (in temporal sense) the load has been displaced (i.e. how many hours away). We do not have this temporal detail, either. Hence further research would be needed in this issue.

However, we propose the following preliminary approximation. We will use for now a cost in €/MWh of displaced energy in each ESST, which has been approximated from some informal conversations with researchers working in these issues at our research Institute¹⁴³, and which in any case be easily changed in the input data to the model . We apply this cost to the total yearly amount of energy displaced of each type of energy in each ESST. In order to account correctly for the displaced energy, it will only be done when the ESST is releasing it (to produce energy service), in order to avoid double counting.

As said above, a non-null cost should be applied to *all* ESSTs where load shifting is allowed to take place. If there are no utility losses due to demand shifting (i.e. this cost is null), a very small penalisation should be used in any case. This would prevent the model to accumulate and release energy at the same time in a same ESST, which would not make sense. This small penalisation would create a (small) cost and not bring any benefit to the system because its net energy effect is null, so the optimisation would not choose to do it.

¹⁴³ IIT, Comillas University, Madrid, Spain

ESSTLSTOTCOST

$$= \sum_{esst} \left\{ ESSTLSCOST_{esst} \cdot \left[\left(\sum_{teesstflows(te,esst)} TOTLSTEENERGY_{esst,te} \right) + \left(\sum_{peesstflows(pe,esst)} TOTLSPEENERGY_{esst,pe} \right) \right] \right\} \quad [M€]$$

Where:

[Eq. 41]

$$\begin{aligned} \forall teesstflows(te, esst): \quad & TOTLSTEENERGY_{esst,te} \\ &= \sum_{p,s,l} ESSTLS\_RLS_{te,esst,p,s,l} \cdot D_{p,s,l} \quad [GWh] \\ \forall peesstflows(pe, esst): \quad & TOTLSPEENERGY_{esst,pe} \\ &= \sum_{p,s,l} ESSTLS\_RLS_{pe,esst,p,s,l} \cdot D_{p,s,l} \quad [GWh] \end{aligned}$$

The total cost of load shifting (which represents the utility losses due to load shifting) is calculated as the load shifting costs in each ESST (€ per each MWh displaced), multiplied by the total amount of energy displaced in the year (be it final energy of primary energy). The total amount of energy displaced is calculated as the sum over all time slices of the year of the released energy (which, due to the accumulation-release balances, must have been previously accumulated) measured in GW, multiplied by the duration of the time slice in hours.

V.8.17. Non-energy usage costs of ESSTs

This term, which is normally very significant in the objective function (can easily represent 60-70% of its total) represents the non-energy usage costs of final energy use technologies (including all investment, fixed O&M and variable O&M costs, only excluding energy costs). The energy costs should not be included here for a simple reason: they are calculated by the rest of the model. Infrastructure costs (e.g. of network transportation modes such as metro or train) are as well included. They can be interpreted as all costs of all the vehicles in Spain, all the gas boilers, all the solar thermal panels, all the trains, all the ships, all the busses, etc.

We include investment costs in all of them (i.e. we assume that all of these devices are new investments) for the following reasons. The first one is that we assume that their depreciation is done during their complete technical life, so in ever year where these devices are present, the annuity of their investment costs must also be considered. Second, given that the model is currently prepared with data for 2030 (a year that is still almost two decades away), we can also assume that the complete currently-existing stock of energy use devices will have to be replaced

by then, hence the hypothesis of all the technologies being new investments also seems to make sense (this is only weaker for the case of associated infrastructures, such as railways or metro tunnels, which can last much more than 20 years). Third, the mathematical modelling would have been more complex (including a variable for the usage/scrappage of old devices, another one for newly invested ones, modeling the universe of total needed devices, etc.). Lastly, and very importantly, due to data availability: the alternative would have been to provide the model with the data of the existing stock, and then modelling the investments on new/replacement devices. Data availability for a sensible estimation of the initial (i.e. already existing) stock is very scarce, as the PhD candidate realised this while directing a MSc engineering thesis (Pérez et al., 2012).

Just as an indication of their magnitude, some of our model runs for the Spanish case have resulted in values of the objective functions close to 200 billion €/year, where this term was about 130 billion €/year¹⁴⁴. As said, these non-energy costs are crucial and allow the optimization to consider the trade-off between: (i.) older, energy inefficient and (economically) less costly; and (ii.) modern, more efficient and (presumably) expensive technologies. If these non-energy usage costs were not included, the model would only choose the most energy efficient technologies, without considering their costs. For instance, we would only have electric cars in the streets, much more energy efficient (if the electricity is generated with modern CCGTs and renewables) but presumably more expensive.

The data gathering and calculation for these costs has been very challenging. In the end, we have obtained a cost per each unit of activity in each ESST for each year, in million €. They are calculated as the annualised investment costs as well as all (non-energy) operational costs of each ESST, divided by an average (expected) value for its activity in a year (e.g. in the case of a car they are the annual costs of the car, excluding gasoline, divided by an average yearly mileage, because activity is measured in vehicle-kilometres). More detail on these calculations is provided in the Data Documentation Annex. Once multiplied for the total activity of all ESSTs in all the time slices within the year we obtain this cost term, which is then added to all the other (energy-related) terms in the objective function.

$$ESSTACTTOTCOST = \sum_{esst,p,s,l} ESSTCOSTPACTUY_{esst} \cdot QACTESST_{esst,p,s,l} \quad [M€]$$

[Eq. 42]

The total non-energy costs of ESSTs in the year is calculated as the sum over all ESSTs and time slices of their total activity, multiplied by the cost per each unit of activity in each ESST for each year.

V.8.18. Non supplied energy cost

Finally, this term includes the penalisation of unsupplied energy in the objective function. As said, it is applied to the consumption of the “non-supplied-energy” commodity by all ESSTs, as described above (in the section “Balances energy – activity, in each ESST”).

$NONSUPFECOST = \sum_{ds} NONSUPFECOST\_DS_{ds} \quad [M\text{€}]$ Where: $NONSUPFECOST\_DS_{ds} = \sum_{esstbds(esst,ds),p,s,l} NSFECOST_{esst,ds} \cdot D_{p,s,l} \cdot \left(\sum_{teesstflows(te,esst)} QPWRNS_{te,esst,p,s,l} + \sum_{peesstflows(pe,esst)} QPWRNS_{pe,esst,p,s,l} \right)$ <i>The total cost of unsupplied energy in all sectors is the sum of the costs of unsupplied energy in each sector. This is calculated as the sum over all ESSTs belonging to the sector and over all time slices of the year of the total unsupplied energy in the sector (both final and primary, measured in power terms e.g. GW), multiplied by the duration of each time slice, and by the non-supplied-energy cost (€/MWh), which is set at a very high level in order for this term to become a penalisation in the objective function and not a quantification of utility losses due to non served demand.</i>	[Eq. 43]

V.9. UTILIZATION MODES, OTHER OPTIONS AND COMPUTER IMPLEMENTATION

MASTER_SO is run including all the above-described sets, parameters, variables and constraints and solving it (in its current implementation) in the sense of *minimization* of the objective function (when a more comprehensive sustainability indicator is included as the objective function, it will then be *maximization*). However, other utilization modes and options are possible, which are described next.

V.9.1. Execution modes

The model can be used in three modes:

- Mode 1. Only operation: the model cannot invest in any new capacity, or in demand variation measures. The objective function therefore does not include these two terms. The variables NEWINSTALLCAP and ESVMLVL are set to zero.

- Mode 2. Operation and investment with previously existing capacity: the model can invest in any new capacity or in demand variation measures; hence the objective function includes all terms. The previously installed capacity is given as exogenous input data and, as its investment cost is sunk, it is not considered in the objective function.
- Mode 3. Investment without previous predefined capacity (*Greenfield* case): it represents the case where the full energy system is built from zero. The model can invest in any new capacity, or in demand variation measures. The previously installed capacity is null and the objective function includes all terms.

V.9.2. Other utilization options

Other utilization options are available to the user through internal flags (0/1):

- Consider the social cost of CO₂ emissions ("*CO2EmissCostInObjFunct*" flag): the social cost of CO₂ emissions is only accounted for in the objective function if this option is activated.
- Energy Services Variation Measures allowed ("*ESVMAllowed*" flag): ESVMs application level is obliged to be null for all ESVMs unless this option is activated. If it is not, the full original demand for energy services has to be supplied. If it is activated, energy services can be reduced.
- Load Shifting in ESSTs allowed ("*LSESTAllowed*" flag): load shifting in ESSTs is obliged to be null unless this option is activated.
- Policy constraint maximum emissions in the complete energy system ("*ActivatePolConstrMaxCO2Emiss*" flag): the limitation on total emissions is activated through this flag.
- Policy constraint establishing the minimum renewables share in energy demand and in power generation ("*ActivatePolConstrMinREShare*" flag): the minimum limitations on renewables use (both in final energy use and in power generation) are activated through this flag.
- Policy constraint for minimum use of solar PV and solar thermal derived from Spanish Technical Building Code ("CTE") ("*ActivatePolConstrMinSolarThAndPVCTE*" flag): the minimum limitation on these technologies' use is activated through this flag.
- Policy constraint for minimum renewables installed electricity generation capacity per technology ("*ActivatePolConstrMin2030RenCapPER*" flag): the constraints fixing the minimum installed capacity of each renewable electricity generation technology (one constraint per technology), trying to replicate the continuation of the Renewable Energy Plan, are all activated through this flag.

V.9.3. Computer implementation

MASTER_SO is programmed in GAMS, and solved with CPLEX. With the last level of data detail (the one documented in this PhD thesis), it is a LP model with about 160,000 equations

and 225,000 variables. On a computer with an Intel Core2 Duo processing unit (two processors at 2.4GHz each) and 4 GB of RAM memory, data reading from Excel and model generation takes around 16 seconds, and then it is solved by CPLEX in 12 seconds. The execution time is even smaller for subsequent runs (e.g. if a loop of runs is implemented for scenario analyses), where data reading from Excel is not needed and where CPLEX already starts from a starting point where variables take values close to the solution ones. This makes MASTER_SO a compact and fast model to compute at the same time that it has a fair level of technical detail, partially fulfilling the objectives of this PhD thesis.

V.10. MAIN OUTPUTS

Some of the main outputs that can be obtained from MASTER_SO are:

- The power flows through the complete energy system (either for the complete year or in any of the time slices), allowing us to represent them in Sankey diagrams of the different policy cases as mentioned above;
- Associated to it, all the energy imports and exports, the domestic energy production, the primary and final energy matrixes of the country, and the energy dependence;
- The use of the different final energy use technologies in the provision of the demand for energy services;
- The emissions in all sectors of the energy sector;
- The capacities (previous, new investments, and active) in all energy conversion processes;
- The complete intra-yearly profile of electricity generation, biofuels production or oil refining per technology and for all load levels;
- The final energy prices of all final energy vectors in all demand sectors;
- The level of use of energy service variation measures and load shifting;
- The costs of energy provision in the country, including imports/exports, social cost of carbon emissions, investment¹⁴⁵, variable and fixed costs of energy infrastructure and energy use devices;
- Lastly, and very importantly, policy costs, effects, synergies and trade-offs, looking (apart from all the above) at the shadow prices of policy constraints and at the variations in the elements of the objective function (as explained in the chapter with our methodological proposal).

¹⁴⁵ Not including, however, the sunk investment costs of previously-installed energy conversion capacities, as said above.

Chapter VI.

MASTER_SO STUDY: RENEWABLES VS. ENERGY EFFICIENCY, THE COST OF CARBON EMISSIONS REDUCTION IN SPAIN¹⁴⁶

VI.1	Outline of this Chapter	245
VI.2	Context of the study	245
VI.3	The methodology, the model and its main parameters	246
VI.4	Considered scenarios	251
VI.5	Results	252
VI.6	Caveats and shortcomings	266
VI.7	Conclusions	267

¹⁴⁶ This chapter is largely based on a participation in the Workshop “The Cost of Renewable Energy in the EU” (European University Institute, Florence, Italy; May 2011), later refined in two publications: (i.) in the Energy Policy journal; and (ii.) on a special issue on economic aspects of climate change in the “Revista ICE” journal of the Spanish Economy Ministry (López-Peña et al., 2011a; López-Peña, Pérez-Arriaga, et al., 2012a).

VI.1. OUTLINE OF THIS CHAPTER

In this chapter we describe a realistic ex-post policy analysis carried out with MASTER_SO. In Spain in the 1996-2008 period, large economic support was given to renewables for power generation, importantly reducing carbon emissions from electricity generation. At the same time, however, energy demand in diffuse sectors (e.g. building, transportation) grew significantly, as did associated carbon emissions. The goal of this study is, besides showcasing the capabilities of the model, to analyse whether, from a cost minimization viewpoint, renewable support has been the best policy for reducing emissions, when compared to the (hypothetical) promotion of energy efficiency in sectors such as transportation or buildings. We conclude that demand side management (DSM) clearly dominates renewable energy (RE) support if reduction of emissions at minimum cost is the only concern. We also quantify the savings that could have been achieved: a total of €5 billion per year, mainly in RE subsidies and in smaller costs of meeting the reduced demand (net of DSM implementation cost). Section 2 presents a brief overview of the study context; Sections 3 and 4 present our methodological approach and considered scenarios; section 5 presents the results; section 6 describes the main shortcomings of our approach and section 7 draws the main conclusions.

VI.2. CONTEXT OF THE STUDY

Within the European Union (EU), Spain is among the worst placed countries to comply with their carbon reduction commitments for 2012 in the framework of the Kyoto Protocol, in spite of some recent improvements (largely due to the present economic crisis). Although the EU burden sharing agreement allowed for an increase of 15% compared to 1990 levels, Spanish emissions prior to the present crisis (in 2007) had grown by 50% (over 1990), and in 2009 they were still 27% above those levels (Ministerio de Medio Ambiente y Medio Rural y Marino, 2011b).

However, not all sectors have contributed equally to this evolution. The electricity sector, by massively introducing gas-based power plants and renewables, has been able to contain its emissions despite a large increase in demand: between 1996 and 2008, electricity demand grew by 72% and CO₂ emissions from power generation by 55%. More than 21GW of combined cycle gas turbines (CCGTs) were installed between 2002 and 2008, making CCGTs share in total installed capacity increase from 0% to 24%. The contribution of renewable capacity (excluding large hydro) grew from 11% to 25% in the same years, mainly due to the installation of 15GW of onshore wind power, what has made Spain become a leader in wind power. The support given to renewable electricity has also positioned Spain favourably towards meeting the European 2020 target for renewables, even if the penetration of non-electric renewables remains low (Labriet et al., 2010). Recently, though, a moratorium of the support for new installations has been approved and the entire support mechanism is currently under review.

This support for renewable sources of electricity production has been arguably the most effective public policy for the mitigation of carbon emissions in Spain, although it originally started with other motivations: reducing energy imports, curbing the emissions of other pollutants, job creation and technological development.

However, these advantages of renewable energies should not hide the fact that, at least in regard to carbon emissions reduction, other alternatives might have been more cost-efficient. In particular, Spain has a large potential for energy efficiency because of its high energy intensity (Mendiluce et al., 2010), particularly in the transport sector (Mendiluce & Schipper, 2011) and also in the residential sector (WWF Spain, 2010). For instance, the potential energy savings in Spain in 2030 at negative or low cost (below the estimated natural gas final price) in a business-as-usual scenario (ignoring efficiency policies or large technological progress) could be around 26% of estimated final demand. This value (demand reduction at negative or low costs) could reach 40% in the presence of efficiency promotion policies (Economics for Energy, 2011).

From the standpoint of pure cost minimization, and ignoring the renewable targets derived from European policy, one has to question if it would have been preferable to prioritize public support for energy efficiency as a better means for CO₂ emissions reduction in Spain. Of course, a combination of both renewables and efficiency is needed in any comprehensive energy policy, which targets more policy objectives than just emissions reduction in the medium term. But if that was the only policy ambition, and given the fact that public budgets are limited, it is interesting to see which measure achieves it at a lower cost.

The aim of this study is to partially answer this question by comparing the cost of achieving the current emissions level through renewable electricity support or through energy conservation. We perform the comparison with an energy policy evaluation model applied to the 1996 – 2008 period in Spain. The results will allow us to confirm what appears to be a general consensus in the literature: that the most cost-efficient means of reducing carbon emissions in the medium term (leaving aside important considerations such as industrial policy, security of supply, and other long-term issues) is to enhance energy efficiency (Enkvist et al., 2007). In particular, our study will allow us to quantify the actual magnitude of this increased cost efficiency, for a real country with a large penetration of renewable energy sources and important energy efficiency potential, such as Spain.

VI.3. THE METHODOLOGY, THE MODEL AND ITS MAIN PARAMETERS

In this section we present first an overview of the rationale behind our methodology. Then we provide further details on the data used, the characterization of demand and demand side management (DSM) measures, and the representation of the rest of the energy sector. For more detail on the numerical data refer to (López-Peña et al., 2011b).

VI.3.1. Overview

For each of our scenarios (defined later), we calculate the least-cost energy supply for the country in a year, given exogenous demands for each type of final energy in each subsector (hence only optimising the supply side, as will be seen later), and without exceeding a specified level of emissions. The cost to be minimized includes the main private costs (no externalities, i.e. no social cost of CO₂) involved in the energy sector: domestic primary energy purchases, energy imports and exports, investments in energy assets or their fixed and variable costs, among others. The main outputs of the model include the energy flows through the entire energy system, its emissions, the required investments, and all the associated costs.

The study covers the 1996 – 2008 period, which has been chosen so that the renewable electricity (RE) development is included from its beginning, while the main effects of the economic crisis on energy demand, which may significantly affect the results, are left out (the main decrease in demand started in 2009). The installed capacity of all power generation technologies (and other energy conversion technologies) in 1996 is an input to the model, while the final energy demands that must be supplied are those of 2008. The model then searches for the minimum-cost supply of the 2008 demand, with the 1996 capacities as input, for which it must determine the investments that are required to satisfy the increase of demand in the period. The solution of the model is constrained so that the computed 2008 CO₂ emissions cannot be higher than the actual ones. This prevents the model from investing in carbon-intensive technologies, even if they were the best choice to meet the increment of demand at a minimum cost. In other words, the model calculates the investments needed in the studied period which, under the assumptions of perfect energy markets and rational policymaking (implicit in the optimization), would have minimized the cost of supplying the 2008 energy demand without exceeding that year's historical emission level. The perfect energy markets hypothesis is a reasonable (and common) one for policy studies because it represents a reasonable trend for energy markets' developments over the long term. The second assumption, rational policymaking, is indeed what allows us to perform this analysis, since our aim is to identify the policies that would have been optimal (taking into account our study's assumptions and limitations).

VI.3.2. Data used

Given that a period of twelve years is represented through a static model, certain precautions must be taken with the data used. The technologies' costs and the prices of primary and final energy in international markets are the average 1996 to 2008 values, measured in constant 2008 Euros. The capacities of gas and electricity interconnections are the average values observed in the period and the model cannot invest in increasing them; in this way the model tries to capture the administrative difficulties that this kind of projects have encountered in the past years in Spain.

VI.3.3. Demand and DSM characterization

We have used a simplified representation of end-use sectors, based on demand for final energy (not for energy services) and on a database for demand side management (DSM) policies. We believe that this approach is a fair enough approximation (for this study, because it refers to a period in the past) and hence we believe our results to be valid, as will be justified below.

Demand side management (DSM) policies must be characterised within the model in order to compare them with RE support policies and therefore be able to answer this study's research question. In order to do this, we created a database of DSM policies, and their potential effects and associated costs are included in Figure 67. The database has been built taking as starting point those measures with significant energy efficiency potential for Spain, such as modern lighting and heating systems in the residential sector (Economics for Energy, 2011). Of them, we have only included those that would have been technologically feasible at reasonable costs during the studied period. This implies that some of the measures that are envisaged for the future, such as the support for massive penetration of electric vehicles, are left out because in the 1996-2008 period it was a very expensive measure. These DSM measures have been characterized using the results from several studies that analyse the potential of energy efficiency measures in Spain: (de la Villa, 2010), (Economics for Energy, 2011), (Fraunhofer ISI et al., 2009), (Lorenzo, 2010), (Ministerio de Fomento, 2011), (Ministerio de Industria, Turismo y Comercio, 2011d), (WWF Spain, 2010). We have calculated the cost of implementing them as the *additional* cost that the country would have to pay to implement the measure (i.e. the marginal cost for society), other things being equal. For example, when characterising energy efficient tyres we have considered the additional cost of an efficient tyre over the cost of a standard one that, in other case, would have been used. Fiscal measures are considered to have zero cost, assuming that they do not involve significant distortions in the economy (i.e. new taxes are considered to be pure wealth transfers that, at the level of detail considered in this partial equilibrium model do not significantly distort economic activity so their overall cost for society as a whole is considered to be null). The effects of measures that act over several years have been standardized for one year, and their associated costs too, by calculating the annuity of the investment from the perspective of the government, i.e. low interest rate (5%) and low payback period (10 years). We have assumed the rebound effect of final energy efficiency gains, if any, to be small or already incorporated in the estimated reduction of demand, as it was the case in (Linares et al., 2008) for the Spanish electricity sector. For electricity, and other final energy sources too, this assumption can be supported by the low estimates of this effect that are observed in OECD households' demand for personal transport, heating or cooling (Sorrell et al., 2009); or in households and firms in the US (Greening et al., 2000). Moreover, if we assume that DSM measures are promoted through price signals, then the rebound effect will be minimized.

Once these DSM measures have been characterised and introduced as data, the model chooses which of them to use, depending on the overall cost minimisation. Those with the worst cost-benefit relation will not be used. So even if we had included measures whose cost was not deemed "reasonable" (such as electric cars for the 1996-2008 period, as explained above), the model would not have used them, hence making no difference in the optimization results.

Figure 67: Demand side management policies database.
Source: own elaboration.

Description	Cost (M€)	Effects
"Eco Driving principles for car drivers"	2.0	-1% gasoline and diesel demand in road transportation
"Teleconference incentives for businesses"	1.3	-2.5% kerosene demand in air transportation, -1% diesel and gasoline demand by cars, -0.01% electricity demand by trains
"Promote correct tyre inflation in cars"	2.0	-1% gasoline and diesel demand in road transportation
"7% share of biofuels in 2008"	0.0	-5% gasoline and diesel, +278% biofuels demand in road transportation in 2008
"Promote fuel saving devices in cars"	68.0	-2% gasoline and diesel demand in road transportation
"Promote urban biking in cities bigger than 200k"	33.4	-0.13% gasoline and -0.03% diesel demand in road transp.
"Promote car scrapping"	13.0	-2.2% gasoline and +0.4% diesel demand in road transportation
"Install regenerative brakes in subway"	3.4	-3% electricity in train transportation
"Rise fuel taxes for particular cars"	0.0	-4% diesel, -4% gasoline, +0.0001% train electricity
"Install access tolls in cities bigger than 200k"	7435.0	-0.84 % gasoline, -0.29% diesel in road transportation
"Improved air traffic operations"	0.4	-1.82% kerosene, air transportation
"Increase freight by railway, decreasing truck"	971.0	-0.4% diesel in road transportation, +20% electricity in train transp.
"Promote freight in ship in Atlantic coast"	3.9	-0.24% diesel in road transportation
"Rational lighting systems residential sector"	422.0	-29% electricity, residential sector
"Rational cooling systems residential sector"	7498.0	-24% electricity, residential sector
"Rational heating systems residential sector"	227.0	-15% electricity, residential sector
"Efficient appliances residential sector"	1191.0	-2% electricity, residential sector
"Efficient electronics residential sector"	97.0	-3% electricity, residential sector
"Efficient tyres for cars"	360.0	-1.5% gasoline and diesel demand in road transportation
"Efficient boilers for residential sector"	932.4	-10% in liquefied petroleum gases (LPGs), natural gas, diesel and biomass demand, residential sector
"Improved thermal insulation for residential sector"	6475.0	-9.4% in LPGs, natural gas, diesel and biomass demand, resid. sector
"Double windows in residential sector"	5180.0	-14% in LPGs, natural gas, diesel and biomass demand, resid. Sector
"In-floor radiating heating devices in resid. sector"	6734.0	-2.4% in LPGs, natural gas, diesel and biomass demand, resid. Sector
"Solar thermal water heating in residential sector"	3108.0	-19% in LPGs, natural gas, diesel and biomass demand, resid. sector

As said above, the model's main aim is to supply 2008 historical final energy demands (inputs to the model) while not exceeding actual carbon emissions in that year and minimizing supply costs. The final energy demands in 2008 have been obtained from (Instituto para la Diversificación y Ahorro de la Energía, 2009). Demand is considered inelastic, except for the possible reductions arising from the application of DSM policies. The adopted demand values are shown in Figure 68.

Figure 68: 2008 final energy demands per type and demanding sector, in PetaJoules.

Source: own elaboration.

PetaJoules (PJ)	Electricity	Coal	Nat. Gas	Gasoline	Diesel	Fuel Oil	LPGs	Kerosene	Other Oil Prods.	Biofuels	Biomass	TOTAL	%
Industry: MCM*	203	74	218	0	14	14	4	0	85	0	6	618	15%
Industry: Chemistry	49	9	138	0	4	7	7	0	3	0	1	218	5%
Industry: Other	142	3	169	0	21	22	3	0	0	0	55	415	10%
Primary Sector	20	0	11	0	104	2	3	0	0	0	1	141	3%
Residential Sector	232	1	151	0	118	9	89	0	0	0	86	686	17%
Tertiary Sector	261	0	30	0	71	5	13	0	0	0	3	384	9%
Road Transportation	0	0	0	268	1015	0	1	0	0	27	0	1310	32%
Railway Transp.	20	0	0	0	29	0	0	0	0	0	0	49	1%
Air Transp.	0	0	0	0	0	0	0	242	0	0	0	242	6%
Sea Transp.	0	0	0	0	50	8	0	0	0	0	0	58	1%
TOTAL	926	87	717	268	1426	67	120	242	89	27	153	4123	100%
%	22%	2%	17%	7%	35%	2%	3%	6%	2%	1%	4%	100%	

*MCM: Mining, Construction and Materials

This approach entails a simplifying assumption: the model must satisfy each of these final energy demands, hence the possible switching between final energy carriers (by investing in new energy-use devices) is not represented with great accuracy. However, in our opinion, competition amongst final energy sources is not as critical in this study as it could be in other studies looking at the future. This competition needs, in most cases, investment in new end-use devices (except for example in the cases of flexi-fuel technologies such as certain cars). These investments take place in a process over the long run where the important influencing factors need time to develop. Since this particular study refers to a short period of time in the past we think that only part of these investments could have taken place, and therefore that the impact of not considering them will be limited. This is why we deemed it enough to approximate this competition through some of the DSMs presented above, which produce energy switching (reductions in some energy carriers and increments in others) and whose promotion costs represent the investment costs in the required new end-use devices. In any case, results must be regarded at taking this into account, as is pointed out below.

VI.3.4. Energy sector representation

We now describe the representation of the energy sector that was done for this study, which is a particularisation of the modelling framework explained before. Power generation is represented by the twenty-two technologies that were relevant to the Spanish case: nuclear, two coal types (domestic and imported), three types of hydro, hydro pumping stations, combined cycle and open cycle natural gas turbines, fuel-gas generators, three types of onshore wind with different quality resource and different maximum potential, one type of offshore wind, three types of biomass, solid waste, solar photovoltaic and concentrated solar power.

Increasingly related to the power sector by the large amount of gas-based generation, LNG regasification must be modelled too. For that, a single reference regasification terminal was used. Its investment and operating costs, efficiencies and emissions are the average values of Spanish terminals. The model is provided, as input, with the 1996 regasification capacity, and can invest in new capacity.

Oil refining is less critical for this study, but as the model covers the entire energy supply sector, it is modelled too. For the sake of simplicity, and seeking to focus on the specific

objectives of the study (we do not consider oil refining a critical aspect of it), we used the 2008 Spanish refining capacity, taking it as fixed, and a single crude oil quality is represented.

Given that this model is a bottom-up one, the modelled energy conversion technologies are characterized in economic and technological terms, as explained in detail in previous chapters. It should be reminded that the fuel costs are accounted for, from a national perspective, in the costs of energy imports.

Limitations on the annual availability of domestic primary energy have been introduced for domestic coal, biomass and hydropower. We have obtained their values through the extrapolation of average historical values.

Unlimited import and export capacity is assumed for all primary and final energies traded in Spain, except for gas pipelines and electricity interconnections with North Africa and Europe, where the average 1996-2008 capacity is used, as stated above. We have assumed biofuels to be entirely imported, and biomass for heat and electricity to be entirely domestic.

VI.4. CONSIDERED SCENARIOS

We will answer our research question by running the model for different scenarios. Four main scenarios are considered. The first one (labelled “Actual case” as seen in Figure 69) reproduces the actual situation in the study horizon, where RE was supported and additional DSM measures were not used. With that purpose, we have used constraints in order to force the model to invest, in each renewable technology, its actual 2008 capacity. Four RE constraints are used, one per technology (wind, biomass, solid waste and solar photovoltaic), and each imposing the installed capacity to be equal to the actual 2008 one. In this first scenario, DSM is not allowed. The second scenario (called “No RE”) aims at isolating the effects of RE promotion and DSM promotion: it does not force the model to invest in renewables, and it does not allow it to use DSM either. It represents the situation where renewables are not supported, hence they compete freely in the market, and DSM is not possible. The third scenario is labelled “Efficiency” because it does allow the use of DSM, and does not force RE, so it gives the model full flexibility to decide the best strategy to follow. The fourth case, called “Effic&RE”, models the combination of policies, forcing RE and allowing for DSM use.

Moreover, considering that the strong investment in CCGTs over the period of the study (21GW) may have a major impact on the results of the model, it is of interest to understand what would have happened should this large deployment of CCGTs had not taken place. Hence, we study the above-mentioned four scenarios under two different circumstances (identified by dark and light grey in Figure 69): the actual investment in CCGTs (21GW) and free investment in CCGTs (“low CC” cases). This is done by using, in the first case, a constraint that forces the model to invest in 21GW of CCGT plants; while in the second group the volume of investment in CCGT is not forced, it is freely decided by the model.

Figure 69: Considered scenarios. Source: own elaboration.

Scenario	RE forced	DSM allowed	CCGTs forced	Emissions constraint
Actual case	Yes	No	Yes	No, "Actual2008" value obtained
No RE	No	No	Yes	Actual2008
Efficiency	No	Yes	Yes	Actual2008
Effic&RE	Yes	Yes	Yes	Actual2008
Actual case_low CC	Yes	No	No	Actual2008
No RE_low CC	No	No	No	Actual2008
Efficiency_low CC	No	Yes	No	Actual2008
Effic&RE_low CC	Yes	Yes	No	Actual2008

As said before, the model minimizes the total energy supply cost in 2008 but cannot exceed the historical 2008 emissions. Hence, an emissions limit must be introduced. For calibration purposes, this limit is obtained by executing the “Actual case” scenario with unbounded emissions. In this case, installed capacities are the actual ones (CCGTs and REs are forced into the model) and additional DSM measures are not allowed (as happened in reality). Hence this scenario should provide a similar emissions value to the historical one. After this calibration phase, the obtained emissions value from this scenario (labelled “Actual2008”) is set as a limit for the other seven cases. Additionally, during the study horizon, a slight increase in nuclear installed capacity took place, due to technological upgrades of the existing plants (from 7.4GW to 7.72GW).

VI.5. RESULTS

In this section, the results of the model for the eight scenarios will be reviewed under the perspective of our research question. First, the results on carbon emissions will be explained, in order to understand where emissions are being produced, how the limit on them is bounding the model’s results and which scenarios represent the cheapest ways of achieving the required emissions level. Second, the investments decided by the model under each case will be discussed. The aim here is to understand the investments that should have taken place for achieving the desired emissions in the most cost-efficient ways under each scenario. The discussion on the shadow prices of the constraints defining the different scenarios will also provide insightful information on which technologies are being more useful to achieve the desired goal. Then, the Sankey diagrams in the six most representative scenarios are presented, in order to obtain the big picture of how the energy system would look under each policy scenario. Finally, the total energy supply cost and its components will be discussed, helping us to understand how different costs interact and why the cheapest ways of achieving the desired emissions levels are, indeed, the cheapest. The combination of all these discussions on the results will allow us to provide an answer to this study’s research question, which is done in the conclusions section.

VI.5.1. Carbon emissions

The results on carbon emissions in each scenario are shown in Figure 70.

Figure 70: Carbon emissions in the different scenarios. Source: own elaboration.

Emissions (Mt CO ₂)	In primary energy	In energy conversion	In final energy consumption	Total emissions	Emiss. constr. shadow price (€/tCO ₂)
Actual case	3.16	103.42	209.30	315.88	No constraint
No RE	2.19	104.39	209.30	315.88	-3.78
Efficiency	3.20	104.77	200.74	308.71	0.00
Effic&RE	2.45	80.68	200.74	283.87	0.00
Actual case_low CC	1.57	105.01	209.30	315.88	-17.78
No RE_low CC	1.42	105.15	209.30	315.88	-20.06
Efficiency_low CC	1.56	113.58	200.74	315.88	-16.52
Effic&RE_low CC	1.70	91.16	200.74	293.60	0.00

The emissions in the “Actual case” case (calibration scenario) were 315.88 MtCO₂, whereas the actual Spanish CO₂ emissions from the energy system in 2008 were 310.6 MtCO₂ (Ministerio de Medio Ambiente y Medio Rural y Marino, 2011b). This is a 1.7% deviation, which is considered valid for this calibration step. Those 315.88 MtCO₂ are then used as emissions limit in the other seven scenarios. This limiting constraint is active in all scenarios except in the “Efficiency”, “Effic&RE” and “Effic&RE_lowCC” ones, where the resulting emissions are lower than the emission constraint. In the scenarios with active constraint, total emissions take that precise value (315.88 MtCO₂) and the shadow prices associated to the constraint are not zero¹⁴⁷. These shadow prices show how total energy system costs would decrease (negative value) when the emissions limit is made marginally looser. Or, to put it differently, they show the marginal cost of abating carbon emissions.

When the system does not have the 21 GW of CCGT power plants (“low CC” cases), the marginal abatement costs are larger, what points to the fact that CCGTs do indeed help in reducing emissions, as could be expected from the low specific emissions of burning natural gas, the high efficiencies of CCGTs, and the fact that in these cases there is considerably more installed capacity in the system. This abatement cost is smaller when the model can use demand side management than when it is required to install renewables and cannot use DSMs, which would imply that demand reduction measures are a cheaper way of reducing emissions than renewables promotion, a preliminary answer to this study’s research question. This confirms what has been said in the literature (Ecofys et al., 2009; Enkvist et al., 2007). However, more results will be analyzed in order to reach a more comprehensive conclusion. In Figure 70 we also show that, roughly, two thirds of Spanish emissions were in 2008 produced in final energy consumption, while the other third belong to energy conversion processes (mainly electricity generation and oil refining). Emissions in primary energy production (coal mining) are insignificant in comparison. In all four “Efficiency” cases, the model reduces final energy consumption (because the costs of implementing the chosen DSM measures are offset by savings, mainly in energy imports, as will be seen later). Hence final energy use emissions fall (from 209.30 to 200.74 MtCO₂), what makes the emissions constraint looser and the carbon marginal abatement cost falls. In three cases (“Efficiency”, “Effic&RE”, “Effic&RE_lowCC”),

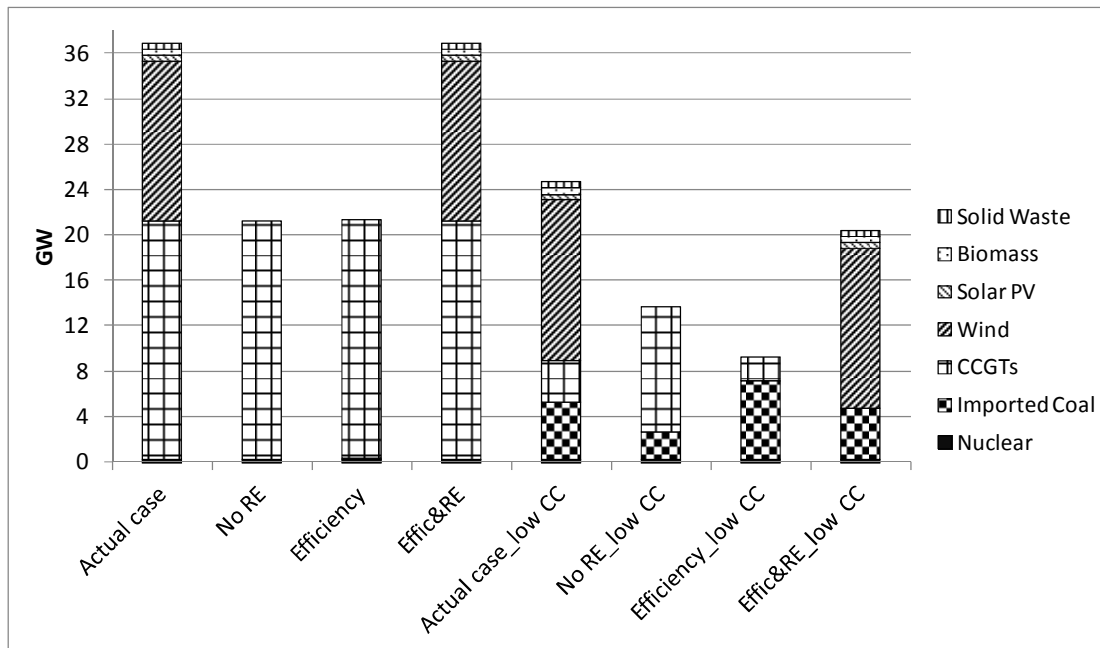
¹⁴⁷ In a linear programming problem, the shadow price associated to a constraint expresses the marginal worsening/improvement of the problem associated to the constraint. By definition, shadow prices take a zero value when the constraint is not active.

emissions fall below the emissions limit, hence the zero value of the carbon marginal abatement cost.

VI.5.2. Investments

According to the model, in each of the scenarios, the optimal power generation capacity additions from 1996 to 2008 would have been the ones shown in Figure 71.

*Figure 71: Capacity additions decided by the model for the studied period (1996-2008).
Source: own elaboration.*



In the four cases where CCGTs are forced to the actual 21GW (scenarios not marked with the “low CC” label), the model does not add any additional capacity unless it is required to, what happens in the scenarios with forced REs. This fact points at the excess capacity that was indeed observed in the actual system, where CCGTs were functioning around 3000 equivalent hours per year.

In the other four scenarios (marked as “low CC”), the model prefers to invest in imported coal, until the emissions limit becomes tight, and then it invests in CCGTs. This is because of two reasons: (i) the lower prices of imported coal versus natural gas (9.7 €/MWhImportedCoal, 15 €/MWhNaturalGas, 18 €/MWhLNG); (ii) the long run effects (the ones affecting actual investment decisions) of European emissions trading, which reduce the competitiveness of coal versus gas, are not completely represented by our emissions limitation. Indeed, our cap on emissions is yielding carbon prices around 20€/tCO₂ (the marginal carbon abatement costs seen above), which are lower than the ones presumably expected for the long run by agents operating under the actual European Trading Scheme (ETS). In addition, actual ETS prices are set at European level and only for carbon-intensive sectors, whereas in our model the emissions cap is applied at Spanish level and for the entire energy sector.

Continuing with the four “low CC” cases, the model can generate more electricity with coal in the case where DSM is allowed, because emissions from final energy use are lower, and therefore it invests more in coal in these cases. The model does not invest in RE unless they are forced, and when that happens, it invests less in CCGTs (even in spite of the reserve requirements imposed to the model) or coal. An additional observation: the CCGT installed capacities in the four “low CC” cases are lower than the 21GW forced in the other four scenarios. This may imply that the large investment in CCGT capacity that took place (21GW) was suboptimal, as could have been guessed from the low functioning equivalent hours actually observed in the market (which have resulted in a possible mothballing of some of these power plants) and as already predicted in the literature (Linares et al., 2006).

VI.5.3. Shadow prices

Useful information can be obtained from the shadow prices of the constraints that impose the 21GW of installed CCGTs and the 2008 RE capacities. By looking at the sign of each of the constraints’ shadow prices, it is possible to identify if, from the optimization perspective, it would be better to *decrease* or to *increase* the required capacity. The results obtained for each constraint in the eight scenarios are shown in Figure 72.

*Figure 72: Shadow prices of the capacity constraints in €/kW, when applied.
Source: own elaboration.*

Shadow prices (€/kW)	Actual case	No RE	Efficiency	Effic&RE	Actual case_low CC	No RE_low CC	Efficiency _low CC	Effic&RE_ low CC
CCGT Capacity	91.09	78.37	87.29	82.18	N. App.	N. App.	N. App.	N. App.
Wind Capacity	113.19	N. App.	N. App.	115.28	82.25	N. App.	N. App.	116.87
Solar PV Capacity	469.40	N. App.	N. App.	466.71	436.98	N. App.	N. App.	457.99
Biomass Capacity	188.33	N. App.	N. App.	192.47	45.33	N. App.	N. App.	188.33
Solid Waste Cap.	391.05	N. App.	N. App.	391.27	373.11	N. App.	N. App.	370.95

The observation that can be made is that signs are always positive, which implies that if the imposed capacity (right hand side of the constraint) is made marginally greater, the objective function (costs of the system) will also increase. In other words, from the optimization perspective it would always be better to decrease capacity in CCGTs and RE. Given that the shadow prices are larger for renewable technologies than for CCGTs, CCGTs are preferred to renewables. The CCGTs are less needed (larger shadow price) when renewables are forced (in the “Actual case” scenario), and then when DSM is allowed (in the “Efficiency” scenario) because electricity demand can be reduced. In the other two cases, there is still too much capacity (still non-negative shadow price), but it is more useful.

Renewable technologies are preferred in the cases without forced CCGTs (smaller shadow prices), because there is less installed capacity in the system and there is more coal capacity, with a high emissions factor. Among the renewable technologies, wind and biomass are the most competitive ones (smaller shadow prices), then solid waste, and solar PV is the most expensive one. Looking at the cases where efficiency and renewables do not coexist (in these cases results are less clear due to interacting effects), when CCGTs are forced wind is more competitive than biomass, being the opposite true when CCGTs are not forced. This is explained by the fact that

biomass is similar to CCGTs in its operation: it is a dispatchable technology with high firmness and operating flexibility, so it is more needed in the system when there are less CCGTs.

From a mathematical perspective, policy conclusions should not be drawn only from shadow prices, because these are by definition only relevant in the neighbouring area of the optimal solution to the problem. This is why in this analysis we will base our conclusions also in other results such as the carbon abatement costs (which are in any case also shadow prices) or investment decisions, both seen above, on the energy supply costs that we will see below, and also on qualitative considerations such as what seems to be suggested by the relevant literature.

VI.5.4. Sankey diagrams of the energy system in different scenarios

In the next pages, the Sankey diagrams of the resulting energy system under six of the scenarios are plotted. The “Effic&RE” and “Effic&RE_low CC” scenarios are not represented since the observed effects are combinations of the effects seen in other scenarios. The same color code as in all our Sankeys (already explained in previous chapters) has been used, but for the reader’s convenience, some useful tags have been included in the first diagram. The same topology (position of main processes) as in the diagrams of the yearly BP Observatory on Energy and Sustainability in Spain is respected, for easier comparison and reference. However, the flows in this case are plotted orthogonal (following 90° angles) because, here, there is a significantly larger number of flows than in the Observatory (the level of disaggregation of the results provided by our MASTER_SO model is larger than the data disaggregation from official energy statistics used for the Observatory), so orthogonal flows produce a clearer diagram. The main observable changes have been marked with orange arrows.

Observable effects in the “No RE” scenario: there is no renewable generation, and since the CCGTs are imposed, the model uses them to generate the electricity not produced by renewables. That implies larger imports of LNG (gas pipelines are already saturated), and larger regasification. The implied increase in emissions, together with the (active) emissions constraint, forces generation with domestic coal to be reduced.

Observable effects in the “Efficiency” scenario: in this case, it generates the same with gas and coal as in the base scenario even if renewables are not present (because they are not imposed). This is because the model decides to reduce electricity demand (applying DSM policies), rather than generating more electricity (to cover the gap left by renewables). It also reduces the demand for other types of final energy (through other DSM policies), and therefore emissions fall and their constraint is not active.

In the “Actual case_low CC” case, since no CCGTs are forced the model invests in imported coal (cheaper) and uses it until the emissions restriction becomes tight, and then generates power with gas. Something similar happens in the “No RE_low CC” scenario, although here (not having RE), the emission constraint becomes tight sooner and hence it uses more gas and less coal. Finally, in the “Efficiency_low CC” case, the reductions in final energy demand make the

emissions constraint looser, and more imported coal (than in previous cases) can be used for power generation.

Figure 73: Sankey diagram, "Actual case" scenario.
Source: own elaboration.

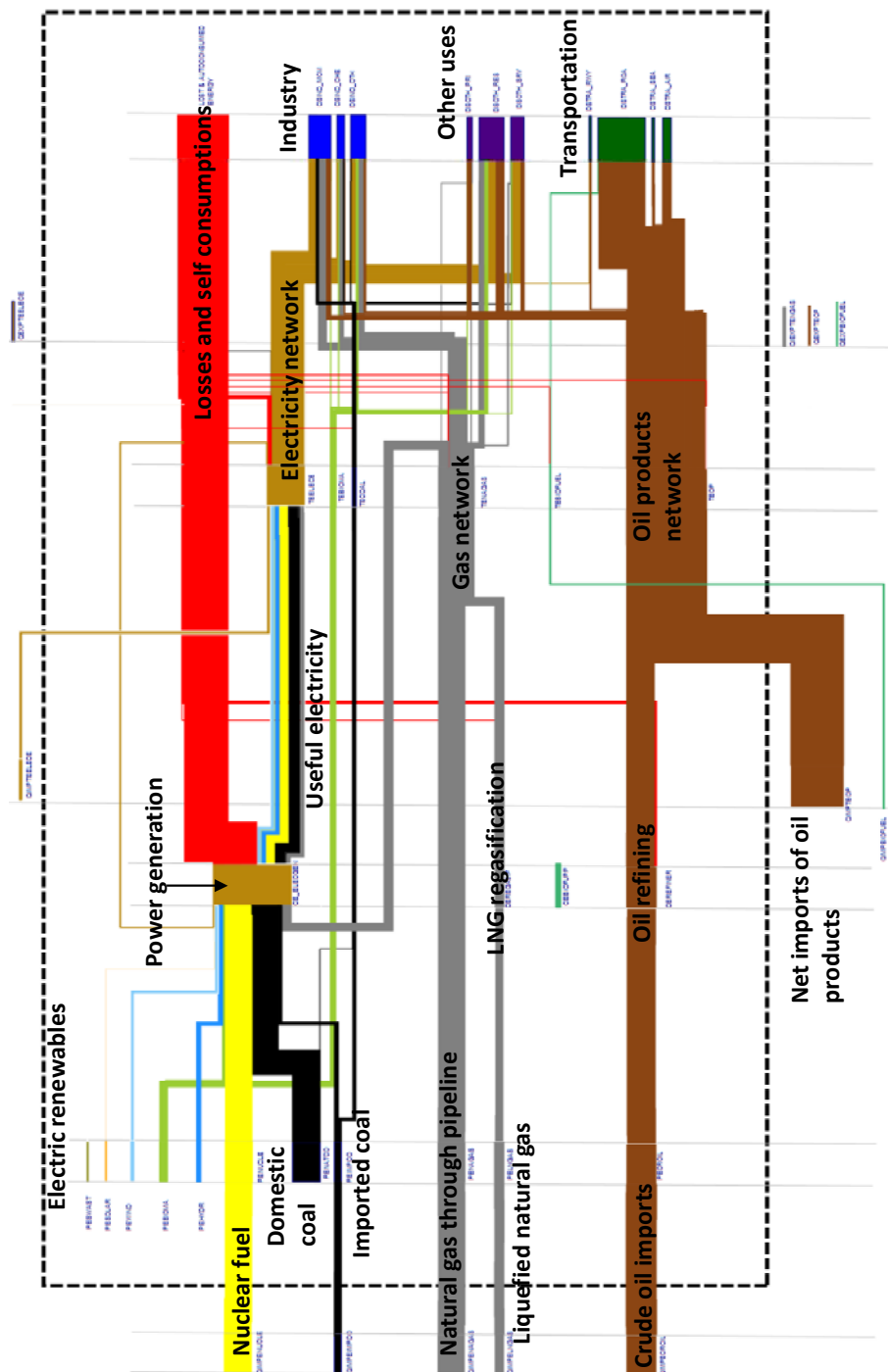
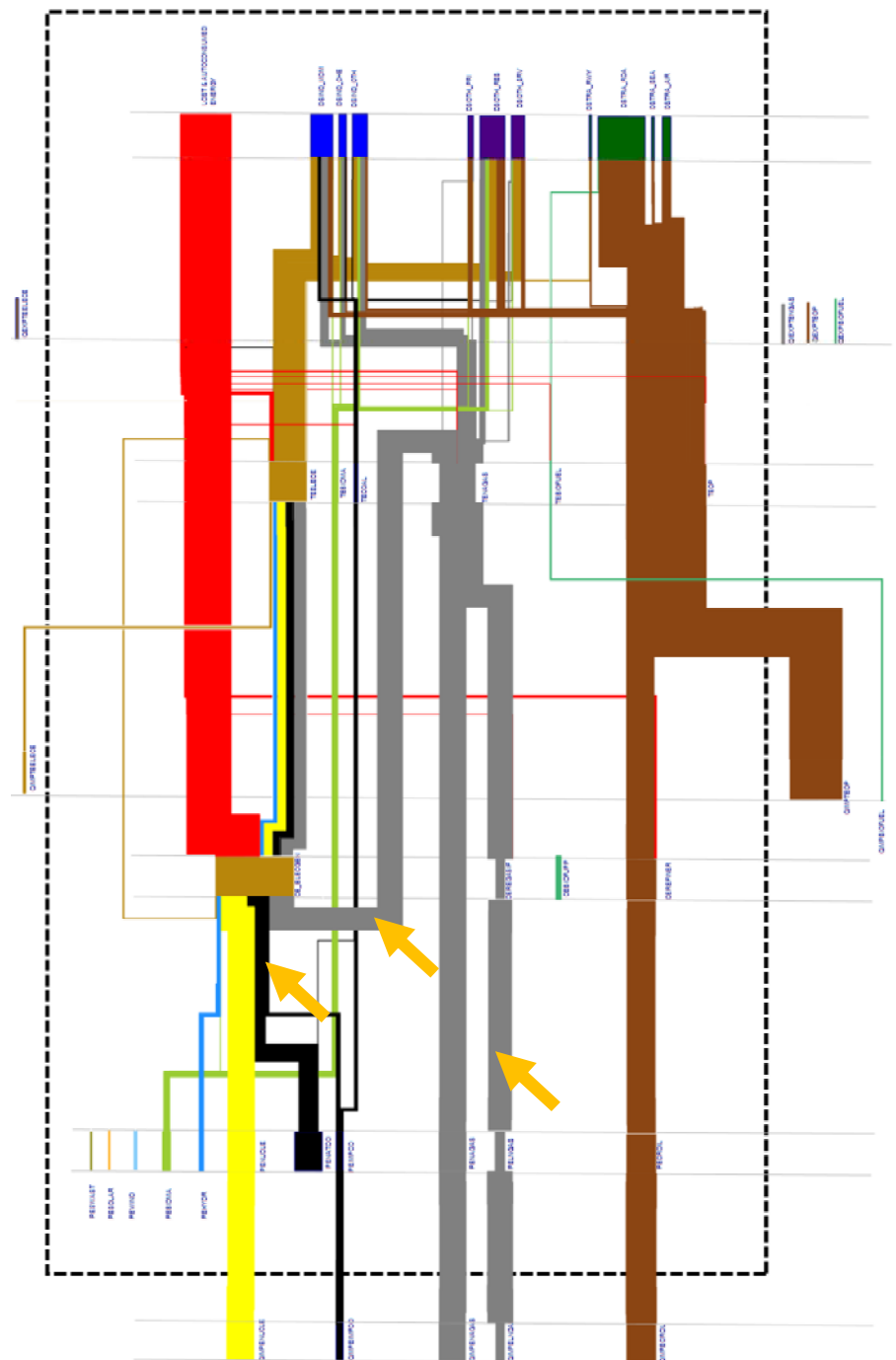


Figure 74: Sankey diagram¹⁴⁸, “No RE” scenario.
 Source: own elaboration.



¹⁴⁸ In this and the following diagrams, the width that the processes had in the first case has been maintained: the flows are thinner or thicker, but the processes remain the same as in the base case. This of course does not mean that less or more energy passes through them (the energy is the one from the actual flows): it has been done to be able to visually compare each case with respect to the base case.

Figure 75: Sankey diagram, "Efficiency" scenario.
 Source: own elaboration.

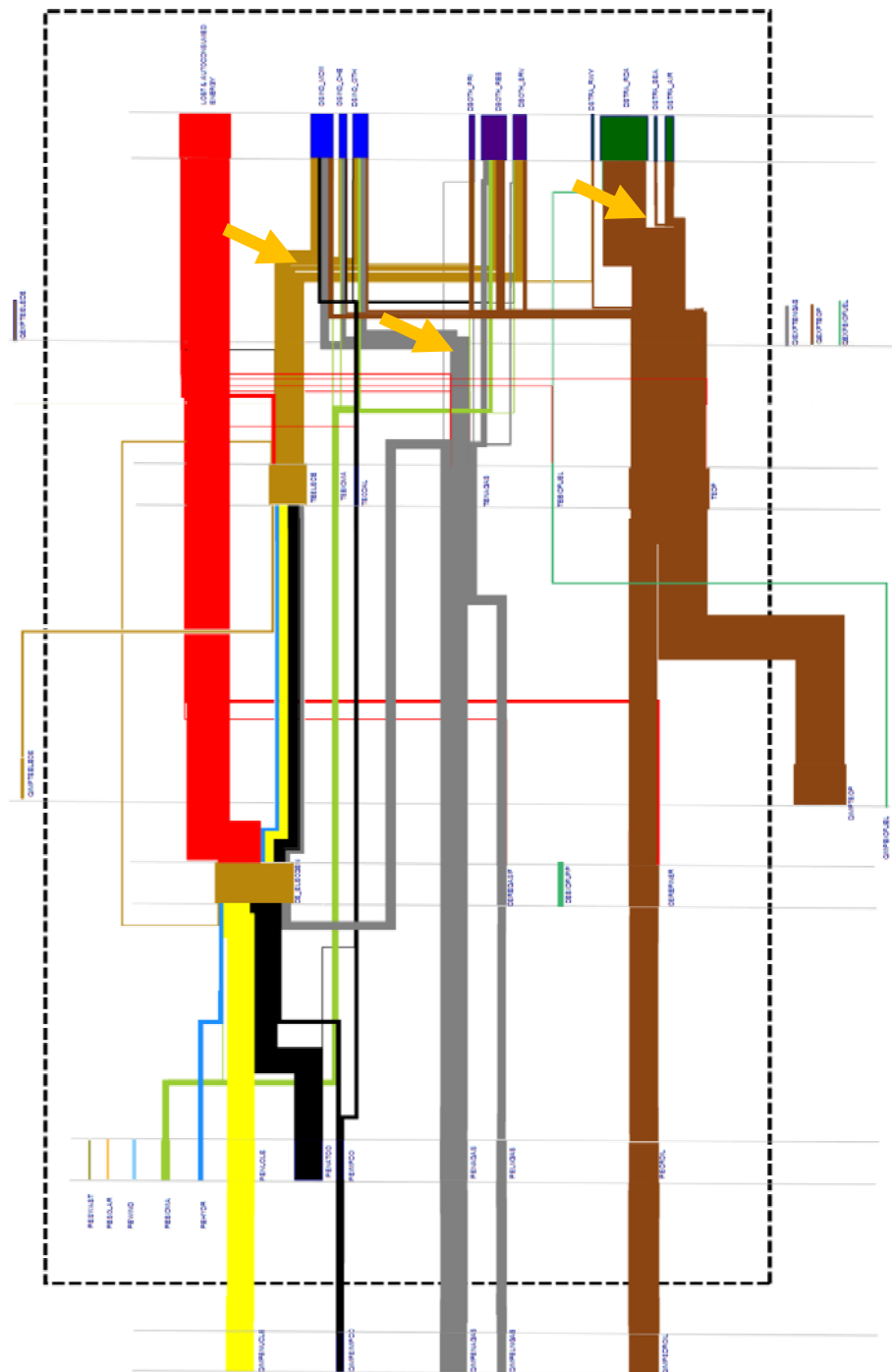


Figure 76: Sankey diagram, "Actual case_low CC" scenario.
 Source: own elaboration.

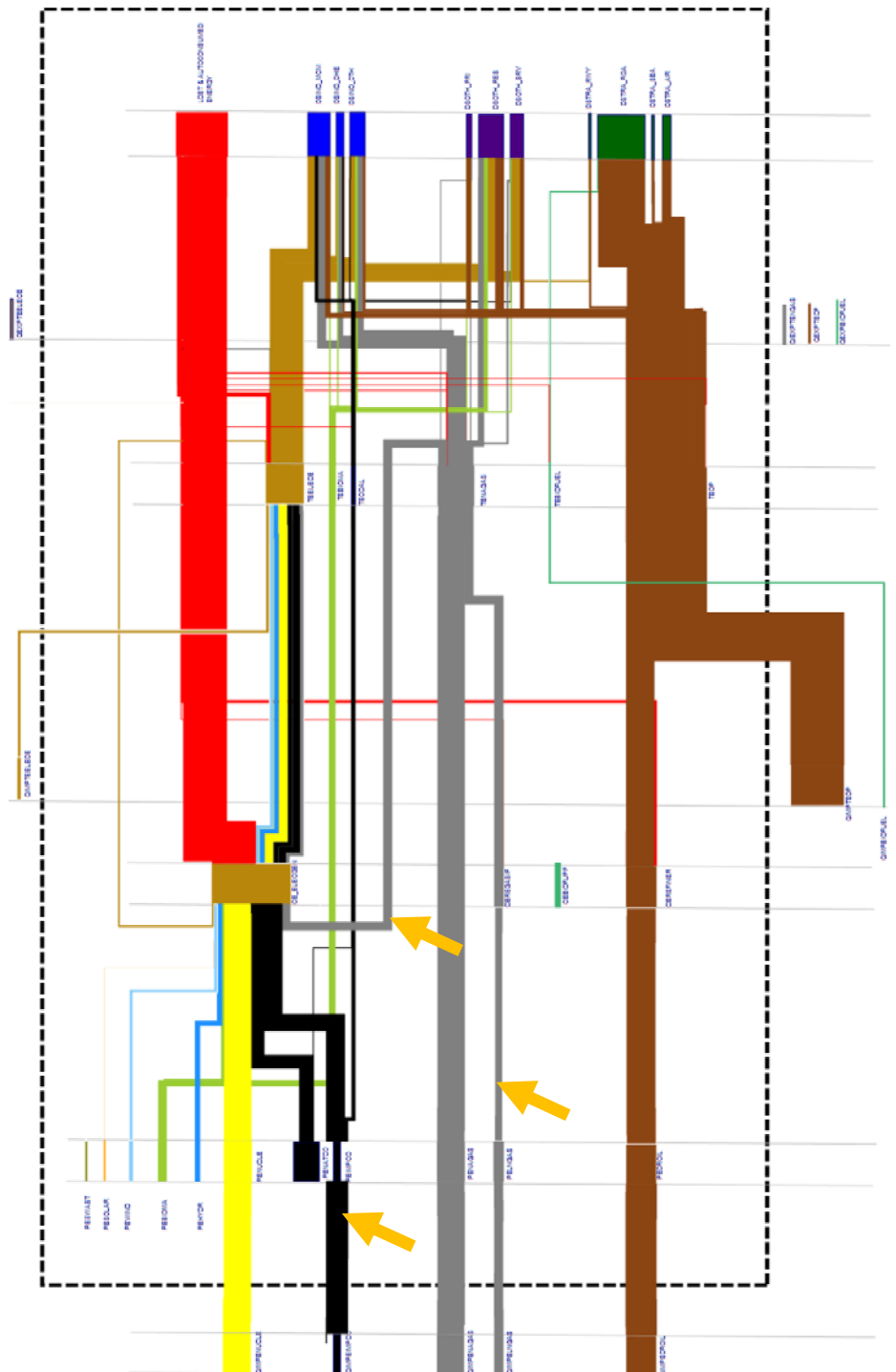
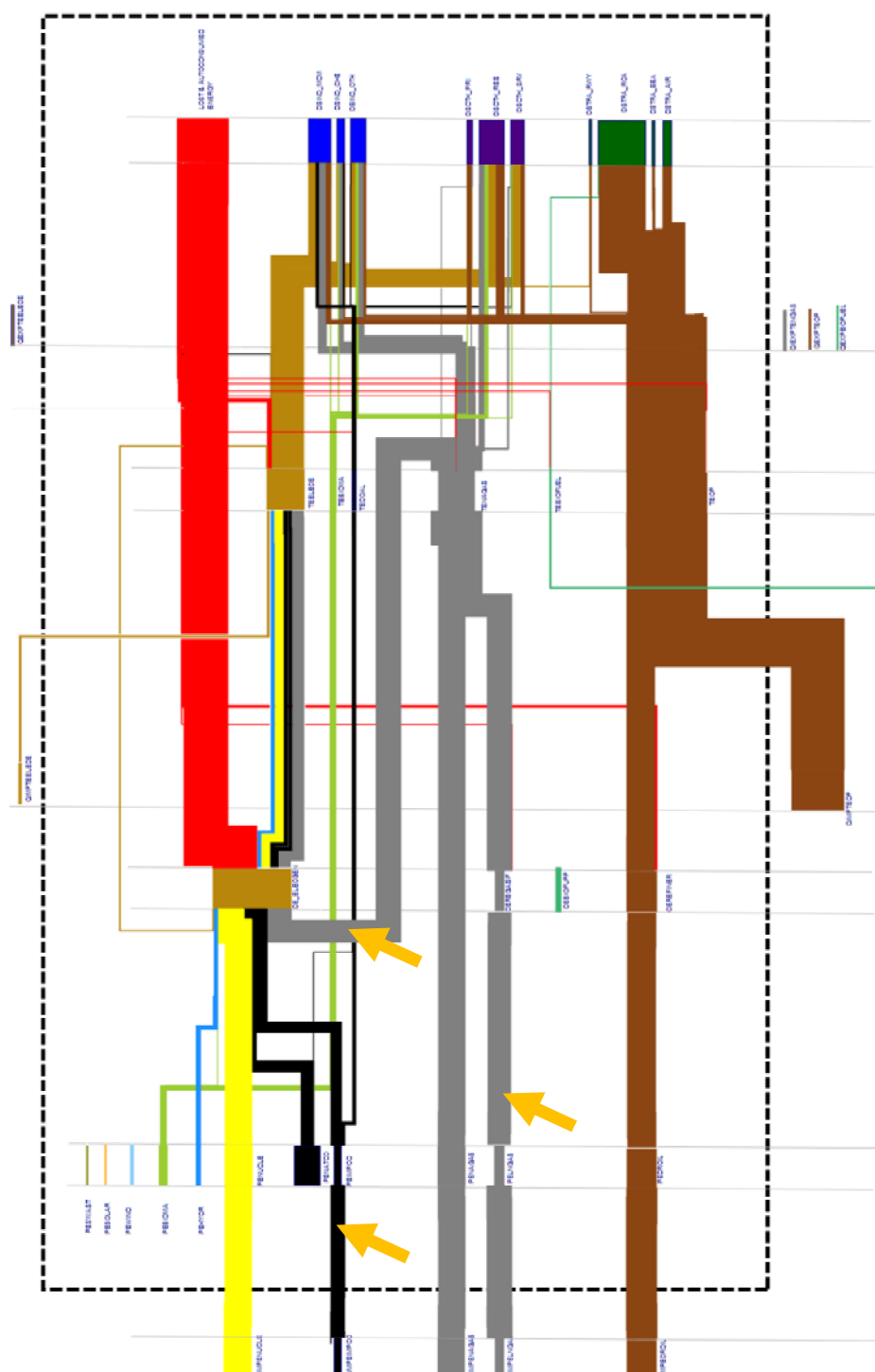


Figure 77: Sankey diagram, “No RE_low CC” scenario.
Source: own elaboration.



VI.5.5. Energy supply costs

Finally, the cost components for the total energy system in each of the scenarios are analysed. The sum of all of them (i.e. the total energy supply cost) is the objective function that is minimized. In this case, the social cost of carbon emissions and other cost components of the ones explained in Chapter 5 (e.g. non-energy costs of ESSTs usage, or load shifting costs) are not included. They can be seen Figure 79.

*Figure 79: Cost components and total energy supply cost in each scenario.
Source: own elaboration.*

Cost (+) and revenues (-). Million €/year	Actual case	No RE	Efficiency	Effic&RE	Actual case_low CC	No RE_low CC	Efficiency_low CC	Effic&RE_low CC
Domestic primary energy production (+)	4,129	2,997	4,073	3,376	2,449	2,189	2,338	2,583
Primary energy imports (+)	7,460	9,735	7,519	6,874	8,371	10,168	8,308	7,376
New conversion capacity investment (+)	4,934	1,888	1,844	4,917	4,410	1,497	1,503	4,029
Conversion capacity fixed O&M (+)	2,154	1,496	1,521	2,103	2,230	1,564	1,674	2,286
Conversion capacity variable O&M (+)	778	790	731	673	783	792	750	696
Final energy transportation (+)	8,068	8,578	7,357	7,217	8,032	8,561	7,202	7,049
Final energy imports (+)	19,495	19,495	18,238	18,238	19,487	19,495	18,202	17,965
Final energy exports (-)	-1,011	-1,011	-1,011	-1,011	-1,010	-1,012	-1,012	-1,012
DSM implementation (+)	0	0	840	840	0	0	840	840
Electricity generation reserve cost (+)	84	65	65	84	103	93	65	84
TOTAL ENERGY SUPPLY COST	46,092	44,032	41,177	43,311	44,855	43,348	39,870	41,896
Total cost increment (billion €/year)		↖ -2.1 ↗	↖ -2.9 ↗	↖ 2.1 ↗		↖ -1.5 ↗	↖ -3.5 ↗	↖ 2.0 ↗
Savings vs. "Actual case" (bln. €/year)	0.0	2.1	5.0	2.9	1.2	2.7	6.2	4.2

The domestic primary energy production costs refer to coal mining and biomass production. They are smaller in the “low CC” scenarios because less domestic coal is used than in the other four cases: the model invests in imported coal capacity and thus prefers to use this fuel rather than domestic coal, which is more expensive (15.9€/MWhDomesticCoal vs. 9.7€/MWhImportedCoal). Domestic coal in Spain is only used because of public subsidies and usage quotas, aiming mainly at maintaining jobs in the sector. The costs of primary energy imports are greater in the “low CC” scenarios due to the larger use of imported coal. Both “No RE” scenarios present bigger primary import costs because of greater gas imports, given that more electricity is produced in CCGTs. In both “Effic&RE” cases, these values are the smallest because less energy is demanded and more power is generated with renewables.

New conversion capacity annualized investment costs present a €2.5-€3 billion increment, other things being equal, when renewable technologies are forced, what represents their larger investment costs. These investment costs are €340-€900 million higher in the cases with forced CCGTs (the ones not marked “low CC”), other things equal. This can be seen as the cost of CCGTs excess capacity, compared to optimal investments in coal and CCGTs in each corresponding “low CC” scenario. Concerning fixed O&M costs, what can be seen is the higher cost of renewable technologies; and the higher cost of imported coal vs CCGTs (fixed O&M costs larger in the “low CC” cases, under ceteris paribus comparisons). Regarding variable O&M costs, different effects are levelled and small differences are observed in these figures.

Energy transportation costs (associated to electricity, gas, and oil products networks operation) are the highest in the two “No RE” cases because of more gas being delivered to CCGTs, and the lowest in both “Effic&RE” scenarios, where total delivered final energy is smaller

due to demand reductions and less gas is used in CCGTs (thanks to RE generation). Final energy imports, mainly associated with oil products imports (diesel and kerosene primarily), and which are not very much linked to the power system, are in general not very influenced by the presence or not of CCGTs. However, they are smaller in the “Effic&RE” scenarios due to demand reductions and less gas-based generation. Final energy exports, mainly electricity, are almost constant. Demand side management (DSM) implementation costs are the same in all cases where DSM is allowed, because the same measures are implemented (the ones shown in Figure 80).

*Figure 80: Demand side management policies chosen by the model.
Source: own elaboration.*

"Eco Driving principles for car drivers"
"Teleconference incentives for businesses"
"Promote correct tyre inflation in cars"
"Promote fuel saving devices in cars"
"Promote car scrapping"
"Install regenerative brakes in subway"
"Rise fuel taxes for particular cars"
"Improved air traffic operations"
"Promote freight in ship in Athlantic coast"
"Rational lighting systems residential sector"
"Rational heating systems residential sector"
"Efficient electronics residential sector"

Finally, electricity reserves costs (calculated as the variable O&M cost of idle capacity that is providing reserves and thus not producing electricity), are higher in the case with renewables, because more reserves are needed in the system due mainly to wind intermittency. The large presence of CCGTs in the system in the scenarios not marked as “low CC” is useful to provide inexpensive reserves to the system, given this technology’s flexibility and small variable O&M costs. In the cases without mandated CCGTs, reserves are provided by fuel-gas generators, hydro power plants and by the lower CCGT capacity. Unsupplied energy (used as the model’s slack variable as seen above) is null in all cases, so its penalization is zero.

Combining all the effects above, and focusing on the cases with the actual CCGT investment (the ones not marked as “low CC”), it can be seen that yearly costs in the “Actual case” scenario (the one representing the actual situation) are €2.1 billion higher than without mandated REs, everything else being equal. This result approximates well the actual 2008 REs support cost (associated to feed in tariffs and premiums), which according to the Spanish Energy Regulatory Commission was €2.3 billion (Comisión Nacional de Energía, 2009). Implementation of DSM policies instead of RE support results in net savings of €5 billion: €2.1 billion of RE promotion and €2.9billion of lower costs of meeting the reduced demand (net of DSM implementation cost).

In the scenarios without mandated CCGTs (“low CC” cases), similar conclusions can be drawn. Implementation of DSM instead of RE support would also imply net savings of €5 billion:

€1.5 billion of savings in RE support and €3.5 of lower costs of meeting demand. These results are confirmed by what is observed in both “Effic&RE” cases: once efficiency measures are applied, if RE are promoted in addition, total costs increase again in around €2 billion.

Looking at the cases without allowed DSM, in the scenarios with actual CCGT capacity, the extra costs of RE support are greater than in the case without mandated combined cycles (€2.1 billion vs. €1.5 billion). This is because in the second case there is less capacity in the system, and the electricity mix is more carbon-intensive (more presence of coal). Thus, if CCGTs investment had not been as important, renewables would be less expensive for the system. This does not apply when DSM are allowed (RE extra costs are almost equal), because in this case less electricity demand must be supplied and less carbon is emitted from final uses.

In both cases it can be seen that total costs are bigger with forced REs, and that when DSM measures are applied, the savings (mainly in energy imports) are larger than the promotion costs, causing the total system’s costs to fall, as expected from the literature (Enkvist et al., 2007), (Gillingham et al., 2006).

Total systems costs are larger in the cases with mandated combined cycles than in the equivalent ones without forced CCGTs. This fact, along with other results seen above, points at the large amount of these power plants being suboptimal.

The savings of DSM implementation are smaller in the scenarios with actual CCGT capacity: €2.9 billion vs. €3.5 billion in the “low CC” cases. This is mainly because, when DSM is used, final energy use emissions fall due to demand reduction, and the model then generates more electricity with expensive domestic coal, incrementing domestic primary energy production costs. This effect is much larger in the cases with 21 GW of CCGTs: the excess capacity in the system prevents the model from investing in imported coal generation and therefore fosters national coal usage. Hence, the greater flexibility of the model in deciding the power generation portfolio in the “low CC” cases increases the benefits of DSM. In other words, an optimal electricity generation mix allows for full exploitation of DSM benefits.

VI.6. CAVEATS AND SHORTCOMINGS

In this section, the caveats and shortcomings of our approach are made explicit.

First, our methodology consists on using an optimization model to analyse the past. Optimisation is widely used, within energy policy assessments, to analyse the future. Clear examples are the studies based on the Markal/TIMES methodology, which minimizes the total discounted cost of the modeled energy system (Loulou et al., 2005). Our study, however, uses an optimization model to ascertain if some decisions that were made in the past are consistent with what we now can determine to be the optimal solution for a prescribed objective (while acknowledging that the decision-maker might have had other objectives in mind). According to (Sterman, 1991), “the output of an optimization model is a statement of the best way to accomplish some goal” and “optimization models are prescriptive, but simulation models are descriptive”. For studying the past, it is usual to use descriptive techniques, such as

econometrics, which allow to describe *what has happened* and to extract conclusions from it. Using an optimization approach, as we do, allows concluding *what should have happened*, or using Stermann's words, what was *the best way to accomplish the goal*. In our study, we want to know what would have been the best way to achieve the 2008 emissions while minimizing the costs. This is why a prescriptive approach –optimization– is used here. By comparing this optimal decision with the actual decisions that were made, policy conclusions can be obtained and lessons can be learnt that may be applicable for the future.

Second, extracting policy conclusions by analysing the past can be problematic, because the circumstances that happened in the past may not hold for the future. Our analysis has been done for Spain for a period of high economic growth, low energy efficiency in sectors such as transportation and buildings, and when renewables were still non-competitive against traditional fossil technologies. The present economic crisis has made the situation change slightly. Energy demand from these sectors has decreased (9% in transportation and 4% in buildings, between 2007 and 2010), but a significant energy efficiency potential is still available: Spanish energy intensity is still above European levels and its evolution has worsened again in 2010 and 2011 (López-Peña, Linares, et al., 2012). In addition, fiscal consolidation needs have made the government freeze support for new renewables, but some of them such as wind in certain areas may soon not need it any more. For the future, renewables are expected to be even more competitive, while efficiency in demand sectors is expected to increase at least as a result of the predictable growing international prices of energy and the technological improvements (Economics for Energy, 2011). These tendencies can make our conclusions not hold for the long term. Even in this case, we believe that analysing the past is itself a valuable exercise for policymaking, in order to extract lessons and avoid making similar policy mistakes.

Third, as explained above, efficiency and final energy substitution have been modelled through the effects of DSMs and not by modelling actual investment in new end-use devices. Therefore, efficiency improvements or competition among final energy carriers, which can be important means of reducing carbon emissions, are not represented in a very accurate manner. However, we think that this is not critical for this study, which refers to a short period of time in the past.

The fourth point concerns the use of a static model for the representation of several years, and of average costs as representative values for the complete period. This makes our study lose the dynamic nature of investments. However, the period represented is quite short, and accordingly also the room for changes and new investments. Therefore, we do not expect this issue to result in significant effects in the case considered.

VI.7. CONCLUSIONS

This chapter presents a realistic study carried out for Spain using MASTER_SO with a clear energy policy purpose. As we have been defending throughout this PhD thesis, we have used a simple and transparent methodology (a static LP model) which at the same time includes the main needed technical and economic details, and which is fed with real data from public and reputed sources for the case of Spain. Through a relatively simple scenario analysis, and

extracting the key results (e.g. emissions throughout the energy sector; shadow prices of key constraints; investment decisions made by the model; all the energy flows, represented intuitively as a Sankey diagram for each scenario; and all the relevant costs) we are able to extract useful and clear conclusions regarding the big picture of energy policy in Spain over the past years. This study also shows the feasibility of using MASTER_SO for ex-post analyses. The main policy conclusions are explained next.

The aim of this study was to analyze whether renewable electricity promotion in Spain has been or not the most cost-efficient means of reducing carbon emissions, when compared to the promotion of energy efficiency in sectors such as transport or buildings. For this purpose, an ex-post study of the evolution of the Spanish energy system over the years 1996 to 2008 has been carried out.

Our study has revealed that the implementation of DSM instead of renewables for the reduction of CO₂ emissions would have resulted in net savings of €5 billion a year, both with the actual level of investment in CCGTs and with an optimal (lower) CCGT capacity. Hence, if minimizing the cost of reducing emissions had been the major concern, DSM measures would have clearly dominated renewables promotion. Of course, RE present other important advantages for society that are not considered here, such as industrial activity or technological development, which will as well bring large benefits in the longer term (in scenarios where energy efficiency potential is almost fully utilised and where renewables are therefore needed, e.g. to largely decarbonise energy sectors).

One element that muddles a bit the analysis of the optimal policy is that the existing investment in new CCGT capacity in the period (21GW) is too large, according to the results. The shadow price of the constraint that forces the model to invest 21GW is always positive. Indeed, without mandated CCGTs, the model installs between 2 and 11 GW (less than the actual 21GW), depending on the case, and total costs are lower. Combined cycles are being helpful in providing operating reserves to the system, but this does not justify the large existing volume of CCGT investment.

In fact, and interestingly, this study's main result is also contingent on the evolution of CCGT capacity. Although the main conclusion remains the same (DSM dominates RE for emissions reduction in both groups of scenarios), the extra cost of renewables for the system would be less, and the benefits of DSM would be greater, if the large investment in CCGTs had not occurred.

Despite the above-mentioned weaknesses of our study, we believe that our main conclusion (for curbing emissions in Spain, energy efficiency would have been cheaper than renewables) does hold for the short and medium term future. This will be true while inexpensive energy efficiency potential remains untapped and until renewable technologies become more competitive. Other institutions point at similar conclusions, such as Bloomberg New Energy Finance for the United States (Turner et al., 2010) or the International Energy Agency at global level (in the last World Energy Outlook).

To sum up, and answering this study's research question, demand side management clearly dominates renewable support instruments if our goal is to reduce carbon emissions to some extent at the lowest cost. Therefore, a natural policy conclusion is that, in this case, energy efficiency policies should be prioritised well above renewable energy promotion ones. This conclusion may still hold under other circumstances, since energy efficiency can also contribute to economic development or technological advances. However, it is also clear that energy efficiency cannot completely eliminate energy consumption. Therefore, if the goal is to have an almost fully decarbonised energy sector, renewables are also required in this second, more aggressive stage, which in turn may ask for support policies that promote their technological development. Hence, in a comprehensive energy policy over the long term, both renewables and efficiency are needed. The question then that can be asked is what should be the share of each, and how to coordinate their support policies to achieve the desired result at the lowest cost. More research is clearly needed to address this question.

Chapter VII.

MASTER_DS: A PROTOTYPE DYNAMIC SIMULATION MODEL.

VII.1	Outline of this chapter	273
VII.2	Model overview	273
VII.3	Our modelling methodology	274
VII.4	Description of the logic within the model	278
VII.5	Main outputs	289

VII.1. OUTLINE OF THIS CHAPTER

In this chapter we will describe the rationale behind our second proposed model, MASTER_DS. First, we provide a brief overview on the model. Then we justify our modelling methodology. Later, we detail the modelling that has been done, pointing out our main assumptions and hypothesis. Finally, we provide an overview of the types of outputs that can be obtained, which allows us to set the ground for a case example using this model (done in Chapter 8).

VII.2. MODEL OVERVIEW

As anticipated in chapter 4, MASTER_DS is a prototype that sets the basis for a modular dynamic simulation model where realistic aspects of energy markets could be represented.

A dynamic model is needed because it allows considering aspects that, by definition, cannot be represented in a static one, such as the temporal change in key parameters or dynamic constraints and how that affects the variables and outputs of model. For instance, MASTER_SO would be able to tell us how much capacity of a certain technology (e.g. Coal Capture and Storage) is needed in 2030. But in order to know in which year this capacity should start to be installed (depending for instance on the temporal evolution of its costs or in the maximum yearly capacity additions that the industrial framework would allow), a dynamic model is needed.

Instead of using MASTER_SO as a platform to build an optimization-based dynamic model, we now propose a completely new System Dynamics-based simulation dynamic model. It allows for the representation of trajectories/evolutions of the energy system under study under a set of policies, for example, between 2010 and 2030. As was said at the end of Chapter 4 when introducing MASTER_DS, the simulation approach allows the modeller to flexibly represent realistic aspects of energy markets such as myopia, imperfect competition or bounded rationality, which would have been more difficult (although not impossible) in the case of developing an optimization model based on MASTER_SO. Within the simulation family, we have used a System Dynamics-inspired technique, as will be justified in the next section

We have conceived MASTER_DS as a flexible and modular structure, a sort of *skeleton* which can be further enriched by future research, but its main structure is already implemented, working and providing useful results. Within our structure there are two main agents (energy consumers and energy utilities) who interact in the different final energy markets. The model is executed in a recursive dynamic manner from the current time towards the future (e.g. from 2010 to 2030), and in each year agents make their decisions. It would have also been interested to implement a backwarding version (executing from the future desired energy system to the present, e.g. from 2030 to 2010), but this has been left for future research. The yearly operation of the complete energy system is done using our optimization model MASTER_SO, which is called every year in its operation-only mode (i.e. capacities are fixed), as will be explained later.

VII.3. OUR MODELLING METHODOLOGY

Our modelling methodology is based on System Dynamics (Forrester, 1989, 1991; Sterman, 2000), although with some interpretation and implementation variations. We have chosen this technique for the following reasons.

First, because of one of its main strengths: it can be used to represent realistic systems where different agents interact, each of them having different behaviours with diverse decision making processes and degrees of rationality, which is very convenient for energy modelling. This is why, as seen in the review of the state of the art, it is a well-established technique for energy modelling with a large tradition over the last decades, since the works of Roger Naill at MIT in the early 1970s, until the present days. Indeed, today, System Dynamics is used for important applications such as the World Energy Model or POLES (both implemented in *Vensim*¹⁴⁹), or for other models with similar approaches such as NEMS: the accounting algorithms that NEMS, and many other models, include within some of their modules are, in essence, derived from the stock-and-flow representation of the System Dynamics tradition.

Second, one of the aspects of System Dynamics that we value the most is the conceptual graphic representation of relations and agents, where each agent or decision maker can be represented with a *box*, and information flows between them are represented with *arrows*. We believed that this had a large potential for enhancing model's transparency and ease of understanding, and it was one of the reasons for us adopting this technique. For instance, if we represent in a graph over time the information flows going in and out of one box (i.e. an agent making some decisions), important insights about the internal logic of the agent could be understood. This is not possible in other types of models, such as those based on optimization.

Third, the above-mentioned graphic representation enhances the modular nature of the technique, where an agent can be initially represented with one *box*, but with future research, its internal dynamics could be further detailed and broken down into several boxes. This also allows for future research to be carried out in parallel. For instance, several researchers could be working on improving the model at the same time, each focusing on one specific module and then put all together once the individual behaviours are well understood and tested.

Fourth and lastly, and related to the former reasoning, its modularity makes it a quite flexible technique, for instance making this approach very synergic with optimisation, which has already been used within this PhD thesis. Indeed, some boxes can represent strictly-optimizing behaviours, and they can be embedded within a broader framework which simulates bounded rationality or other behaviours. In our case, for example, we will use, within our dynamic model, a simplified version of MASTER_SO. Related to this, the flexibility is also from the *software* point of view: it can be implemented in various software tools/platforms. The most straightforward

¹⁴⁹ Vensim is one of the most common software packages for System Dynamics modeling. It has been developed by Ventana Systems. <http://vensim.com/>

ones are System Dynamics software packages, such as *Vensim* or *iThink*¹⁵⁰, where the visual/graphical characteristics of the technique, very relevant to collaborative modelling as advocated by System Dynamics practitioners (Morecroft, 2007), can be fully exploited. It can also be implemented directly in any other programming language, such as general-purpose languages (e.g. C) but in this case the graphical component, very relevant in this technique, may be lost. An interesting example is the BEST model¹⁵¹ (Sánchez, 2009), where the *causal loop diagram*¹⁵² is given through an Excel book, and then the internal logic within each box is programmed in Matlab. The use of general purpose languages or mathematical software such as Matlab, however, may provide some advantages in linking the model with external software such as mathematical programming languages and optimising software (e.g. GAMS+CPLEX). Vensim also includes, lately, these possibilities, but we believe that other languages provide more flexibility.

In addition, choosing System Dynamics had clear synergies with the PhD author's previous experience with this technique (Centeno et al., 2008; González-Blanch et al., 2010; López-Peña et al., 2009; Sánchez et al., 2007a, 2007b, 2008). He used it in his Master's thesis and during the supervision of a MSc. engineering thesis. In addition, during his PhD research visit to MIT, he established contacts with some researchers using System Dynamics for energy modelling (under the supervision of Professor Sterman).

Taking into consideration all the above we have decided to propose our dynamic simulation model MASTER_DS (whose internal logic will be described in the next section) with the following software implementation. It is a System Dynamics-inspired model, but instead of implementing it in specific System Dynamics software, and in order to be able to have full flexibility in interacting with other software packages (e.g. GAMS), we have decided to base it on Matlab. In order to keep the graphical aspect of System Dynamics (we wanted to keep the *box and arrows* approach), instead of only using Matlab code (as done in the BEST model mentioned above), we have used Simulink for the arrows and boxes. A screen capture of our Simulink model can be seen in Figure 81 (in this figure the reader should not worry about the details, which will be explained later: for the moment it is enough to simply grasp a broad idea of the aspect of the model). Each Simulink block is an "Embedded Matlab Function" block. These blocks allow us to define their inputs, outputs and all internal logic/calculations using Matlab code¹⁵³, which gives us very large modelling flexibility and possibility to interact with external software packages (e.g. GAMS).

¹⁵⁰ <http://www.iseesystems.com/software/Business/ithinkSoftware.aspx>

¹⁵¹ This model, also developed at IIT (Comillas University, Madrid) represents electric utilities' behavior over the long term in issues such as investment decisions in new power generation capacity, or forward contracting.

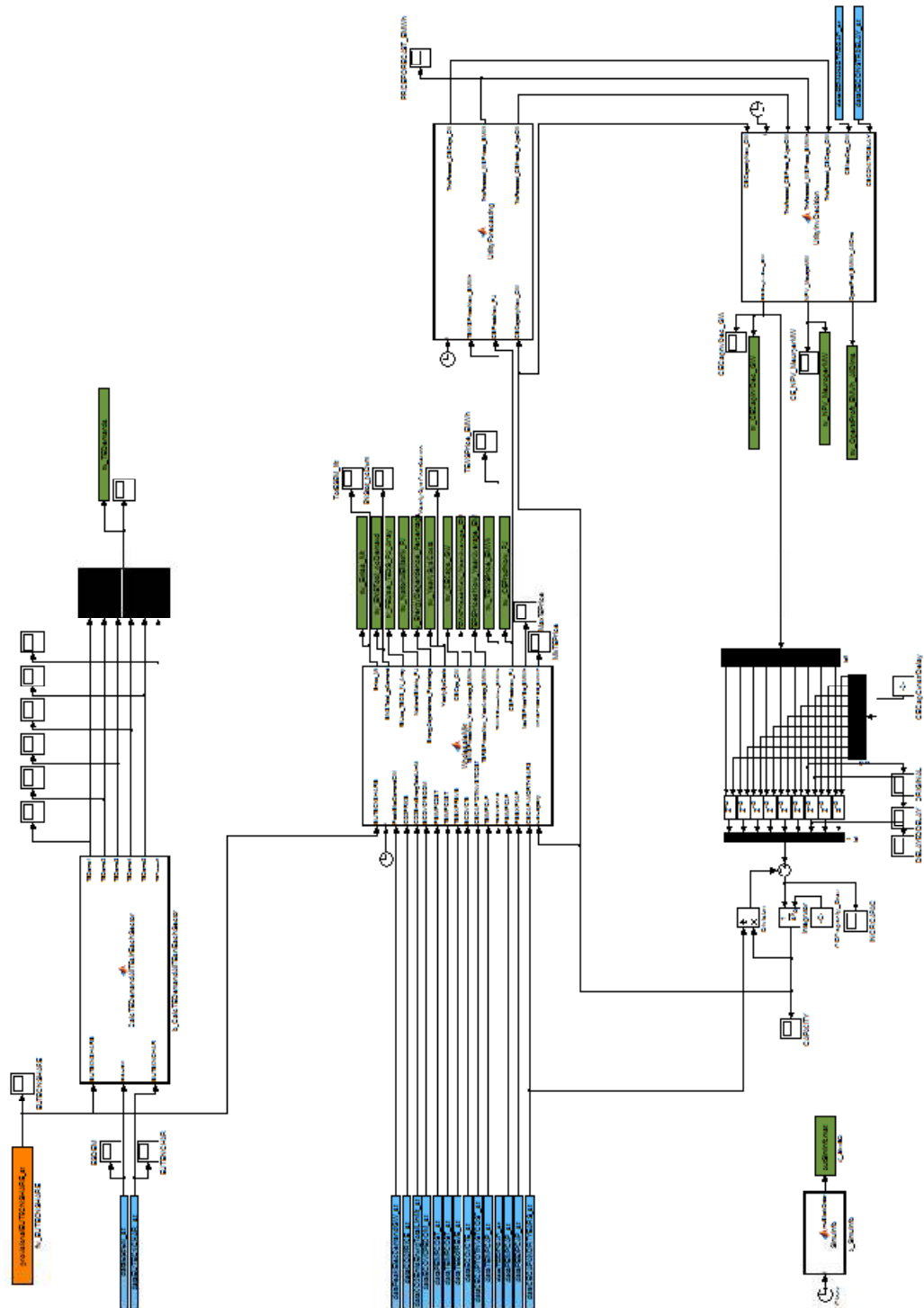
¹⁵² In the System Dynamics terminology, the *causal loop diagram* is the graphical structure representing all the information flows and variables in the system, as will be explained later.

¹⁵³ Simulink requires blocks with internal code to be converted into C code and then compiled prior to simulation. This is known as "code generation" in the Matlab terminology. However, not all Matlab code and commands are supported for code generation. This is why the code within "Embedded Matlab Function" blocks is not exactly Matlab code, but a subset of it called "Embedded Matlab". Furthermore, specific informatics requirements are

The model runs in a yearly recursive dynamic manner and in each simulation step (that is in each year, e.g. 2010, 2011, 2012, ... 2030), the different agents make their decisions (e.g. investing in new capacity, decommissioning assets, etc.). In each year, the agents interact in the energy market, which is represented as a minimization of the total costs of supplying demand for energy services within the country. For this, we use in each year our static optimization MASTER_SO model, which is called from one of the blocks in the MASTER_DS model. This allows us, also, to be able to obtain as output of our model the Sankey diagrams over the complete study horizon, which is very useful to obtain insights about its transformation in time under different policy scenarios. Some examples of this are provided in Chapter 8. In the next section, we give further detail about the internal logic and assumptions in MASTER_DS.

needed in the computer where the model is going to be run (e.g. a C compiler, some libraries, GAMS compatibility, etc.). This (which has been quite challenging) is detailed in one of the annexes in this thesis, where the full reference guide on how to prepare a computer for MASTER_DS to be run is explained.

Figure 81: Overview of the Simulink implementation of MASTER_DS.
 Source: own elaboration.



VII.4. DESCRIPTION OF THE LOGIC WITHIN THE MODEL

In this section we detail the specific modelling method that we propose for MASTER_DS, including its main internal logic, equations and assumptions. This framework is inspired on the BEST model (Sánchez, 2009), with which the PhD author worked in his pre-doctoral Master's thesis (López-Peña et al., 2009). This PhD thesis builds on the approach of that model in order to consider the full energy system (not only electricity).

VII.4.1. Agents in the system

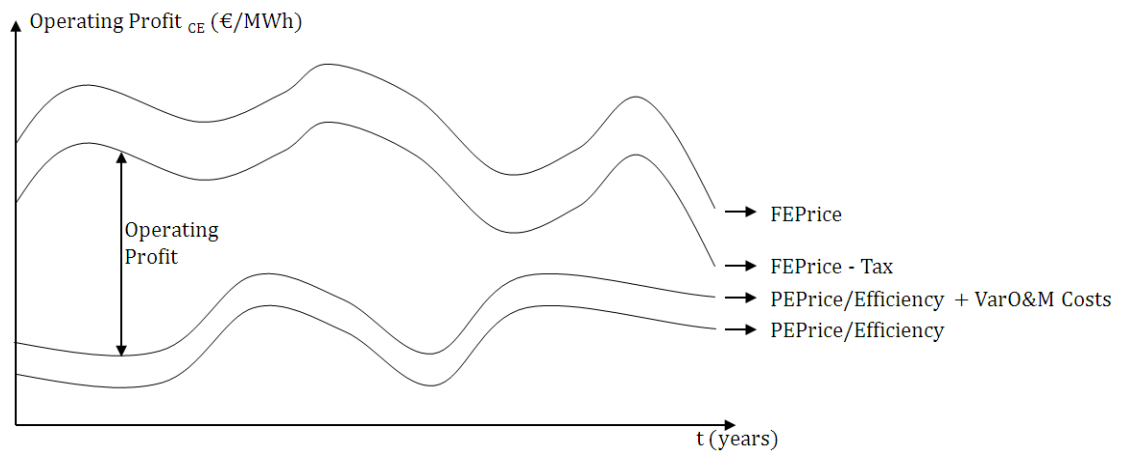
The first modelling hypothesis is that there are two main groups of agents in our energy system: energy consumers and energy producers. The first ones require energy services (e.g. mobility, illumination, etc.), which are exogenous parameters (our modelling approach is partial equilibrium with inelastic demand). In order to obtain those energy services, energy consumers own energy use equipment, which in our terminology are called Energy Services Supply Technologies, ESSTs (e.g. cars, lamps, etc.). This equipment consumes final energy (e.g. gasoline, electricity) to provide energy services. Energy consumers make the decisions of purchasing new energy use equipment, or decommissioning old equipment, according to some criteria, such as how they expect final energy prices to be, their reaction to energy efficiency policies, their forecasted evolution of technology costs, among other factors. For instance, if they forecast gasoline prices to increase, they may be interested in buying more efficient cars (even if they are more expensive than less efficient ones). The adopted hypotheses about future foresight or rationality (which in the end affect the discount rates used in these decisions) are key here. Another example would be consumers' investment/decommissioning decisions following governmental policies of cars' scrappage or subsidies for more efficient ones.

Energy producers are the ones producing the final energy that consumers (more precisely, their ESSTs) demand. Given that the MASTER_DS model is conceived for the Spanish energy system or other similar cases, we assume that energy producers only perform activity in the energy conversion business (identified in previous chapters with the "CE" acronym, and represented in the schemes in chapter 4 as "the third column" of our Sankey diagrams). We assume that energy extraction/production/import is done by other agents/companies. This is of course a simplification: in reality, energy utilities operate not only in the energy conversion business but also in energy production, trading, or transportation and distribution, through networks, to final consumers. Within our model we assume, for instance, that electric utilities purchase their gas in international markets and then transform it into electricity through the energy conversion equipment (e.g. gas-fired power plants) that they own. An improvement in this hypothesis on energy companies' business structure could be a very interesting line for future research, for instance in oil companies, which own at the same time upstream assets (exploration and production), trading/upstream transportation business, energy conversion (i.e. oil refining), and final products' logistics (downstream transportation, distribution and retailing).

If we assume that energy producers only operate in energy conversion, we can also assume that they make the investment/decommissioning decisions on conversion assets (e.g. power plants, LNG regasification terminals, oil refineries, biofuels production plants) mainly (but not only) considering the profitability of each energy conversion technology. This profitability is determined by several factors such as, but not only: (i.) the spread between the prices of primary energy and the wholesale markets for final energy; (ii.) the conversion relation or efficiency; (iii.) the costs of the conversion equipment; or (iv.) policies influencing these or other issues. In other words, energy utilities make their equipment investment/decommissioning decisions according to how they expect primary and final energy prices to be (i.e. how they expect the spread to evolve), according to the expected evolution of technologies and their costs, or according to energy policies such as subsidies, standards or taxes. Of course, in reality companies make their decisions based on other aspects, sometimes not easy to quantify, such as business strategy.

Our approach can be seen as an adaptation of the *operating profit* concept in energy conversion industries such as electricity generation. For example, one could say that a gas-fired power plant is more profitable the bigger the spark spread (the spread between the price of electricity it sells and the price of gas it burns), the bigger its conversion efficiency, the smaller its costs, and the smaller the price of CO₂ emissions (i.e. a policy). An illustration of this concept is given in Figure 82. In it, a conceptual representation of the evolution of the operating profit (only considering variable costs) is shown. It is the spread between the final energy price (after the application of taxes or subsidies), and the primary energy purchase costs (price divided by conversion efficiency) plus variable O&M costs. As said, this is only a conceptual representation (with illustrative purposes), among other reasons, because fixed and investment costs, or other factors, must also be considered when simulating the profitability of these assets and the decisions from energy companies to invest/decommission them. More detail will be given later.

Figure 82: representation of our idea of operating profit for an energy conversion plant.
 Source: own elaboration.



VII.4.2. Agent's interaction: final energy markets and the role of networks

Given that energy companies produce the final energy that consumers demand, they both interact in the markets for final energy. Just as we did in the static model, we assume that these markets take place in a single node configuration; in other words, there is only one wholesale price for each type of final energy in the country modelled (e.g. one electricity price for all Spain, one price for natural gas, one price for gasoline, or one price for kerosene). This wholesale price is the price just after the energy conversion process, where energy companies sell their product.

Then, each type of final energy is transported to final energy consumers through energy transportation (TE) processes (just as was done in the static mode). Each of these TE processes has its costs and efficiencies (e.g., in the current Spain, the electric grid has an efficiency of around 87% and costs of around 23€ per transported MWh, while the gasoline network has an efficiency of around 99% and costs of around 1.5€/MWh). This creates a spread between the wholesale and the retail price that consumers pay. Of course, this price difference is used to pay for the losses and for the services of the energy transportation and distribution companies. The behaviour of these companies has not been represented in our model: the costs and losses of the TE processes are fixed. We have not modelled it because they are (normally) regulated monopolies so we estimate that their behaviour is less relevant for the first steps of a prototype model like ours. This hypothesis is less valid in the oil business where downstream logistics (from a certain point) are mainly done through trucks and gas stations, and hence it is more subject to competition than natural gas and electricity distribution, which are indeed completely done through networks, being natural monopolies and hence regulated. In any case, representing these companies could be an interesting line for future research.

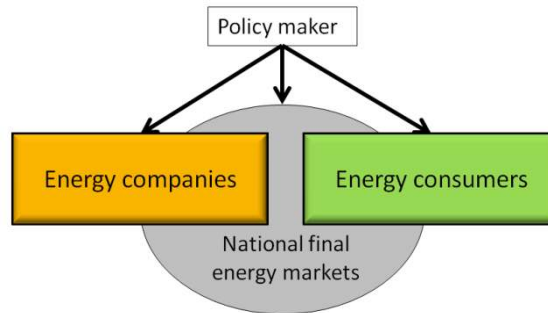
To sum up: the only agents we have modelled are energy consumers (owners of final energy use technologies which consume final energy and produce energy services), and energy producers only operating in the conversion business¹⁵⁴ (owners of energy conversion assets which transform primary energy into final energy). Both agents interact in the markets for final energy, where consumers pay the retail price and utilities perceive the wholesale price. The difference between these prices is given by losses and costs in energy transportation processes, which are input parameters.

This modelling framework is represented in Figure 83. In this figure we have also represented the policy maker (although it is not an agent itself in our model). Through its policies, the policy maker can affect the decisions made by both energy companies and energy consumers (e.g. giving a subsidy to a certain technology or fixing some type of standard). It can also affect the outcome of energy markets, for instance, through a tax on carbon emissions,

¹⁵⁴ We are aware of the simplification that this implies specially in the case of LNG regasification terminals, which we treat as conversion assets (hence operated by private energy utilities) but which, in the case of Spain, are owned and operated mainly by the natural gas transportation system operator, a regulated monopoly.

which may increase the relative attractiveness of less carbon intensive sources of energy. This could, for instance, cause energy companies to invest more on gas-fired power plants and less on coal-fired ones, or it could make consumers to buy biomass furnaces instead of diesel heating devices.

Figure 83: representation of the main agents in our prototype model and their interaction.
Source: own elaboration.

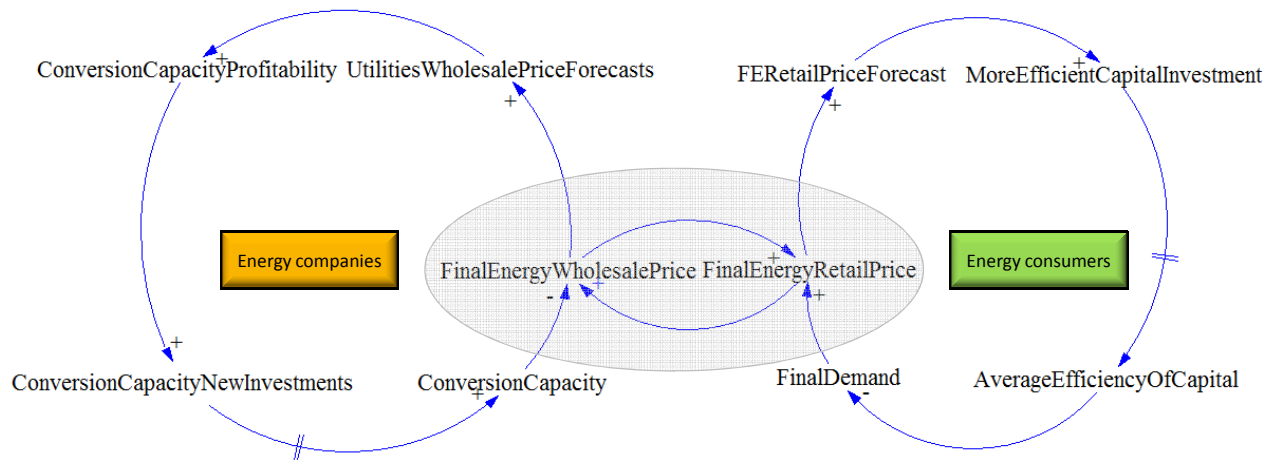


VII.4.3. The proposed causal loop diagram

Once this general modelling philosophy is clear, we can now present what in the System Dynamics terminology is termed the *causal loop diagram* (Sterman, 2000). A causal loop diagram represents the main qualitative relations between the variables of the system under *ceteris paribus* conditions, that is, if all the other influencing variables remain constant. We must emphasize the word *qualitative*: it does not represent how much one variable will change for a certain change in other variable, but rather the sign of this change (i.e. if it will *increase* or *decrease* its value). This is why it is key to assign each variable with a name that clearly states the direction: for example, instead of calling a variable “number of efficient appliances”, which can be confusing (e.g. out of how many total appliances?), it would be advisable to use something like “average efficiency of all appliances”, which has a clear sense (i.e. *increased* or *decreased* efficiency). In a causal loop diagram, two variables are related if there is an arrow linking them. This relation can be positive or negative, and each will be represented through a “+” or “-” sign. A positive (negative) relation means that if the first variable increases its value, the second one will increase (decrease) its value, under *ceteris paribus* conditions (all other variables remaining constant).

The main causal loop diagram in our proposed model is reproduced in Figure 84, and it will allow us to understand the two main feedback loops that interact within our proposed simulation model. In the figure, we have graphically identified (with similar colours as done in the previous figure) the loop that characterises the behaviour of energy producers, the one that characterises energy consumers, and in light grey we have identified their interaction through prices in the markets for final energy.

Figure 84: main causal loop diagram in our proposed model.
 Source: own elaboration.



Now, we will explain the main relations in each of these loops, beginning with the energy producers' one. Let's start with the wholesale price of final energy "FinalEnergyWholesalePrice". If this price goes up, companies will probably (although not necessarily, especially in the case of ambitious policies and large transformations in the energy system) estimate higher prices also for the future, so their forecasts of future wholesale prices "UtilitiesWholesalePriceForecasts" will also go up (positive relation, i.e. an arrow with a "+" sign). This will also increase the expected profitability of conversion capacity (if primary energy prices and technological costs remain constant, i.e. under *ceteris paribus* conditions), making the company invest in more conversion capacity. This capacity will come into the market with a certain delay (the two short parallel lines mean that a delay exists in this relation), which is the permitting and construction delay. The more the conversion capacity in the market, in principle, the less the wholesale energy price, being this last relation negative. This implies that the complete loop, now closed, has a negative feedback with a delay, which according to System Dynamics theory would imply an oscillatory behavior, just like the one observed in capital-intensive industries such as energy, where there are the typical boom and bust cycles (Ford, 2001).

In the energy consumers' loop, there is a second negative feedback loop. An increase in retail prices for final energy will make them forecast higher final energy prices in the future, and hence they will tend to invest in more energy efficient equipment. This, with a certain delay, will increase the average efficiency of final energy use capital, what will make final energy demand fall (there is a negative relation here). Given that demand and prices are positively related, there is an overall negative feedback in this loop as well, as expected. Finally, as wholesale and retail energy prices are linked through constant parameters (the energy transportation and distribution losses and costs), they are positively related in both senses.

Of this proposed general structure, we have only implemented the loop of energy companies. The consumer's loop, although its main conceptual basis is proposed, remained out of this PhD thesis scope, especially since some of its internal parameters can be subject of intensive research dealing with not only economic but also psychological or sociological issues.

We will now explain in further detail how energy companies behave. We will describe three main blocks: the first one is the representation of energy markets (both wholesale and retail) in the current year within the simulation; the second one describes how energy companies perform their forecasts for the future (concerning wholesale prices for final energy and the production of different conversion assets); and the third one consists of their decisions to invest in new conversion capacity (comprising the estimation of the profitability of future conversion assets and the actual decisions regarding new investments). Once these new investments are decided, they come into the system after a lag, which represents the number of years needed by each technology to obtain the needed permits and to be built. The decommissioning decisions from utilities have been simplified (it is not represented in the loop above): we simply assume that existing capacity is gradually (and linearly) phased-out during the number of years of its technical life.

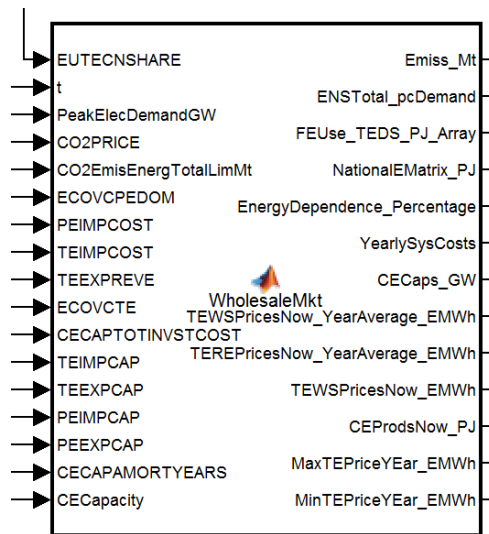
For all these decisions, even if simulation models can be very useful to replicate realistic aspects of energy markets (imperfect rationality, myopia, etc.), simulating these issues requires, as said in previous chapters, hard to estimate internal parameters. Doing this is an interesting line for future research, but in this first prototype we have tried to avoid them as much as possible: we preferred to avoid unknown parameters than to use them with arbitrary numbers.

VII.4.4. The energy markets within each year

As said in the specific objectives for this PhD thesis (chapter 1), the dynamic model, in each of its yearly steps, should have a representation similar to the static model. We have done this by computing the yearly energy markets (which can be considered as part of the total energy system) by solving our static model. More specifically, the dynamic model in every year calls (from the block represented in Figure 85) the static MASTER_SO model in its operation-only mode, i.e. fixed CE capacities, no new investments (because investments are decided out of this block, they are decided in each agent's loop). This execution of MASTER_SO yields all the energy flows within the system, the emissions, the prices, etc., as seen in Chapter 5. Of all these results, the energy markets are characterised by two main results, prices and productions/consumptions:

- **Prices:** these are the wholesale and retail prices (i.e. pre- and post-transportation/distribution processes), which are obtained for all types of final energy and for all load levels within the executed year.
- **Productions/consumptions:** the productions are the energy flows going from each conversion process to each final energy transportation/distribution process, while the consumptions are the flows going from these processes to each final energy demand sector.

Figure 85: Simulink block representing energy markets¹⁵⁵.
Source: own elaboration.



VII.4.5. Utilities forecasts

In our proposed model, utilities forecast, for the next 20 years, two main things: (i.) final energy wholesale prices; and (ii.) productions by each conversion technology of each type of final energy. The productions are forecasted in units of PJ/MW (equivalent to working hours, after a change in units), in order to be able to ensure comparability between different technologies in homogenous terms (even if we do not represent discrete investments in our model, i.e. the fact that some technologies such as solar are much more modular than others such as nuclear).

Both prices and productions are predicted as a linear interpolation between the current market result (the present, which is obtained by the block executing the energy markets in each year) and a future hypothesis in $t+20$. This future hypothesis assumes an ideal energy system in which the whole overall cost is minimized, which implies assuming perfect rationality and energy markets in that year in the future.

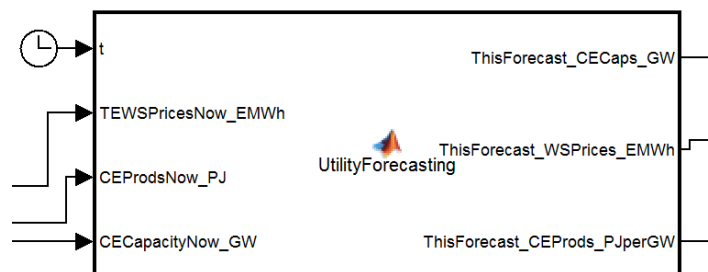
More precisely, this future situation is calculated executing, for the year “ $t+20$ ” the static model MASTER_SO having as input:

¹⁵⁵ The block is called “WholesaleMarket” because for now (we have only modeled the utilities’ loop) the only results of the MASTER_SO model that we need are those corresponding to the wholesale market. When consumers’ loop is modeled, the Matlab code within this block should be modified to (also) obtain from MASTER_SO the results of the retail markets, and then this block could be called “EnergyMarkets”. Also, many other auxiliary inputs and outputs appear on the Simulink figure, but the main ones are the ones explained within this chapter.

- The conversion capacities present today that will still be present after those 20 years (calculated through linear phase-out according to current capacity and technology's lifetime).
- The technology costs and primary energy prices used for this "t+20" foresight are the ones given through data for that year in the future, what implies perfect foresight (e.g. agents use for the year 2034 the price of gas in that year given through data, which is assumed to be the real one, and not an own estimation).
- The structure of final energy use technologies¹⁵⁶, which would in reality be decided by (presumably boundedly rational) consumers within their loop, are freely decided within the optimization model, which tries to replicate an ideal perfectly rational situation, and that all energy use technologies can be changed in 20 years¹⁵⁷.
- The demands for final energy (actual *energy*, not energy services) are perfectly known because they are calculated as the future demand for energy services (assumed to be known, i.e. perfect foresight again) multiplied by the structure of final energy use technologies (described in the previous paragraph) and by the needed conversion parameters of each final use technology (from energy services to final energy, as done in MASTER_SO), which are input parameters.

Of course, within this block (represented in Figure 86) the MASTER_SO model is called in its operation + investment mode with given previous capacity, contrary to what is done the energy markets' representation explained above. This difference is because in each year "t", the existing capacities are decided by utilities and consumers in their respective loops, being fixed for the market operation. On the contrary, for a year in the future we can make the hypothesis that in that future ("t+20") year the energy system will look like the one forecasted by our model in its operation + investment mode. Of course this may not be the case if, for instance, competition between utilities is not perfect.

*Figure 86: Simulink block representing utilities' forecasts.
Source: own elaboration.*



¹⁵⁶ Characterized through the "eutecnshares" variables which model the shares of each energy service provided by each final use technology.

¹⁵⁷ That is, none of the current "eutechshares" in "t" affect the year "t+20", it is "greenfield" from the point of view of demand technologies.

Many of these hypotheses regarding forecasts could be changed to add more realistic features of energy markets, such as myopia (using for example trend extrapolations for the future prices of primary energy) or less optimality in the consumers' decision defining the structure of final energy use technologies.

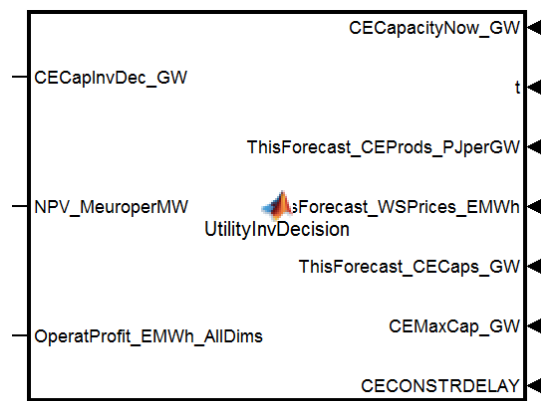
Finally, for the years between “t” (executed in the “energy markets” block) and “t+20” (executed here), we perform a linear interpolation of all relevant variables (prices, productions and capacities). The productions in PJ/MW terms are simply obtained by dividing the last two.

VII.4.6. Utilities investment decisions

In this module, which is represented in Figure 87, two main activities are modeled, of the ones represented in the causal loop diagram above: (i.) profitability calculation (based on the forecasts; and (ii.) actual investment decisions in new conversion capacity. Both will be explained next.

Figure 87: Simulink block representing utilities' investment decisions.

Source: own elaboration.



As was done with production forecast, the profitability is computed per unit of installed capacity (i.e. per MW), in order to ensure comparability among technologies. This profitability is calculated using the net present value (NPV) concept, which consists on discounting (during the forecasted 20 years used) a stream of free cash flows (FCF), as commonly explained in financial literature and as mathematically described in the equation below. The discount rate depends on the technology (i.e. general rate + possible risk premium of the technology).

$\forall y, ce:$

$$NPV_{y,ce} = \sum_{t=y}^{y+20} \frac{FCF_{t,ce}}{(1 + DiscRate_{ce})^{t-y}}$$

[Eq. 44]

For all energy conversion technologies “ce”, in each execution year “y” (i.e. from current time towards the future, such as 2010, 2011... 2030), the NPV is the actualised value of free-cash-flows from year “t=y” to year “t=y+20” using the exogenously given discount rate.

In each year, the FCF is calculated as the operational profit minus the fixed operating and maintenance costs minus the annuity (i.e. depreciation) of the investment costs, as detailed below:

$\forall t, ce:$

$$FCF_{t,ce} = OperatProfit_{t,ce} - FixedO\&MCosts_{t,ce} - AnnuityInvestCosts_{t,ce}$$

$$OperatProfit_{t,ce}$$

$$= \sum_{te,p,s,l} \left[ForecProd_{t,ce,te,p,s,l} \cdot \left(ForecFEPrice_{t,te,p,s,l} + Premium_{t,te} - Taxes_{t,te} - \sum_{pe} \frac{ForecPEPrice_{t,pe,p,s,l}}{ConversionEfficiency_{te,pe}} - CEVAROMCOST_{ce,te} \right) \right]$$

$$FixedO\&MCosts_{t,ce} = InstalledCap_{t,ce} \cdot FixedO\&MCostsPerCap_{t,ce}$$

$$AnnuityInvestCosts_{t,ce} = InstalledCap_{t,ce} \cdot CECapTotInvestCost_{ce}$$

$$\cdot \frac{AmortRate_{ce}}{\left(1 - \left(\frac{1}{1 + AmortRate_{ce}} \right)^{CECapAmortYears_{ce}} \right)}$$

[Eq. 45]

For all energy conversion technologies “ce”, in each forecast year “t” (i.e. from current year until 20 years in the future), the FCF is the operational profit minus fixed O&M costs in the year minus the annuity of the investment costs.

The operating profit is calculated as the forecasted production of this “ce” (of all types of final energy, in all time slices) multiplied by the unitary operating profit, which is the price perceived (wholesale) plus premiums minus taxes minus costs of each used primary energy (price divided by conversion efficiency) minus variable O&M costs. To better understand this it may be useful to look again at Figure 82 above.

The fixed O&M costs are calculated just by multiplying the annual unitary fixed O&M cost (M€/MW-year) and the installed capacity in the year.

The annuity of the investment costs is calculated considering the installed capacity, the total overnight investment cost (M€/MW, for the complete life of the asset), and lineally depreciating it during the amortization years (assumed to be the same as the technical life of the asset) and an amortization rate (which tries to replicate the weighted average cost of capital of the technology), calculated as the general discount rate plus a technology-specific risk premium.

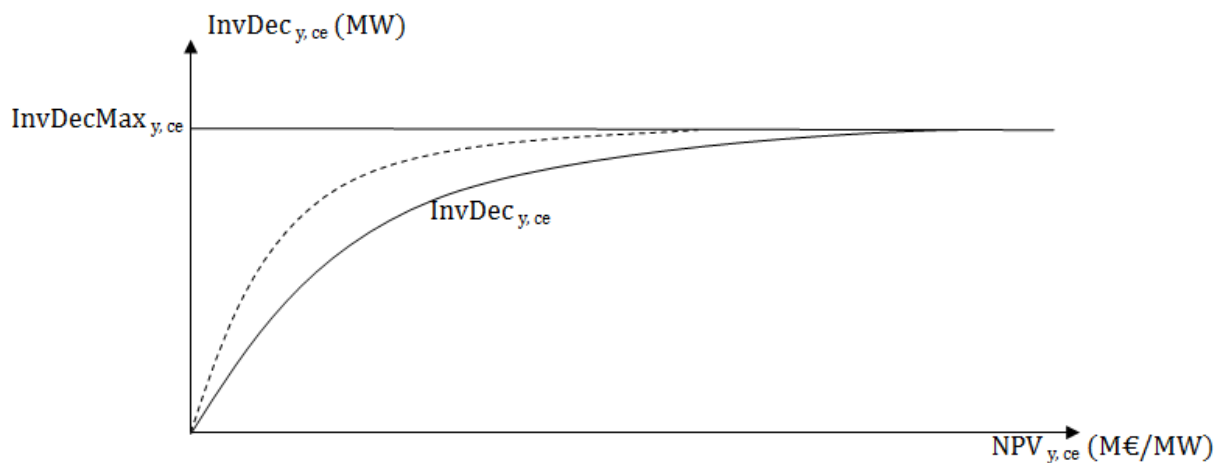
Then, once this profitability per technology (NPV) has been calculated, the investment decisions are taken. In reality, this relation can be very complex, involving many different factors. We have followed the same approach as (Sánchez, 2009): we have approximated it with an experimental curve. This is another of the basic features of the System Dynamics technique: very complex relations can be simply modeled through empirical mathematical expressions which (ideally) are consulted and agreed with the users of the model and other experts or

decision makers. In our case, the used relation establishes that a growing profitability will involve growing investment, but with a saturation which reflects many different issues such as the possible risk averse or strategic behavior of agents limiting invested capacity in the case of high profitability, the possible lack /cost of financing, or the supply chain constraints (i.e. a country not being able to build a very large amount of a technology if a certain industrial backbone has not been established yet).

Hence in each time step, the investment decision in each CE technology is decided according to the following exponential relation shown in Figure 88 and the equation below it. The saturation speed in the curve is an exogenous parameter, and we have assumed it to be inversely proportional to the investment cost: as the investment cost grows, the saturation is slower, i.e. for the same profitability, if the investment cost grows, the agent will invest less. This can be interpreted as an indicator of companies' risk aversion. This is represented in the figure with the dashed line, which represents a technology with a smaller investment cost in which agents are less risk-averse and hence saturation is faster, or in other words, for a same profitability level, tend to invest more.

Figure 88: investment decisions as a function of profitability.

Source: own elaboration.



$\forall y, ce:$

$$InvDec_{y,CE} = InvDecMax_{y,CE} \cdot \left(1 - e^{-\frac{NPV_{y,CE}}{InvCost_{y,CE}}}\right)$$

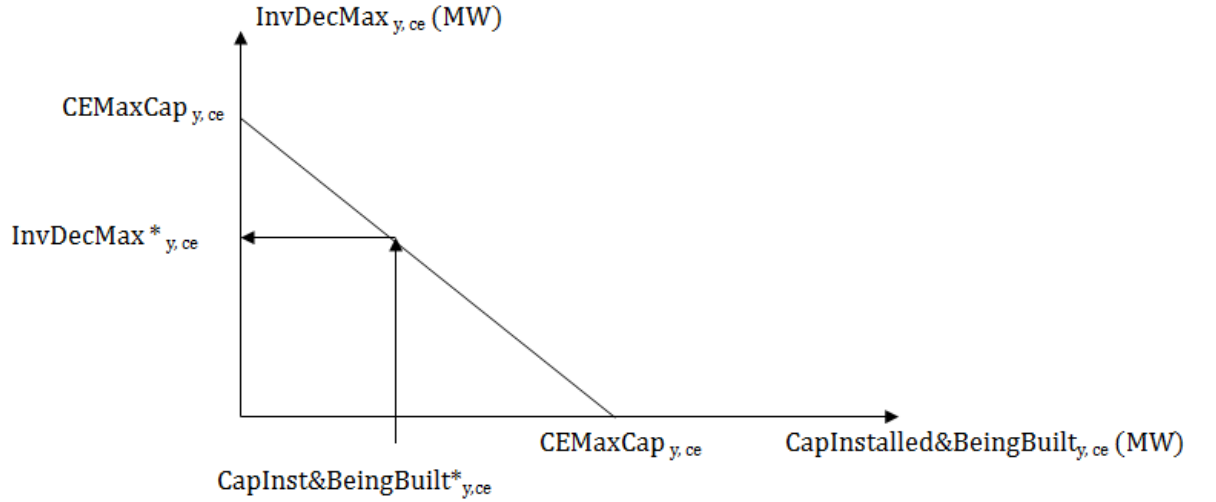
[Eq. 46]

For all energy conversion technologies “ce”, in each execution year “y” the investment decision in MW is approximated as an exponential curve which grows with profitability but saturates in the maximum investment decision “InvDecMax” (see below a discussion on this factor). The saturation speed is inversely proportional to the investment costs.

To compute the maximum investment decision factor, we have assumed that it depends on the current installed capacity, the maximum possible installed capacity (per technology) and the amount of capacity that is being built but has not yet entered the system (depends on each

technology's construction time). A graphical representation of the calculation of these values is represented in Figure 89 and detailed in the equation below it. The absolute maximum “CEMaxCap” that we have used (for the case where there is neither capacity installed nor being built) is the total amount of capacity that can be built of each technology (“CEMaxActiveCap”), applying a 0.1 factor to model that this maximum capacity can only be reached within 10 years. We have assumed this maximum capacity to be 80GW for manageable power generation (i.e. assuming an 80% share in the mix over a 100GW total installed capacity, similar to the current one in Spain), 300GW for intermittent power generation (because of the large potential of solar power in Spain), and 200GW for LNG regasification and oil refining. For simplicity, a linear relation is assumed in the intermediate values.

Figure 89: maximum investment decisions calculation.
 Source: own elaboration.



$\forall y, ce:$ $InvDecMax_{y,ce} = 0.1 * CEMaxCap_{y,ce} \cdot \left(1 - \frac{CapInst\&BeingBuilt_{y,ce}}{CEMaxCap_{y,ce}}\right)$	[Eq. 47]

VII.5. MAIN OUTPUTS

From this model, which has more of a exploratory/descriptive nature, we can obtain outputs such as the temporal evolution of system costs (and each cost component), emissions, technology penetration, energy prices, energy use, the primary energy matrix, or the Sankey diagrams in each year, under different policy scenarios. A case example is shown in Chapter 8.

Chapter VIII.

AN ILLUSTRATIVE CASE STUDY WITH MASTER_DS: PATHWAYS FOR THE SPANISH ENERGY SYSTEM.

VIII.1	Outline of this chapter	293
VIII.2	Research question, energy sector representation, data and scenarios	293
VIII.3	Results and discussion	297
VIII.4	Conclusions	312

VIII.1. OUTLINE OF THIS CHAPTER

In this chapter we present an illustrative case study with the MASTER_DS model, which allows us to show that, even being a prototype for now, we can obtain interesting results and insights on the possible pathways of the Spanish energy system. In this chapter we shall avoid text as much as possible and will use graphs instead to describe the observed evolutions. First we introduce our research question, we provide an overview of the considered energy sector representation (i.e. energy types, technologies, etc.), then we comment on the data used and later we introduce the scenarios analysed. After, we present the results obtained, which include, for all scenarios, the evolution of final energy use, the energy matrix of the country and its energy dependence, the Sankey diagrams, prices for final energy, the evolution of energy conversion capacities, the CO₂ emissions or the system costs. Finally, we draw some methodological conclusions.

VIII.2. RESEARCH QUESTION, ENERGY SECTOR REPRESENTATION, DATA AND SCENARIOS

The research question that we try to answer within this chapter is mainly methodological (i.e. not strictly related to energy policy itself). We have proposed a prototype System Dynamics-based simulation model of the Spanish energy sector (MASTER_DS). Now we will try to see if, using realistic data and assumptions, MASTER_DS can already be used with an exploratory rationale (i.e. to explore possible future evolutions under different scenarios) and if it yields realistic and useful results. From the policy perspective, although this is not our main research question, we will try to see how different evolutions of the energy demand side (and notably its average energy efficiency), affect key variables of the Spanish energy system such as energy use, costs, energy dependence or emissions.

In the next paragraphs, our energy sector representation, used data and considered scenarios will be explained. Even if the core of MASTER_DS is the execution of MASTER_SO (to represent the yearly energy system operation), we have adopted a representation of the energy system that is simpler than the one described in previous chapters. This is due to modeling and data availability issues, as well as computer running times. Indeed, doing such a complete representation of end use technologies as done in MASTER_DS (refer to chapters 4 and 5) would have implied many uncertain parameters on the evolution of many technologies, and the size of the yearly optimization problem would have grown importantly, making execution times almost ten times larger (currently each execution takes around 4 minutes).

Each year is represented with 12 time slices: we assume three seasons (winter, summer and medium, which is equivalent to spring and autumn), two day types per season (weekday and weekend) and two load levels per day (peak and off-peak).

The primary and final energy types we have used, and the considered conversion technologies, are detailed in the next figures.

Figure 90: primary energy types considered for the MASTER_DS model.
Source: own elaboration.

PENUCLE	"PE Nuclear"
PECOAL	"PE Coal"
PELNGAS	"PE Liquefied Natural Gas"
PECROIL	"PE Crude Oil"
PERESGEST	"PE Renewable Energy Sources Manageable"
PERESINT	"PE Renewable Energy Sources Intermittent"

Figure 91: energy conversion technologies considered for the MASTER_DS model.
Source: own elaboration.

CEELENUCL	"CE Nuclear Power Plant"
CEELECOAL	"CE Coal Power Plant"
CEELECCGT	"CE Combined Cycle Gas Turbine"
CEELEOCGT	"CE Open Cycle Gas Turbine"
CEELEREGEST	"CE Renewable Power Manageable"
CEELEREINTE	"CE Renewable Power Intermittent"
CELNGREG	"CE Liquefied Natural Gas Regasification"
CEOILREFMC	"CE Oil Refinery Medium Complexity"
CEOILREFHC	"CE Oil Refinery High Complexity"

Figure 92: final energy types considered for the MASTER_DS model.
Source: own elaboration.

TEELE	"TE Electricity"
TEGAS	"TE Natural Gas"
TEOPGSN	"TE Oil Product Gasoline"
TEOPDIE	"TE Oil Product Diesel"
TEOPLPG	"TE Oil Product Liquefied Petroleum Gas"
TEOPKER	"TE Oil Product Kerosene"
TEREN	"TE Renewable"

We assume investment costs of each conversion technology to evolve according to the projections documented in the Data Documentation Annex and outlined in Figure 93: we assume cost improvements mainly in nuclear, coal (modern technologies), CCGTs and intermittent renewables.

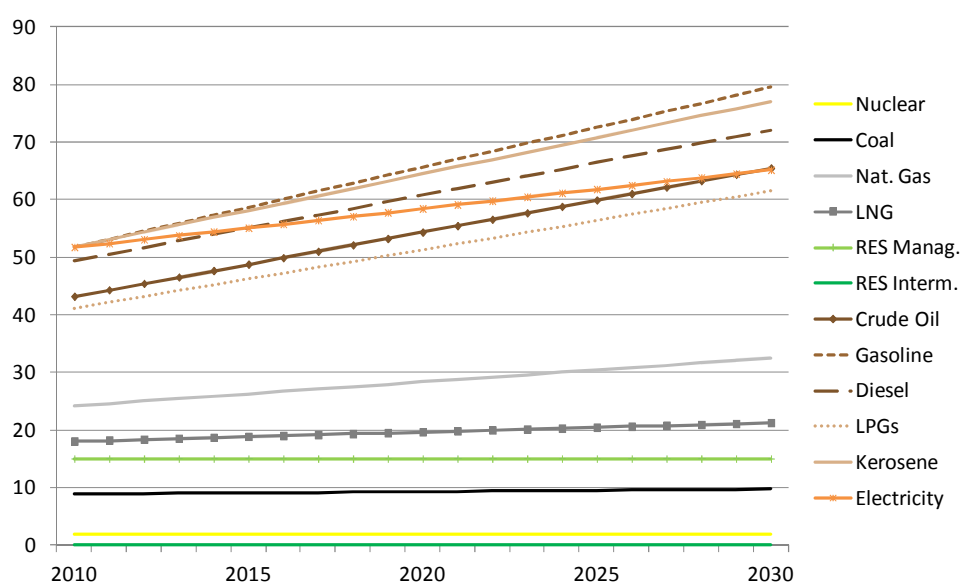
Figure 93: evolution of energy conversion capacity investment costs considered (€/kW output).
Source: own elaboration.

	2010	2020	2030
Nuclear Power Plant	3579	3680	2850
Coal Power Plant	2021	2058	1724
Combined Cycle Gas Turbine	760	720	581
Open Cycle Gas Turbine	682	680	640
Renewable Power Gestionable	2330	1880	1840
Renewable Power Intermittent	1383	1104	923
Liquefied Natural Gas Regasification	35	35	35
Oil Refinery Medium Complexity	350	350	350
Oil Refinery High Complexity	700	700	700

Also, we consider a CO₂ price which is applied to all emissions (not just to the European Emission Trading Scheme sectors), which grows lineally from 19€/tCO₂ in 2010 to 119€/tCO₂ in 2030. As an illustrative case, we have also assumed a constant premium of 10€/MWh to both renewable generation technologies.

Concerning international prices of energy, our hypotheses are based on the latest official projections (as shown in the Data Documentation Annex), but adapted to the case of Spain (see Figure 94, where these prices are plotted in constant 2010 € per MWh). The case of gas is notable, where we have assumed LNG prices (set in a hypothetical global market) to evolve more favourably than natural gas (from Algeria through pipeline), in order to account for the possible arbitrage of shale gas exporters¹⁵⁸.

Figure 94: evolution of the import prices of primary and final energy (€/2010/MWh) for all the scenarios.
Source: own elaboration.



We have considered five demand sectors, shown in Figure 95.

¹⁵⁸ This may be a questionable hypothesis, but as said this case example is just for illustrative purposes.

*Figure 95: final energy demand sectors considered for the MASTER_DS model.
Source: own elaboration.*

DSIND	"DS Industry"
DSRESID	"DS Residential"
DSCOM	"DS Commercial"
DSTRAPASPRIV	"DS Transportation Passengers Private"
DSTRAPASPROF	"DS Transportation Passengers Professional"
DSTRAFREPROF	"DS Transportation Freight Professional"

Within MASTER_DS, the yearly executions of MASTER_SO consider most of the technical constraints explained in chapters 4 and 5, of course adapted to this case where a significantly smaller number of energy types and technologies are considered. Concerning data, we have used the values shown in Data Documentation Annex, with adaptations if needed. This means that the figures and quantities obtained are representative of the actual Spanish energy system, and the results obtained are in the correct orders of magnitude (of course, taking into account that models are just models, and their results may differ from reality).

As introduced in chapter 7, when describing the modeling rationale used in MASTER_DS, simulation models allow representing different degrees of rationality, myopic forecasting capabilities, imperfect markets, etc. But for that, internal parameters are needed which may be difficult to estimate and may play against the transparency and trustworthiness of a model. Given that this PhD thesis proposes a prototype/basic structure for such a model, obtaining these parameters was out of our scope. Consequently, in this case study we have used some hypotheses which represent perfect rationality, perfect markets and full forecasting capabilities from agents, such as assuming that in their forecasts agents know the correct future value of international energy prices, technology costs or demand for energy services (all given through data), or that they assume the energy system in the future to be the result of a cost minimization (for their forecasts in $t+20$).

We have considered four scenarios, which represent possible evolutions of the demand side in the Spanish energy system. More precisely, they represent four possible evolutions of the stock of energy-use equipment, which determine the average efficiency (i.e. the total demand for final energy, given that the demand for energy services is considered to be the same in all scenarios) and the types of final energy demanded (e.g. larger electrification, larger share of renewables for final use, etc.). We have used this approach because, as said above, modeling consumers' loop (which would represent consumers' decisions and policy measures affecting demand side, and eventually, the evolution of this stock) was out of the scope of this PhD thesis.. The four considered scenarios are called "Base", "Gas", "Electricity", and "Green", as shown in Figure 96.

Figure 96: scenarios considered for this case study.
Source: own elaboration.

Scenario	Efficiency	EnergyTypes
Base	Important	Electricity, Gasoline, Renewables, Gas,...
Gas	Important	Larger final use gasification
Electricity	Very important	Larger final use electrification
Green	Very important	Larger share of renewables in final use

The first scenario (“Base”) intends to simulate a case where the level of achieved energy efficiency is already quite important and the final energy mix is diversified. It should be made clear that this energy efficiency scenario (important efficiency gains implying 20% final energy use reduction between 2010 and 2030) may seem very optimistic, but it is feasible: it corresponds with the “Policy” case in (Economics for Energy, 2011). We have assumed that our “Base” scenario fulfills these reductions because of the large importance that energy efficiency policies should play in any set of sustainable energy policies, especially in energy inefficient countries such as Spain, hence we opt to consider this case as our reference. These demand reductions go much further than the official projections, which are inexistent until 2030 but forecast, for 2020, the same level of final energy use as in 2010¹⁵⁹ (Ministerio de Industria, Turismo y Comercio, 2011a). Our “Gas” scenario represents the same level of final energy efficiency, and models a larger gasification of the economy, especially in the transportation sector. The “Electricity” and “Green” cases simulate a significantly higher level of energy efficiency (another 15%, i.e. 35% reduction over 2010 levels in 2030) which may be slightly optimistic but is used here for illustrative purposes. The “Electricity” case models a large electrification of final energy uses, notably transport and residential sectors, while the “Green” one represents a very significant adoption of renewable-based end use equipment, consuming renewables such as solar thermal, biomass or biofuels.

It should be noted that this case example does not exactly follow the methodological approach proposed in Chapter 4, where MASTER_SO is first used to decide the energy system in a year in the future (e.g. 2013) and then, MASTER_DS is used to assess the best way to reach that point, considering realistic aspects of energy markets (e.g. myopia, bounded rationality, etc.). This is because MASTER_DS is for now just a prototype model which, eventually, could incorporate these capabilities (as pointed out in the “Further research” section below), but which are not included yet. For now, MASTER_DS is used with an explorative approach, under four different scenarios which four different energy systems in 2030.

VIII.3. RESULTS AND DISCUSSION

As said, we will show the results in a very graphical way, mainly using figures. First, we will provide the main results showing how energy is used in Spain throughout the studied

¹⁵⁹ Assumes a 2% real GDP growth rate between 2010 and 2020, combined with a yearly improvement of 2% in the final energy intensity, implying a flat level of final energy use.

period (2010-2030), mainly: (i.) the evolution of final energy use per sector and per type; (ii.) the evolution of the national energy matrix and energy dependence; and (iii.) the Sankey-based representation of the evolution of the Spanish energy system. After that we will provide the evolutions of final energy prices (yearly averages, not for all the 12 time slices) both at the wholesale and retail levels. Then we will show the evolution of the installed capacities of energy conversion technologies under each of the four scenarios, and to better understand these evolutions we will show the investment decisions and the profitability per technology. Finally, we will show the emissions levels and the system costs, including its components.

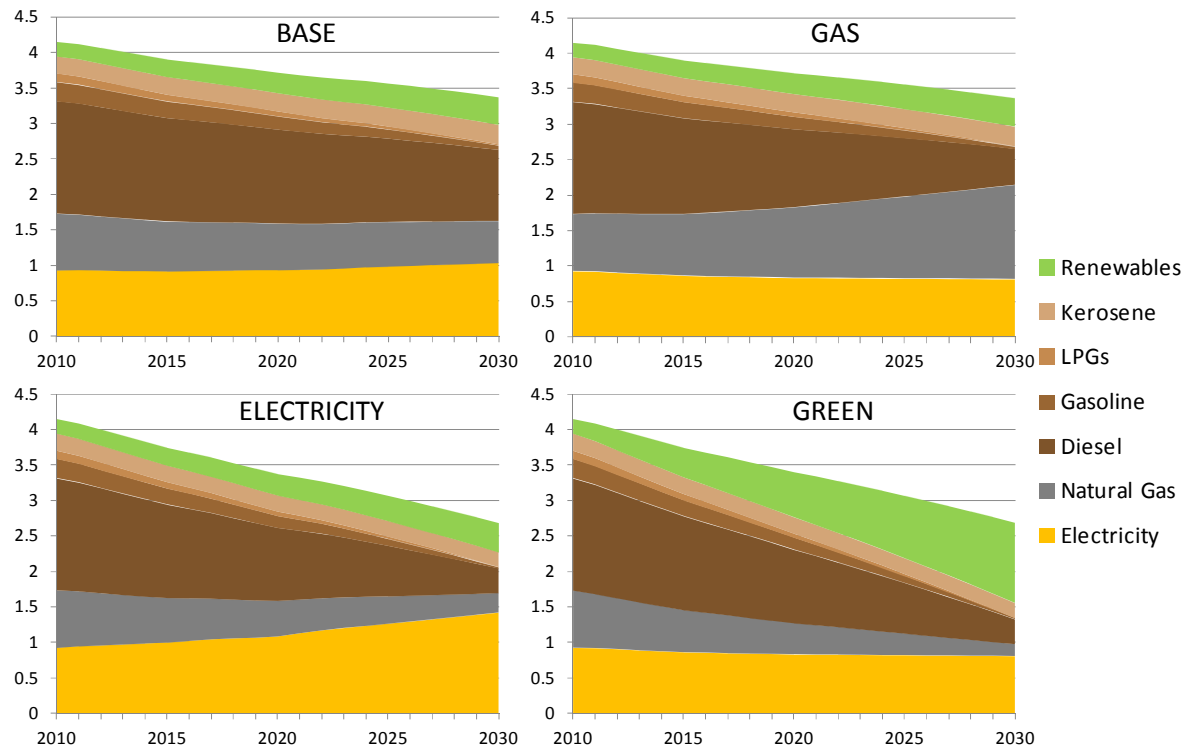
The colour code used is the same as throughout this entire PhD thesis: yellow for nuclear, green for renewables, grey for natural gas, brown for oil products, black for coal and light orange for electricity. Losses and self consumptions are represented in red, and final demand sectors in the same colours as in the Sankey diagrams: purple for industries, dark green for transportation, and blue for other uses sector (notably commercial and residential). In some cases, slight tone variations are used to differentiate between products of a same family.

VIII.3.1. Energy use

VIII.3.1.a. Final energy use

In Figure 97 the final energy use per type under each of the four scenarios can be seen. The first thing that should be noticed is that all four scenarios present important energy use reductions, in line with our hypotheses regarding energy efficiency (explained above). In the “Base” and “Gas” scenarios, the reduction of energy use between 2010 and 2030 is around 20% (from 4.1 EJ to around 3.3 EJ), while in than the last two scenarios (i.e. “Electricity” and “Green”) a higher degree of energy efficiency is achieved, with total demand in 2030 falling below 2.7 EJ (i.e. -35%). Also, it is clear that each final energy type plays a special role in each corresponding scenario (e.g. important role of natural gas in the “Gas” scenario or of electricity in the “Electricity” one).

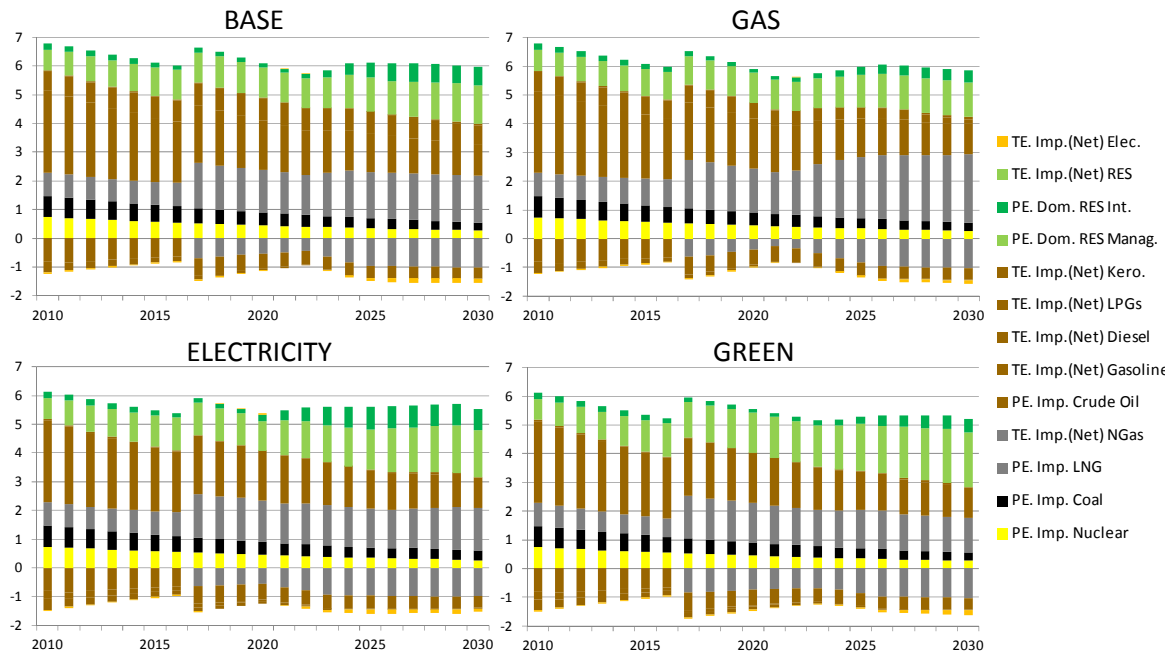
Figure 97: evolution of final energy used per type (measured in EJ) in the four scenarios.
 Source: own elaboration.



VIII.3.1.b. National (primary and final) energy matrix

In Figure 98, the evolution of the national energy matrix in the four scenarios is represented. We call it *national* because it does not refer to *final* or *primary* energy, but to the total energy (of all kinds, be it primary or final energies) used by the country, including domestic production, exports and imports. Primary energies are identified as “PE” while final energies are identified as “TE”. For primary energies we have depicted their imports and their domestic production (which for the Spanish case is only of renewable energy sources “RES”, both manageable and intermittent). For final energies we have represented their *net* imports (i.e. imports-exports), which take negative values for energy carriers which are exported in net terms in each year. We represent them together in the same graph because it allows to correctly understanding their relative magnitudes and how they all add up in the total energy use in the country.

*Figure 98: evolution of the national energy matrix (in EJ) in the four scenarios.
Source: own elaboration.*



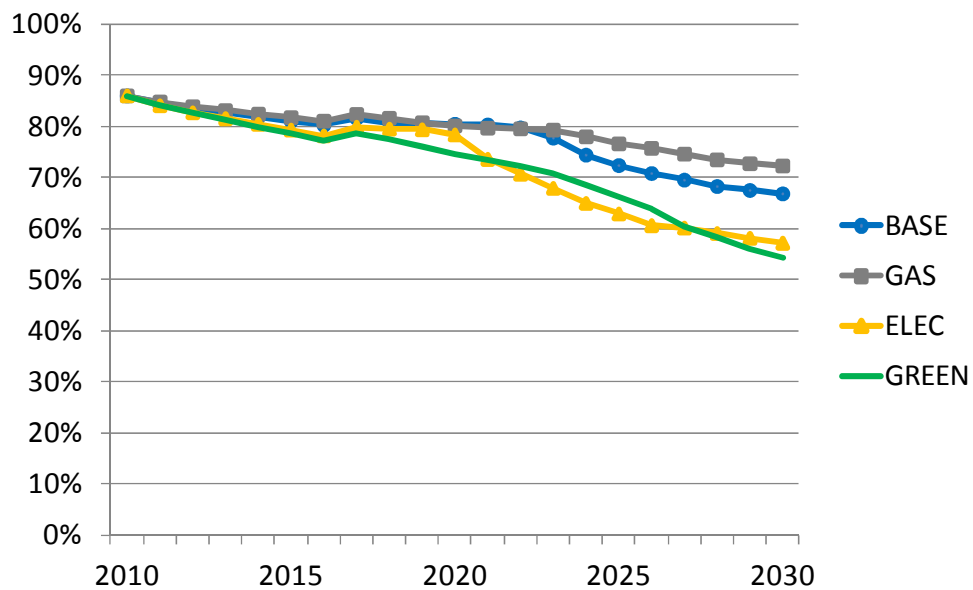
It can be seen how the imports of coal and nuclear decrease linearly in all cases while these technologies are phased out of the power generation mix (see section VIII.3.3 below). The model only imports gas in the form of LNG (less expensive) and, when the price differential between both is enough (this spread grows, as seen above), it decides to increment regasification capacity, import more LNG to regasify it and export it towards France until the interconnection capacity is fully utilised (no investments allowed). Spain is a net importer of crude oil and diesel, and net exporter of gasoline (concerning other oil products, less relevant in energy terms, mixed trends are observed). Concerning renewables, they have important share gains as they become more competitive for power generation, as the prices of fossil fuels and CO₂ emissions grow while policy support is maintained (which is reflected in the constant feed in premiums). The share of renewables in the national energy matrix grows especially in the “Green” scenario.

VIII.3.1.c. Energy dependence

As a direct implication of the values behind the national energy matrix, the level of energy dependence in each scenario can be seen in Figure 99. It should be reminded that we consider nuclear power as entirely imported for the case Spain (hence the current energy dependence is higher than the one reported in official statistics). It can be seen that the reduced use of final energy in all four scenarios, in which renewables play also larger roles, produces an important improvement in energy dependence, improving more in the two cases with higher energy efficiency. Energy independence should hence be another reason to pursue ambitious policies for energy efficiency and renewables penetration, as repeatedly reported in the literature. The “Gas” scenario represents a worsening in energy dependence, because end use technologies that

in the “Base” case consume domestic renewables (e.g. biofuels-based¹⁶⁰ transportation, biomass furnaces for space heating, etc.) or electricity (largely) generated with renewables, switch to gas-based technologies, being gas entirely imported. The “Electricity” and “Green” scenarios yield similar outputs since much of the added power demand that the “Electricity” case represents is generated with renewables. In other words, the amount of renewables consumed in final energy in the “Green” case is similar to the one consumed (embodied within electricity) in the “Electricity” scenario.

*Figure 99: evolution of the energy dependence (%) for the four scenarios.
 Source: own elaboration.*



VIII.3.1.d. Sankey diagrams

In this section we present the evolution of energy flows throughout the complete energy system using Sankey diagrams. For clarity purposes, and given that we are representing 20 years, i.e. from 2010 to 2030, we will only show the diagram in 5-years steps. We include a first diagram (Figure 100) showing the situation in 2010, which is common for the four scenarios, and where some tags have been included to indentify the main processes and flows. Then, in Figure 101, we show the diagrams in 2015, 2020, 2025 and 2030 in the four scenarios, put all next to each other and in the same scale, to improve comparability. As said above, the four energy systems in 2030 are different, because in this case example we have used the model with an exploratory rationale.

¹⁶⁰ We have assumed biofuels to be entirely domestic, which is not the case currently in Spain.

Figure 100: Sankey diagram of the Spanish energy system in 2010, common for the four scenarios.
Source: own elaboration.

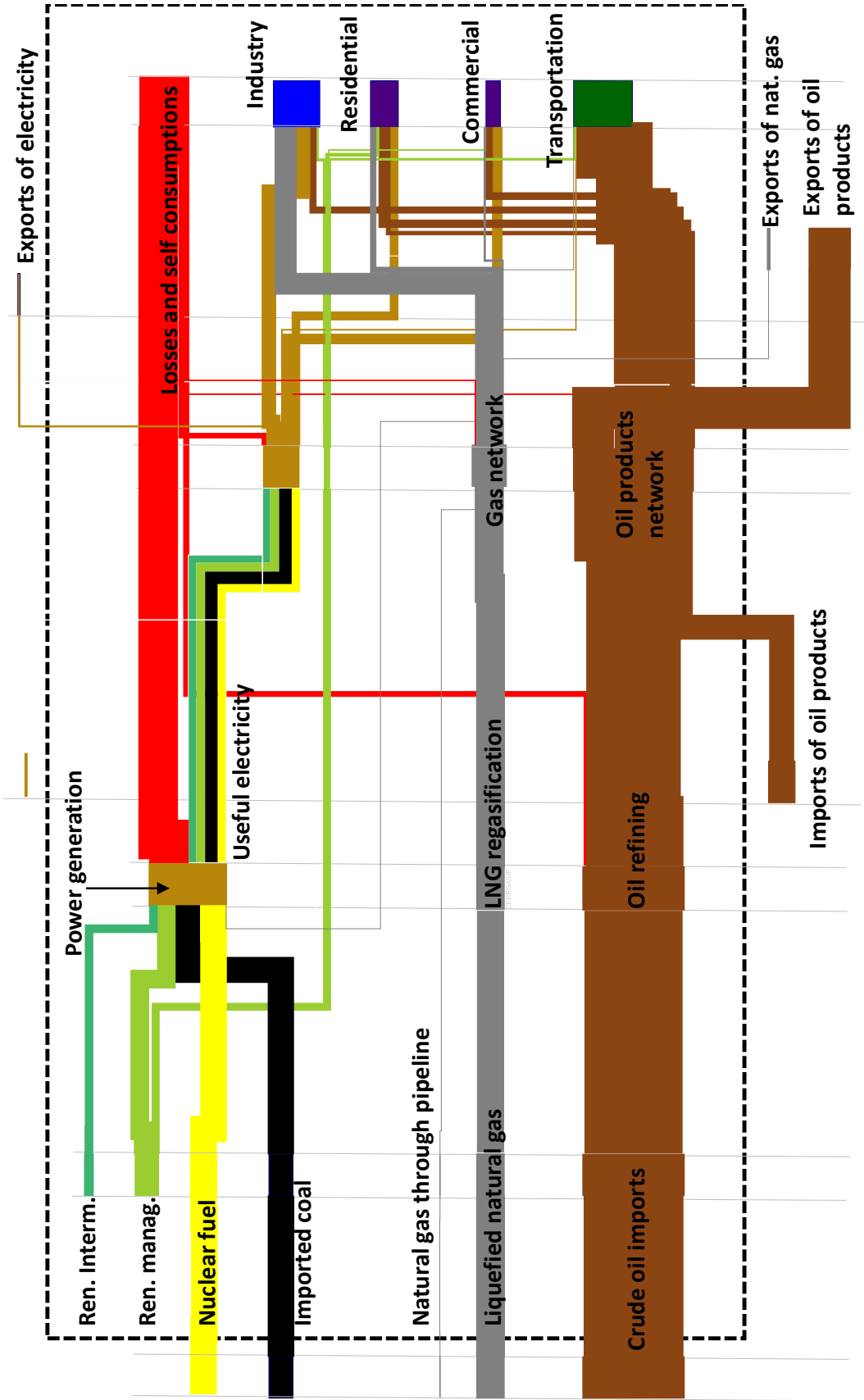
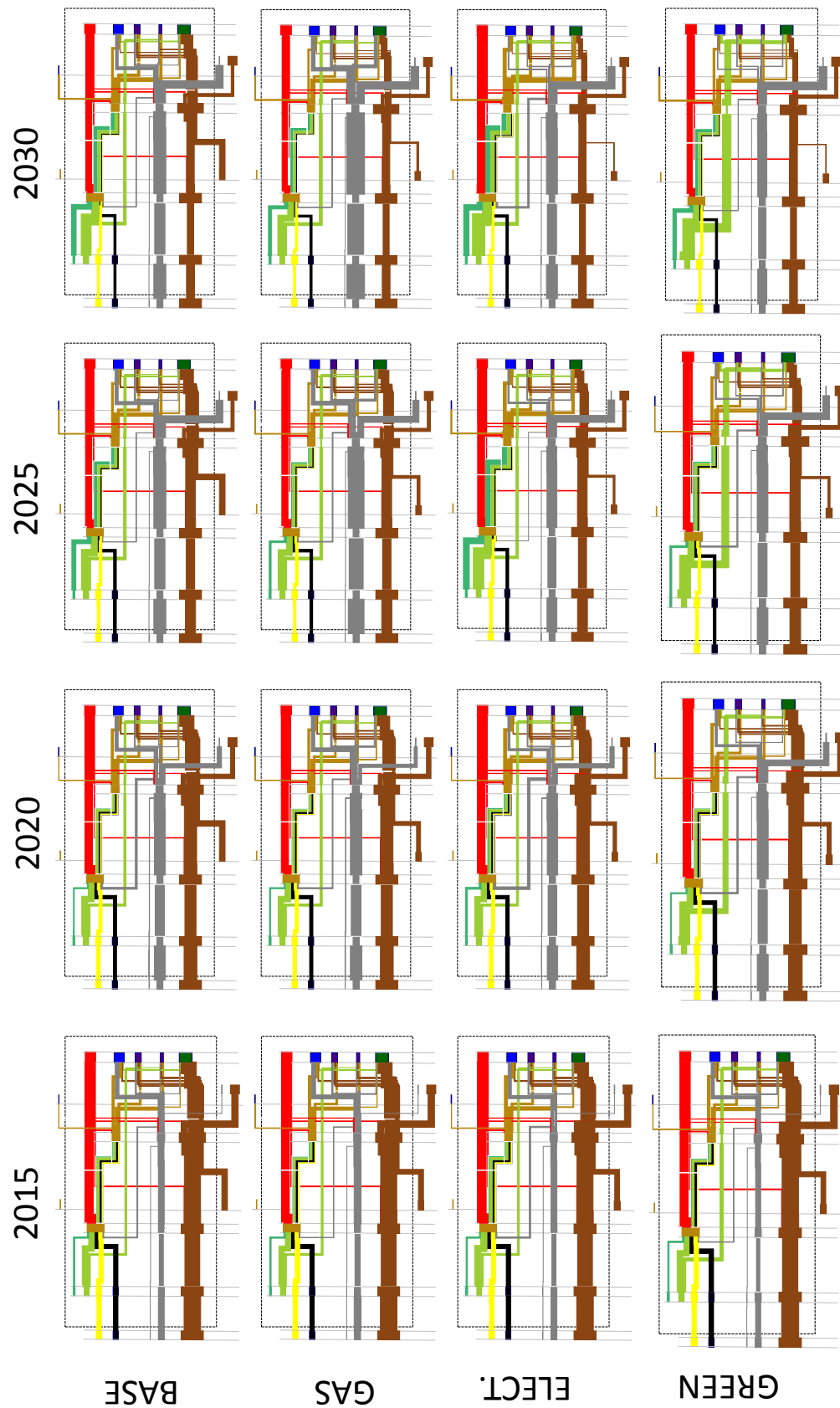


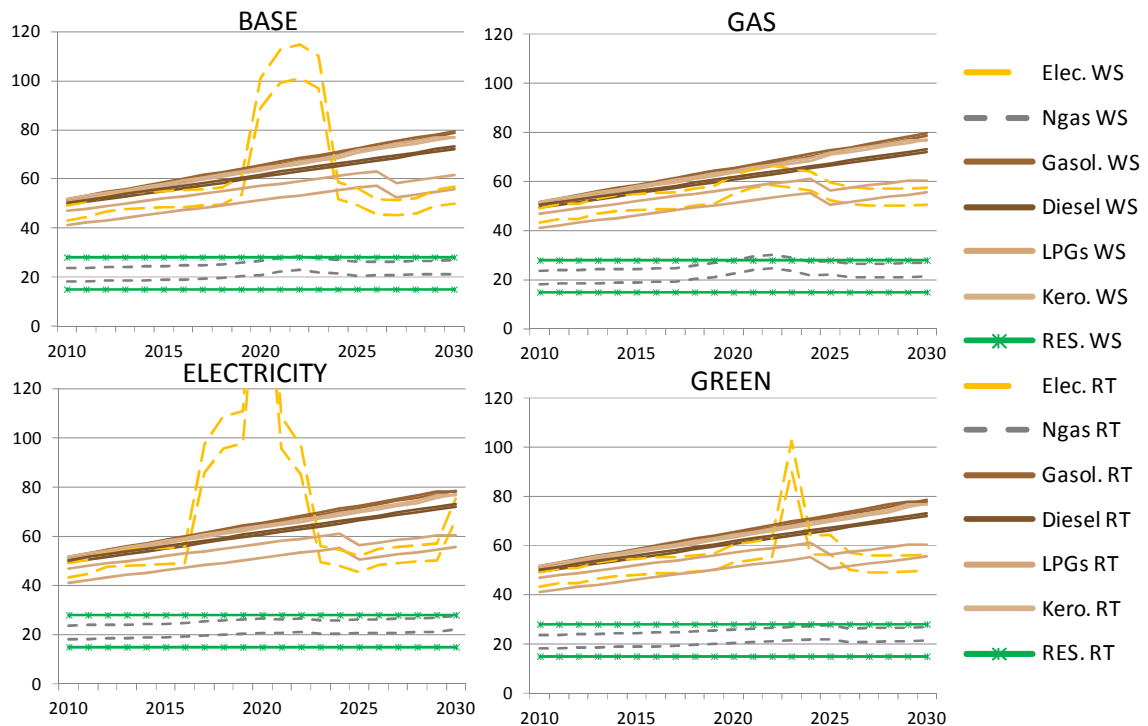
Figure 101: Sankey diagrams of the Spanish energy system in 2015, 2020 2025 and 2030 under each case.
 Source: own elaboration.



VIII.3.2. Prices for final energy

Figure 102 represents how wholesale (“WS”) and retail (“RT”) energy prices evolve in each scenario. It should be reminded that the prices shown here are yearly averages (i.e. for all the time slices in the year) and that the differences between wholesale and retail prices are due to the costs and losses of energy transportation and distribution (i.e. being retail prices higher). As these costs and losses are constant in our model (we have not represented the behaviour of energy transportation companies, which are regulated monopolies in the case of Spain), both lines evolve in parallel. We see a general upwards trend, especially in the case of oil products as could be expected from the values shown in Figure 94.

Figure 102: evolution wholesale and retail energy prices (€/2010/MWh) in the four scenarios.
 Source: own elaboration.



The case of electricity deserves a special comment, where in the scenarios with higher demand the wholesale and retail prices go up significantly in the middle of the study horizon, due to the lack of capacity (due to progressive phase out, as will be seen next), which causes some unsupplied electricity to appear (this is especially relevant in the “Electricity” scenario where electricity prices raise up to 188€/MWh and 212€/MWh respectively, which are very high values considering that they are yearly averages). This is also a consequence of the dynamic model not correctly capturing the *adequacy* requirements on the system (as described in chapter 4). This is clear because, even if non-supplied energy is very highly penalised in the objective function (at 10,000€/MWh), the MASTER_SO executes the optimization in operation-only mode: if utilities do not receive a strong enough investment signal in their loop, or if the dynamic nature of the model implies boom and bust investment cycles, unsupplied energy will appear

irrespective of its penalisation. We say “strong enough” because, through the used empiric relation profitability vs. investment decision, this signal is being somehow included in our model. In any case, the investment cycles were to be expected given that the utilities’ loop represents a negative feedback with a delay (which according to the System Dynamics theory should present some kind of oscillatory behaviour), that energy is a capital intensive industry and, very importantly, that it is also observed in reality. Improving this remains as an interesting line for future research, maybe implementing (to complement utilities’ loop) some type of capacity mechanism as reported in (Batlle & Pérez-Arriaga, 2008). In the cases where more gas is demanded (“Base” and “Gas”), the opportunity cost of using gas to generate electricity is bigger, what creates certain coupling between the gas and power prices, as can be seen around year 23.

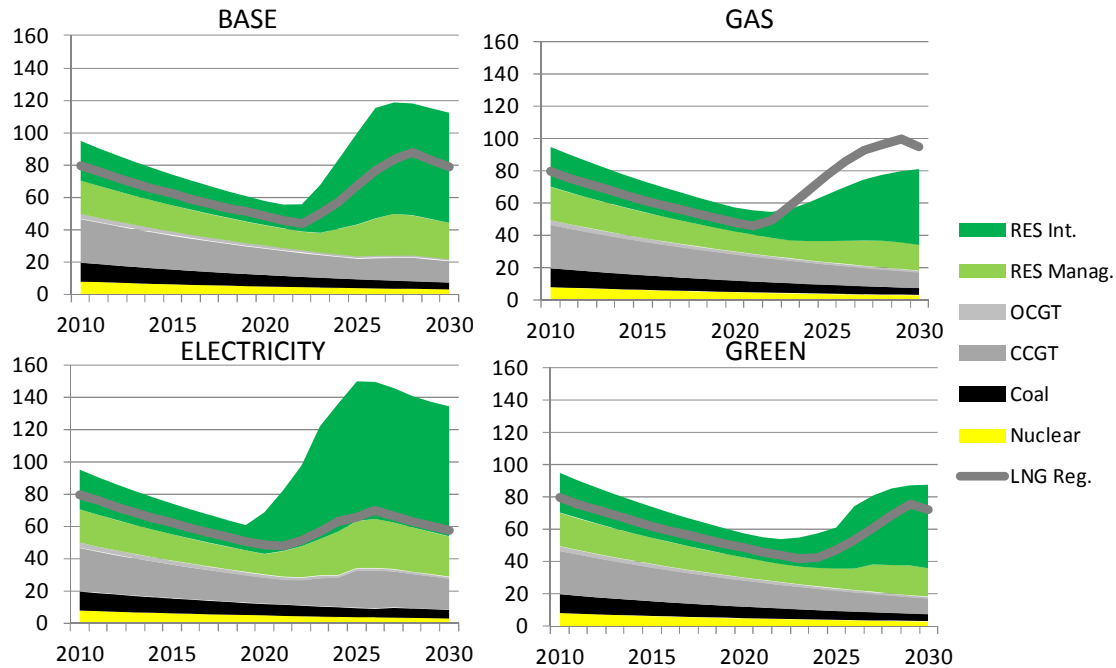
VIII.3.3. Energy conversions

Now, we will discuss briefly the evolution of energy conversion processes, that is, those where energy utilities invest. This will allow us to put all the rest of the results in context and to understand how the model is actually working (regarding the loop of utilities).

VIII.3.3.a. Installed capacities

In Figure 103, the installed capacities of power generation and LNG regasification under the four scenarios are represented. We have not represented oil refining since the capacities are the same in all four scenarios. LNG regasification capacity is represented as a line and plotted against the right axis, while the electricity generation capacity is shown as accumulated areas and plotted against the left axis. It can be seen how capacities tend to decrease lineally (due to the linear phasing-out of capacity that we have assumed), and at some point agents decide to invest again, creating, in the long run, a kind of boom-and-bust cycle as was expected. The main technologies in which the agents tend to invest are renewables, and CCGTs, as will be seen below. More power generation capacity exists in the scenarios with the greatest power demand: mainly the “Electricity” one, but also in the “Base” case, and in these cases also some new CCGT capacity is built. The LNG regasification capacity is greater (reaching around 100GW) in the “Gas” scenario, which is normal given the higher gas demand.

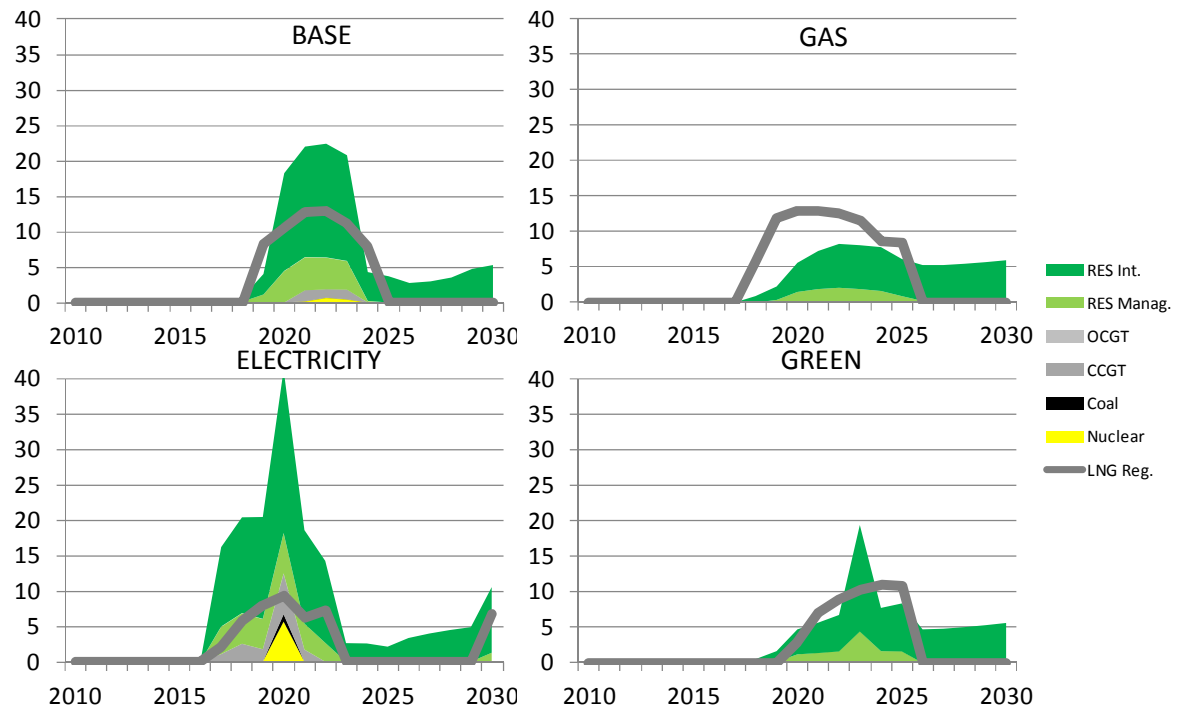
*Figure 103: evolution of conversion capacity per technology (measured in GW) in the four scenarios.
 Source: own elaboration.*



VIII.3.3.b. Investment decisions

Figure 104 shows the investment decisions that utilities make in each year, per technology, and expressed in GW. We have not shown oil refining capacity, in which agents do not decide to invest. These decisions become actual capacity after the permitting and construction delay, which depends on the technology. This is why the renewables capacities decided around year 22 are incorporated (as seen in Figure 103) around year 25 (their construction time is short) while the newly-decided nuclear capacity is not seen (it will come into the system after the last year of the execution). It can be seen that, as expected, the years where the power prices spike (due to the retirement of previous capacity), power generation technologies become very profitable, boosting investment decisions. These are mainly in renewables' technologies, although some investment is also observed in CCGTs, nuclear or even coal, especially in the cases with higher electricity demand ("Base" and "Electricity"). The investments in LNG regasification also take place around the middle of the study horizon, being bigger in the scenarios with higher gas demand. The "Electricity" case deserves a special comment: in one year, the level of investment reaches almost 40GW, which is a significantly large amount. Some type of financial limitation to investment (e.g. representing limited capital availability), which could be included in further research, would be useful to limit this effect.

Figure 104: investment decisions in conversion capacity per technology (GW) in the four scenarios.
 Source: own elaboration.

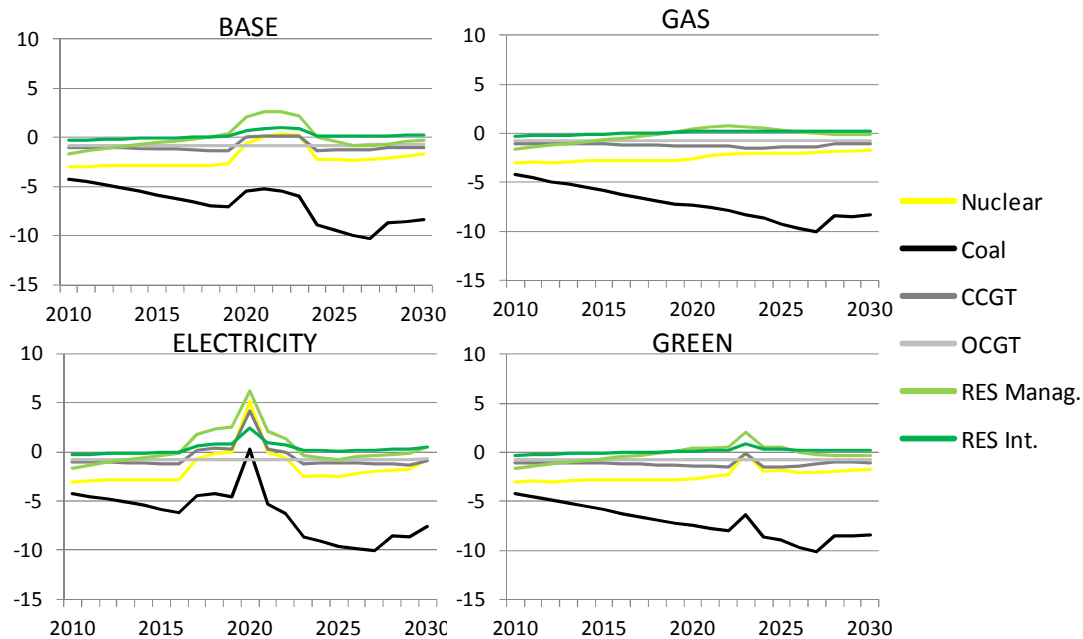


VIII.3.3.c. Profitability

In Figure 105, the profitability of each power generation technology in each year is plotted, all of them measured as the net present value (NPV) in specific terms (per MW) for comparability (and in constant 2010 terms). The above-shown investment decisions are, clearly, the consequences of these profitabilities (although the relation is not linear, as seen in Chapter 7.) It seems that coal is the least profitable, and that it loses attractiveness with time, as CO₂ prices raise (which, interestingly, is not what is happening nowadays). The most profitable technologies are renewables (because they perceive a premium and they do not emit CO₂). Analysing a case without a premium for renewables, which currently may seem more realistic, would be interesting future research. Nuclear, also emissions-free, tends to become more competitive with time, as its investment costs decline (as most official projections expect but which may be a strong hypothesis which would need some type of sensitivity analysis) and electricity prices grow (as will be seen below). Gas-fired technologies (specially CCGTs) are profitable when electricity prices grow enough.

Profitabilities tend to be higher when power prices are higher, which mainly happens when installed capacities are smaller (as happens around 2020 and in the end of the horizon), and when power demand is higher (in the “Electricity” scenario specially, but also in the “Base” one).

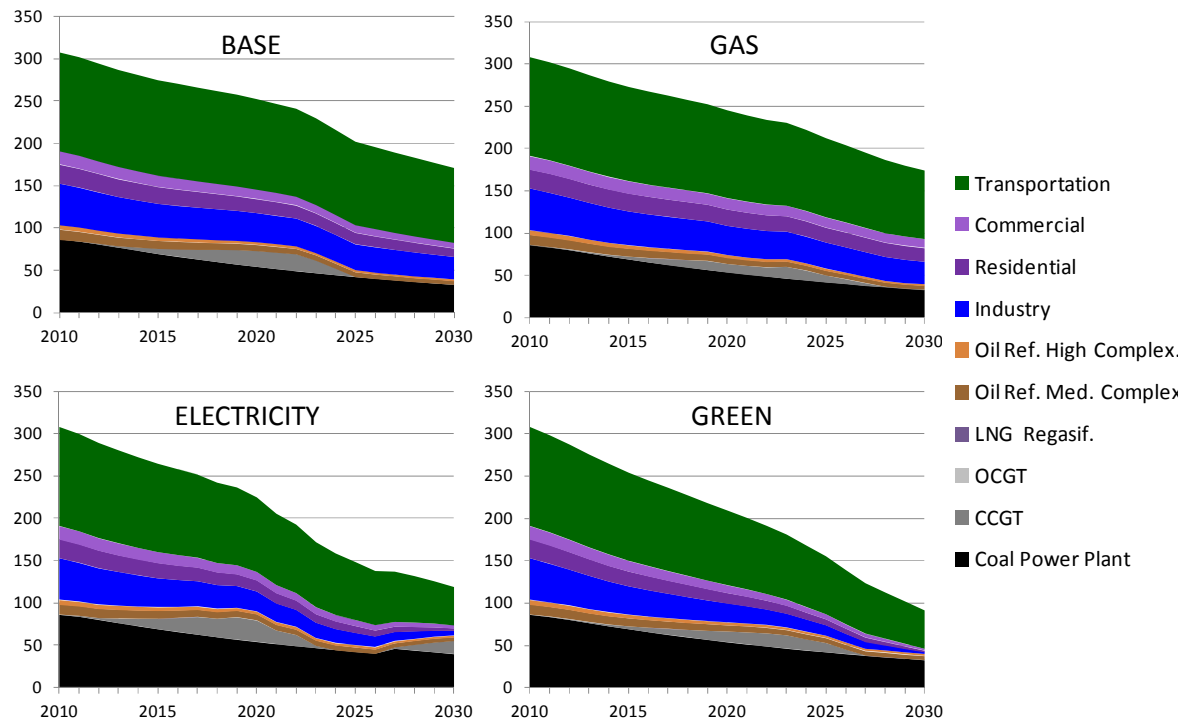
Figure 105: profitability (NPV) of each conversion capacity (M€'2010/MW) in the four scenarios.
 Source: own elaboration.



VIII.3.4. Emissions

Figure 106 shows the CO₂ emissions from the complete Spanish energy sector under the four scenarios. In the two cases “Base” and “Gas” the evolution of emissions is in line with the needed 2030 levels needed to be in a good trend towards the ambitious European objectives for 2050 (European Commission, 2011b), as can be seen in the Data Documentation Annex and in (Dietrich & López-Peña, 2013). The other two cases may seem too ambitious from the emissions perspective, mainly due to the large energy demand reductions and renewables penetration (either through electricity or directly for final use). It can be seen how the transportation sector is a key source of emissions, and how coal (used to supply base load) is also important. Emissions from LNG regasification are null, and oil refineries do not emit much in our cases. The scenarios with higher power demand present larger emissions from CCGTs.

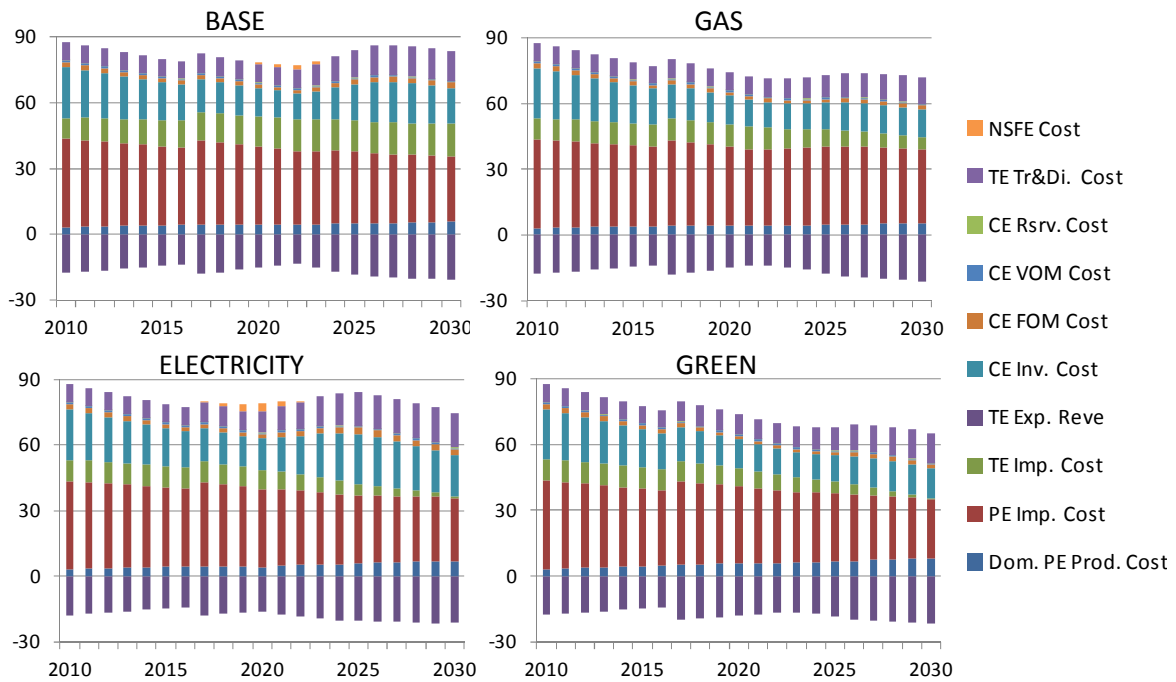
*Figure 106: emissions from all sources, conversions and final use, (MtCO₂) in the four scenarios.
 Source: own elaboration.*



VIII.3.5. Costs

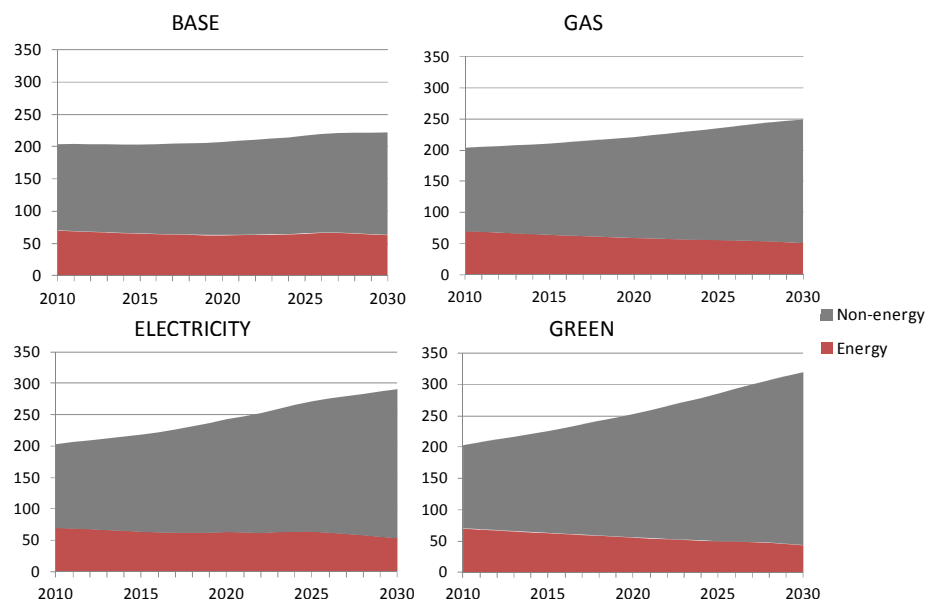
Figure 107 shows the energy-related costs in the four scenarios. These costs are negative when they represent a source of revenue to the country, mainly from energy exports. All of these cost elements have been explained in Chapter 5, and they are calculated in the same way here (these are directly extracted from the yearly executions of MASTER_SO). On top of them, the non-supplied energy costs can be seen just in the two cases where it appears. It may seem that the “Base” case is the one with higher total costs, because more energy is demanded (energy efficiency is not as high as in the last two scenarios) and it is more expensive than gas (refer to Figure 94). But it should be reminded that these costs are only the energy-related ones: even if the “Green” scenario seems to be the best one, on top of these costs should be considered the non-energy costs of final use technologies, which may cause the “Green” case less desirable than the “Base” case (i.e. green final use technologies being more expensive than base ones). This is actually the case in our scenarios, although we have not represented the graphs for clarity.

Figure 107: energy-related costs (billion €'2010) in the four scenarios.
 Source: own elaboration.



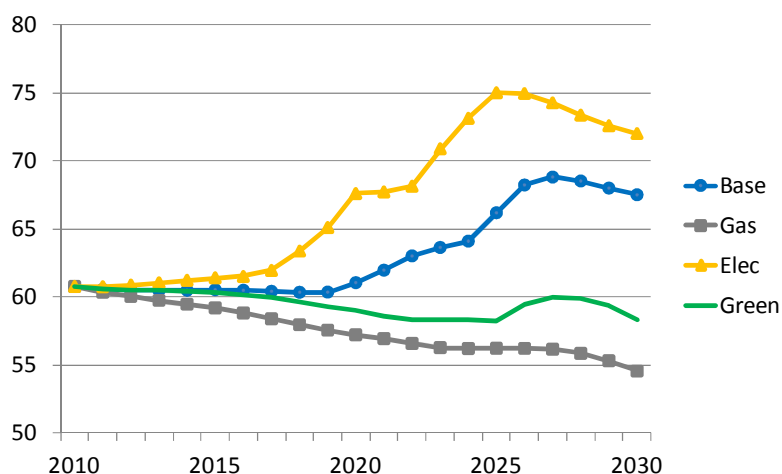
In Figure 108 we show the evolution of energy- and non energy-related costs in the four scenarios. It should be reminded that the energy ones are the ones just described, while the non-energy costs represent the (investment and O&M) costs for the economy of all the energy use equipment (e.g. cars, trucks, boilers, lamps, furnaces, etc.). As has been explained before, these costs are significantly larger than the energy costs, because this equipment plays a very important role within the economy (it cannot be seen as, *simply*, energy use equipment, but also as transportation equipment, industries, etc.). The case with larger electrification and larger use of renewables in final use are the ones with larger non-energy costs, because this equipment has been assumed to be more expensive than its traditional equivalents (e.g. an electric car is assumed to be more expensive than a gasoline one, and a biomass furnace is assumed to be more expensive than a fossil fuel-based one). In these cases, even if the energy costs decrease (largely due to the reduced energy usage thanks to the increased efficiency), the non-energy costs increase up to the point of making total costs larger than in the base case. Of course, this is largely subject to our data assumptions on the evolution of energy-use equipment. In any case, this may point out at a possible interesting trade-off (very subject to our data hypotheses): the important benefits in the two last scenarios (i.e. reduced energy dependence, reduced emissions, etc.) may imply a larger cost in energy-use equipment.

*Figure 108: energy- and non energy-related costs (billion €'2010) in the four scenarios.
 Source: own elaboration.*



Lastly, Figure 109 shows the energy related costs seen above per unit of final energy demand, that is, the average costs of supplying all energy types to all final energy demand sectors within the economy. It is interesting to see that the case with a larger electrification presents the higher values, because of electricity being a largely flexible high quality (and expensive) energy type. The observed boom and bust cycles are also more observable the larger the share of electricity use (in the “Electricity” and “Base” scenarios). The “Green” case presents a low value, given our hypotheses on the (low or even null) costs of renewables. The “Gas” scenario also reflects a low value, mainly due to our hypothesis on the low future prices of imported LNG, which may however be a very optimistic assumption.

*Figure 109: energy- related costs per unit of final energy demand (€'2010/MWh) in the four scenarios.
 Source: own elaboration.*



VIII.4. CONCLUSIONS

As explained at the beginning of this chapter, our main objective here was methodological. From such a perspective, we have shown that MASTER_DS, although being a prototype, can already be used with an exploratory rationale and it yields realistic and useful results, after being fed with real data from the Spanish energy system. We have observed some interesting (and realistic) features of energy markets such as boom and bust investment cycles, their effects on prices and how these affect profitability of new investments, how capacity mechanisms may be needed to send strong investment signals to energy producers, the effects that energy use equipment and its energy efficiency have on the energy matrix of the country, and how this affects issues such as emissions, energy dependence or costs. Of course, this model can be further enriched by future research, but it is already working and providing some useful results.

Given that the model used in this study is for now only a prototype, we prefer to not extract any specific policy conclusion. The only one that will be mentioned (and because it is subject to wide consensus in the literature) is that energy efficiency seems to be a desirable policy in the case of Spain, helping to reduce emissions, energy dependence and energy-related costs of the system, although it could lead to higher costs of energy use equipment (this being very dependent on our hypotheses on the costs of these technologies). An energy efficiency scenario of -20% final energy demand with respect to 2010 levels by 2030, which is technically and economically feasible according to (Economics for Energy, 2011), would put us on the good way towards longer term (i.e. 2050) objectives, significantly reducing our emissions and energy dependence. More research is needed to address the energy efficiency potentials in Spain, part of it being already carried out by the PhD candidate, supervising an Engineering Thesis within the BP Chair on Energy and Sustainability at Comillas University which uses the MASTER_SO model.

Chapter IX.

SUMMARY, CONCLUSIONS, MAIN CONTRIBUTIONS AND FUTURE RESEARCH.

IX.1	Outline of this chapter	315
IX.2	Summary	315
IX.3	Conclusions	319
IX.4	Main Contributions	326
IX.5	Future Research	328

IX.1. OUTLINE OF THIS CHAPTER

In this chapter we close this PhD thesis by reviewing the main issues that have been addressed, formulating our main conclusions, highlighting our main contributions, and proposing the main future research lines that we consider of interest.

IX.2. SUMMARY

Chapter I of the thesis introduces its context and motivation, which can be summarised as follows: (i.) global energy unsustainability needs urgent and ambitious policy action; (ii.) our energy-economic-environmental systems are very complex and interrelated, and energy policies significantly affect them in complex ways; (iii.) policymakers need the means of analysing policy measures thoroughly, before adopting them; (iv.) computer-based mathematical models for energy policy assessment are key in this process: to simulate policies' effects, to assess if the desired goals are achieved, the costs and benefits of the measures, their synergies and interactions, or their possible unexpected consequences, among others; (v.) out of the existing models that can be found in the literature, most fail in providing policy-useful insights about the *big picture* of energy policymaking: they have overly detailed modelling and complicated internal structures which frequently produce counterintuitive results, increment the time and resources needed for obtaining useful conclusions, and reduce users' trust in the model; (vi.) this PhD thesis focuses on overcoming such difficulties by proposing models for sustainable energy policy assessment applicable to Spain (or similar countries). Still in Chapter I and after this brief context, the motivation section presents the main driver of this PhD thesis (i.e. the identified need for improved tools and models for sustainable energy policy analysis), and describes the key features that, in our opinion, such tools should incorporate (which are, later, backed by an extensive literature review). The aim is to show that the real difficulty is not in the tool itself but in understanding, with a comprehensive but simplified quantitative analysis, the policies' mutual implications and trade-offs, how a policy can be counterproductive with another or the relative weight of each policy in making the system more sustainable. Finally, Chapter I presents both the general and specific objectives of this PhD thesis. The four specific objectives are: (i.) methodology definition and data structuring and acquisition; (ii.) development of a full-fledged static optimisation model; (iii.) development of a prototype of a dynamic simulation model; and (iv.) applications to actual policy-relevant cases in Spain.

Chapter II presents in greater detail the context of this thesis, which sits within the energy and sustainability problem, the need for sustainable energy policies to complement markets, and the need for mathematical models to analyse these policies. This chapter starts with a definition of the concept of *Sustainable Development* from the *capitals* perspective (a more comprehensive one than the traditional *three pillars* perspective). Then, it highlights how our current global energy model is unsustainable (from the perspective of each of these capitals and from the equity point of view) and how it contributes to global unsustainability in general. It also explains

how we have reached this point, and outlines the main forecasts for the future. This analysis is backed by an extensive and up to date review of the most relevant and reputed sources of information on the issue. Then, we focus on the lack of sustainability of the Spanish energy system, giving insights about its main trends and forecasted evolution and presenting a number of indicators on the issue, making use of four useful Sankey diagrams of the Spanish energy system. Later, we briefly introduce the liberalization processes that have taken place in the energy sector in many countries, and how energy markets are not perfect and do not necessarily account for sustainability, what finally allows us to highlight the need for sustainable energy policies to complement the markets, and for tools (i.e. mathematical models) to evaluate these policies. This allows us to focus, in the remaining of the thesis, on such models.

Chapter III presents the literature review of this thesis. We first introduce the key concepts and techniques for energy modelling, which in our classification are: (i.) economic representation and environmental feedbacks; (ii.) modeling techniques, discussing optimization and simulation; (iii.) technological detail, explaining both the bottom-up and top-down approaches; (iv.) geographic perspective; (v.) time representation; (vi.) uncertainties and future foresight; (vii.) technological change; and (viii.) international energy markets. Then, we perform a review of the mainstream energy models, whose selection also tries to cover a diverse representation of techniques and modelling approaches. The reviewed models are: (i.) MARKAL/TIMES; (ii.) POLES; (iii.) the IEA's World Energy Model; (iv.) PRIMES; (v.) NEMS; (vi.) EPPA; and (vii.) WITCH. For each, we provide some background, we describe its main modelling approach with a special focus on the above-introduced eight key concepts, and we provide examples of other related models and their use and applications in the literature. Also, and importantly, we highlight their main strong and weak points from the perspective of seven aspects that we consider key in a sustainable energy policy assessment tool, along the lines described in the Motivation section in chapter I. This allows us to compare them in each of these aspects, to justify the need for a new methodological approach (of which our main model MASTER_SO could be an example) and to graphically place MASTER_SO within the literature. Then, some other models are also reviewed, all of which have interesting features from the point of view of this PhD thesis, and finally, the main gaps in the literature are identified, some of which are covered by this thesis.

Chapter IV contains the detailed methodological justification and proposal of this PhD thesis. First we give an overview on our methodology. Then we describe our proposed detailed representation of the energy sector, which: (i.) has a bottom-up partial equilibrium approach with a special focus on end use energy technologies and is based upon the Sankey representation of national energy systems; and (ii.) presents a significantly detailed modelling of each energy subsector. Later, we explain our approach to data, magnitudes and units, which is key in achieving some of our main methodological purposes such as being able to analyse the *big picture* of the studied energy system and to understand well the main policy interactions and trade-offs. An extensive process of abstraction, representation and data collection has been done in order to characterize the studied energy system with public data, and this has been well documented in Chapters IV and V, and in the Data Documentation Annex. Data sources, hypothesis, previous calculations, etc. are well documented and made public so that anyone could criticize the values or perform her own calculations with different ones. Next, still within

Chapter IV, we explain our approach to energy sustainability indicators, which should be the maximised figure in a comprehensive sustainable energy policy analysis. Afterwards, we detail our modelling framework, which consists of two different but complementary models, a static optimisation one (MASTER_SO) and a dynamic simulation one (MASTER_DS). Of the seven aspects that we consider key in a sustainable energy policy assessment tool (introduced in Chapter I and used for classifying the existing models in our literature review), the MASTER_SO model provides transparency/ease of utilization, technological detail, modeling flexibility and capabilities for synergies/trade-offs analysis and direct policy effect modeling, among others. Concerning the representation of realistic energy markets, the MASTER_DS model provides a simulation framework within which these aspects could be represented. After introducing both models, we also propose in Chapter IV a specific two-step-process for using them. Finally, we explain our approach to output representation, which makes use of Sankey diagrams and of uniform magnitudes and units, allowing comprehending the *big picture* of the analyzed policies and the studied energy system. This chapter, together the modeling and data gathering work contained in the following chapters, achieves the first specific objective of this PhD thesis: “methodology definition and data structuring and acquisition”.

Chapter V describes MASTER_SO in detail. Given that it is an optimization model implemented in GAMS, it uses the same GAMS terminology for the sake of the reader's convenience (i.e. sets, parameters, variables, constraints and objective function). This chapter intends to provide the rationale on the mathematical modelling carried out, but in addition it has been written to be a useful reference guide for future users, also increasing transparency. This chapter also outlines the main utilization modes, execution options, outputs, and computer implementation. MASTER_SO is a bottom-up, partial equilibrium, static, linear programming (LP), optimization model for sustainable energy policy analysis. It contains a complete representation of the energy system under study, including all energy vectors and all energy demanding sectors. It makes use of a fair but not excessive level of technological detail. It has as main input the demand for energy services in energy demanding sectors and optimises the complete upstream energy sector (energy use devices, energy transportation and distribution, energy conversion, energy trade and primary energy production). It is modular, leaving open to future research the possibility of improving sectoral models (electricity, transport, specific industries, etc.). The objective function can be flexibly modified in order to represent, if desired, a quantitative measure of the sustainability of the studied energy system or any other aspects (e.g. minimization of total private economic cost of energy supply, minimization of energy dependence, minimization of emissions, minimization of primary or final energy use, etc.). Being a mathematically-simple static LP model, it clearly identifies the trade-offs or synergies between policies and it also represents the direct effect of policies, as mentioned above. Indeed, by introducing policies as constraints in a certain specific order, the constraints' dual variables can provide useful insights, as is showed for instance in the case study within Chapter VI. Some policies that could be studied include: (i.) minimum penetration of certain technologies (e.g. renewable power generation or specific end-use devices such as electric cars or biomass furnaces); (ii.) limits to the CO₂ emissions, either total or per sector; (iii.) improvement of the energy efficiency or energy intensity level; (iv.) establishment of minimum shares of renewable energy or some type of domestic fuel consumption; (v.) maximum level of energy dependence,

(vi.) total or unit cost of energy supply. The combination of a flexible objective function definition and the easy introduction of policies as constraints would for instance allow to perform state-of-the-art energy policy analyses such as: (i.) obtain marginal abatement cost (MAC) curves and costs of emission reduction in different subsectors; (ii.) analyze the costs and subsidies needed for introducing renewables in different subsectors, while also assessing the needed infrastructure investments, what would allow to choose the most cost-efficient sectors and technologies; (iii.) analyze energy efficiency policies in different subsectors and in the complete energy sector, considering both energy service demand reductions or end use technological change, obtaining marginal costs of demand reduction; (iv.) assess policies for reducing energy dependence and improve supply diversification, or the costs and consequences of promoting different types of domestic energy sources (e.g. domestic coal, bioenergy, etc.); or (v.) perform preliminary studies of environmental taxation, for instance on CO₂, on certain types of energy use (e.g. “green centime”), on energy inefficiency, etc., although a general equilibrium approach would be better for this. This chapter completes the second specific objective of this PhD thesis: “development of a full-fledged static optimisation model”.

Chapter VI presents a specific study for Spain carried out with MASTER_SO. It analyses whether, from a cost minimization viewpoint, renewable support has been the best policy for reducing emissions in Spain, when compared to the promotion of energy efficiency in sectors such as transportation or buildings. We answer questions such as: (i.) what would have been the economic savings in the best alternative?; (ii.) what would be the change in emissions, installed power generation capacities, or energy flows throughout the complete energy system?; or (iii.) what about the energy supply costs and its main components? We conclude that demand side management clearly dominates renewable energy support if the reduction of emissions at minimum cost is the only concern. We also quantify the savings that could have been achieved: a total of €5 billion per year, mainly in RE subsidies and in smaller costs of meeting the reduced demand (net of DSM implementation cost).

Chapter VII describes in detail the second model proposed in this PhD thesis: MASTER_DS. It is a System Dynamics-based simulation model which sets the basis for a modular model of the Spanish energy system that is able to represent realistic features of energy markets such as bounded rationality or myopia. It is also modular, because it leaves open to future research the possibility of improving specific sectoral models (e.g. electricity, transport, specific industries, etc.). In each yearly step, it has a similar representation as in the static model MASTER_SO, precisely because it executes it in order to represent the operation of the energy market in each year. It is for now only a prototype, but it is already able to represent realistic evolutions of the studied system and to provide some useful insights. This chapter fulfills the third specific objective of this PhD thesis: “development of a prototype of a dynamic simulation model”.

Chapter VIII illustrates that, indeed, MASTER_DS is already able to provide some useful policy insights. In this chapter, four possible evolutions of the Spanish energy system are simulated with MASTER_DS, each representing a different scenario of the evolution of the demand side. We answer questions such as: (i.) which would be the foreseeable advantages that strongly pursuing end-use energy efficiency and savings could bring?; (ii.) how would the energy matrix in Spain look?; (iii.) how would CO₂ emissions evolve?; (iv.) which level of energy

dependence would be reached? The main conclusion of this chapter is methodological: even if MASTER_DS is for now only a prototype, it already allows obtaining useful policy insights. These insights highlight issues such as: (i) energy efficiency (very much needed in Spain as outlined in Chapter II) could indeed improve issues such as emissions or energy dependence, which are key issues in the current unsustainability of the Spanish energy system; (ii.) the electricity sector presents investment cycles which, maybe, should be addressed through some type of capacity mechanism. This chapter, together with the policy study contained in Chapter VI, fulfills the fourth specific objective of this PhD thesis: “applications to actual policy-relevant cases in Spain”.

Finally, Chapter IX presents the thesis’ summary, the conclusions, the main contributions and the future research lines.

IX.3. CONCLUSIONS

We shall structure this section in three subsections, which follow an order similar to the one in the complete PhD thesis. The first section contains some conclusions regarding energy and sustainability. The second one contains the main conclusions of this PhD thesis, which are mainly methodological and refer to the gap that we have found in the literature for adequate sustainable energy policy analysis tools. Lastly, the third one contains some policy conclusions, more specific to the case of Spain.

IX.3.1. Energy and sustainability conclusions

From our analysis of the evidence presented in the literature and the proposed sustainability criteria we conclude in Chapter II that the global energy system, largely based on fossil fuels, is unsustainable from the point of view of the natural, economic, social and human capital perspectives, as well as from the equity point of view. Unless aggressive policy action is put in place, the reference scenarios of the most reputable institutions point out that this will still be true in the next decades, playing a large role in global unsustainability and putting important pressure on our sustaining ecosystems (both from the resource and from the pollution perspectives). The Spanish case is not an exception to this. Even more, our low energy efficiency, especially in diffuse sectors (e.g. transportation, buildings), which has evolved very negatively compared to our peers, plays an important role on our energy unsustainability and in some of our key macroeconomic weaknesses.

IX.3.2. Methodological conclusions

The main conclusions of this PhD thesis, which have a methodological nature, are explained next. The results of the analysis of the mainstream energy models carried out within our literature review are summarised in Figure 110. This table contains: (i.) on the top part, the classification of these models according to the key modelling concepts and techniques reviewed; and (ii.) on the bottom part, the numerical classification (from 1 to 5) that we have assigned to each model in each of the seven reviewed aspects, according to our judgement on how well each

issue is addressed. In the same table we have also placed our proposed models, MASTER_SO and MASTER_DS. Both have synergic modelling approaches, namely static optimisation and dynamic simulation, as can be seen on the top part of the table. In any case, and for fair comparison with the other reviewed models, the bottom part of the table presents our classification only for MASTER_SO.

Figure 110: summary table with the main information about the reviewed models, and placing the developed MASTER models. Source: own elaboration.

	MARKAL/TIMES	POLES	WEIM	PRIMES	NEMS	EPPA	WITCH	MASTER
Economic representation	Partial Equilibrium	Partial Equilibrium	Partial Equilibrium	Partial Equilibrium	General Equilibrium	General Equilibrium	General Equilibrium	Partial Equilibrium
Env. Feedbacks	No	No	No	No	No	Mainstream EPPA no. Yes, if coupled with IGSM or EPPA-HE.	Yes, IAM	No
Modelling technique	Optimization	Simulation	Simulation	Optimization	Simulation	Optimization	Optimization	Optim (MASTER_SO) and Simul (MASTER_DS)
Technological detail	Bottom-up	Bottom-up	Bottom-up	Bottom-up	Bottom-up	Top-Down	Top-Down	Bottom-up
Geographic perspective	Customizable	World (46 regions)	World (25 regions)	Extended Europe	USA (sub divisions)	World (16 regions)	World (12 regions)	National
Time representation	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic	Static (MASTER_SO) and Dynamic (MASTER_DS)
Future foresight	Perfect	Myopic (recursive dynamic)	Myopic (recursive dynamic)	Myopic or perfect	Myopic or perfect	Myopic or perfect	Perfect	Perfect (MASTER_SO) and Perfect/Myopic (MASTER_DS)
Technological change	Exogenous	Endogenous (both learning by doing and research)	Endogenous (only learning by doing)	Endogenous (only learning by doing)	Endogenous (only learning by doing)	Endogenous	Endogenous (both learning by doing and research)	Exogenous
Internat. energy mkts.	Exogenous	Exogenous	Exogenous	Exogenous	Exogenous	Exogenous	Exogenous	Exogenous
Modelling flexibility	5	2	2	3	3	2	2	(ONLY MASTER_SO)
Technological detail	5	3	4	5	5	2	3	4
Economic representation	2	3	3	2	4	5	4	1
Real energy markets	1	3	2	5	5	3	2	1
Transparency/ ease of utilization	2	2	2	1	1	2	3	4
Direct policy effect modelling	3	2	2	3	2	3	3	5
Synergies/ tradeoff analysis	3	1	1	1	1	2	2	5

As can be seen in the table (i.e. low punctuations in transparency/ease of utilization), most of the mainstream models reviewed share to a certain extent, a common characteristic: opacity. They are complex models, with large data and bulky results, difficult internal structures and advanced mathematical techniques. Hence the policy maker has to use them mostly as black

boxes. Of course those complexities have a reason: accurate modelling of the highly complex energy sector. These models can be adequate for studies where there is a solid and well trained modelling team, in charge of a large, sound and well-maintained database, which deeply understands the main hypothesis, limitations and internal dynamics of the models and their effects on the results, and where extensive sensitivity analyses on the main parameters are carried out, to obtain the main trends and the most robust conclusions. This, however, involves a great work load: these models fail in providing, with a reasonable amount of analysis in a short time period, simple but sound and useful conclusions about the *big picture* of energy policymaking. This is why sometimes they are distrusted by policymakers, and why the wide public cannot be engaged into the energy debate, which is a pressing need in the current days.

Apart from the lack of transparency, other issues can be seen in the table above. The best-represented features in the literature are technological detail and economic representation, respectively. This is due to the important presence of bottom-up partial equilibrium and top-down general equilibrium models in the literature. On the other hand the analysis of policy synergies and trade-offs, and the direct policy-effect modelling (both necessary in a policy-useful model as we have described in this PhD thesis) seem to be less treated in the reviewed models.

Some *optimization* models (e.g. TIMES) normally make the hypothesis of perfect markets, perfect rationality and perfect foresight, which can be somehow optimistic. Also, linear programming optimization models may sometimes produce extreme (e.g. knife-edge) results, which can be far from reality. To solve this, *simulation* models (e.g. NEMS, WEM, POLES), can model more realistic behaviours (myopia, some degree of bounded rationality, etc.). But, for this, the modeller relies on a (potentially large) number of internal parameters, some of them without clear physical interpretations, which can be hard to estimate, significantly affect the results of the model and finally, reduce user's confidence in the model.

Spain, where this thesis focuses, is one of the few large European countries without a clear politically agreed long-term energy strategy, and where the energy debate has not taken place in a transparent and comprehensive manner, as we have repeatedly denounced in the annual Observatory of the BP Chair on Energy and Sustainability (López-Peña, Linares, Pérez-Arriaga, et al., 2013). This may also be due to the lack of publicly available, transparent and sound models of the Spanish energy system.

This thesis is motivated by these findings: there is the need for models that, while being quite simple and transparent, are also able to capture in a sound way the big numbers of sustainable energy policy making, allowing us to directly represent policy effects and to understand policy trade-offs and synergies. This thesis sustains that, from a realistic perspective, in many cases it is better to provide some easily-understandable quantitative assessments on these issues, than complex studies that cannot be understood by those who have to make the actual decisions. We believe that the recent presence of other open source, transparent or user-friendly models in the literature (as seen in Chapter III) supports our view.

Given that this thesis intends to be useful (and used) from the policy makers' perspective, it tries to dwell in that middle point. In the hands of a policy maker, the main tool that has been developed in this PhD thesis (MASTER_SO) can be seen as a powerful *energy calculator*. The

table above shows how MASTER_SO clearly addresses some of the main weak points in the literature, notably synergies and trade-offs analysis, direct policy-effect modelling, and transparency/ease of utilization. Its performance in (i.) economic representation, and (ii.) real energy markets, is not as good. This is due to (i.) the use of a partial-equilibrium approach with inelastic demand, and (ii.) because it has an optimization approach assuming perfect energy markets and perfect foresight..

The second model we propose, MASTER_DS, tries to set the methodological basis for a model with a good representation of real energy markets, while also keeping transparency and ease of utilization. Even if it is for now just a prototype, it has already been used for a case study (Chapter VIII) after being fed with realistic data from Spain. We have observed some interesting (and realistic) features of energy markets such as boom and bust investment cycles.

By proposing two complementary models and a specific method of utilization, we have tried to capture the best features of static and dynamic models and simulation and optimization techniques.

If our main proposed model, MASTER_SO, is an LP bottom-up partial equilibrium model with a similar approach and representation as TIMES, two questions arise. Firstly, why have we not used TIMES itself? and secondly, what does it add to the TIMES-Spain model from CIEMAT? The author has, during the supervision of three engineering thesis (García-Barredo et al., 2011; García-Maestro et al., 2010; Pérez et al., 2012), devoted a significant amount of work to develop a TIMES-based model of the Spanish energy system (independent of the TIMES-Spain model at CIEMAT), using the same data and knowledge about the Spanish sector that we have used for MASTER_SO. However, we have experienced serious difficulties: (i.) in the modeling process (e.g. the different Excel templates and sheets, the coding of parameters, etc.); (ii.) in understanding the mathematical formulations and some parameters, for example the reliability equation (i.e. “PEAK”) or the units in the parameters to convert from capacity to activity and from commodities to activity (i.e. “CAP2ACT” and “ACTFLO”); (iii.) in doing a correct use of the interpolation options; (iv.) in correctly implementing user constraints; (v.) when finally obtaining knife-edge solutions that were not useful (e.g. technologies that, for one reason or another, were totally dominant); etc. Even more, when we managed to obtain results, they have sometimes been hard to interpret, since the internal logic of the model has not been easy to grasp, and we have obtained somehow unrealistic results (e.g. very large increments in installed wind capacity from one year to another). Of course this may be related to a somehow incorrect modeling, but this is exactly our point: with a significant amount of work over three years, we have not managed to obtain a correct model providing useful results. For this, a permanently dedicated and professional modeling team is needed, such as the one in CIEMAT working with TIMES-Spain.

In order to answer the second question (which is our added value over TIMES-Spain), in addition to the literature review, an informal consultation with experts from the TIMES-Spain modeling team at CIEMAT has been done, concluding:

- Even if TIMES-Spain does also have a disaggregated representation of end use technologies based on demand for energy services, our model includes a more detailed

one (with a larger number of technologies), which in addition have been characterized from scratch from public data.

- TIMES-Spain has been developed using the VEDA interface for TIMES, but it is not a full model built from zero through a programming language. What is more, there are not many modelers who could actually get into the code of TIMES-Spain and modify it, if needed. The PhD candidate has, on the contrary, built the full MASTER_SO model from zero, looking for all the needed data, writing all the GAMS code in a well-explained, easy to understand way, and has documented it all in great detail (in Chapter V). This has never been done for Spain.
- MASTER_SO has been conceived as an easy to use tool, much more accessible and transparent than TIMES-Spain. Part of this is also due to the fact that the database behind MASTER_SO has been built from zero and will be made publicly available and well-documented, whereas TIMES-Spain is a proprietary model with a restricted database, so researchers can only work with it through the team at CIEMAT.
- MASTER_SO is the only model of the complete energy system in Spain that, even having a significant level of detail, has been completely built by a single researcher.

Other key question that arises is: have we really managed to build a transparent, user-friendly model? Of course our models do have some level of internal complexity; they require some knowledge of programming languages such as GAMS or Matlab, they have a somehow important number of parameters, and not everyone can use them. However, we believe that MASTER_SO (which is the main model in this PhD thesis), strikes a good balance between technical and economic detail on one side and simplicity, transparency and ease of use in the other (being a static LP model), being able to answer the type of high-level energy policy questions that we deem necessary, as detailed in the Introduction to this thesis. Proof of this is that the model has been used not only within this PhD thesis, but it is also being used by other researchers in a number of studies such as the evaluation of energy efficiency policies for Spain, the analysis of the water-energy nexus in Spain, or the assessment of the economic returns of energy innovation in Spain (Conchado et al., 2013). Furthermore, its adoption to developing countries, such as Kenya or Peru, in the context of universal access to modern forms of energy is also being explored. In this thesis, specifically in Chapter VI, we have shown that MASTER_SO, once fed with real data from public and reputed Spanish sources can be used to analyze realistic policy questions. Through a relatively simple scenario analysis, and extracting the key results (e.g. emissions throughout the energy sector; shadow prices of key constraints; investment decisions made by the model; all the energy flows, represented intuitively as a Sankey diagram for each scenario; and all the relevant costs) we have been able to arrive at useful and clear conclusions regarding the *big picture* of energy policy in Spain (i.e. regarding support for renewables or for energy efficiency as a means to reduce CO₂ emissions). Finally, the PhD candidate has also used it for other studies regarding the decarbonisation of private road transportation in Spain (López-Peña, Pérez-Arriaga, et al., 2012c), or the technical challenges of large scale penetration of intermittent generation in Spain, in line with the European 2050 Energy Roadmap (Dietrich & López-Peña, 2013).

What is more, the methodological value of this PhD thesis is not only the models themselves, but the complete package that they form with other issues in which the PhD author has been a key or the only researcher. These are: (i.) the identification of the need for long term model-based energy prospective exercises in Spain (there is no one that considers for instance the current economic crisis), and the lack of publicly available and suitable tools to support a sound debate on the future of the Spanish energy sector; (ii.) the identification, elaboration, structuring and documentation of public data for the yearly Observatory of Energy and Sustainability in Spain (López-Peña, Linares, Pérez-Arriaga, et al., 2013), which has been also used for this PhD thesis; (iii.) the definition of some possible energy sustainability indicators which could be used for policy analysis; (iv.) adapting to Spain the methodology for energy sector representation based on Sankey diagrams, originally developed for the Observatory but which has also been used for the outputs of the models within this PhD thesis; (v.) the identification and justification, after carrying out important work with the TIMES model and after an extensive literature review, of a gap regarding specific tools for sustainable energy policy analysis and the main features they should have; (vi.) the definition of a modeling framework that could make use of comprehensive energy sustainability indicators; (vii.) assessing the importance that using uniform data and magnitudes can have in easing the understanding of main energy policy effects and magnitudes, and expressing the processed data and obtain results in such magnitudes, which is novel in the case of Spain; and (viii.) making all this information publicly available through the present document or other means and via future collaborations to be arranged.

IX.3.3. Policy conclusions

From the case study in Chapter VI, several policy conclusions for the 1996-2008 period in Spain can be extracted. The implementation of demand side management (DSM) measures instead of renewables (RE) for the reduction of CO₂ emissions would have resulted in net savings of €5 billion a year, both with the actual level of investment in CCGTs and with an optimal (lower) CCGT capacity. Hence, if minimizing the cost of reducing emissions had been the major concern, DSM measures would have clearly dominated renewables promotion.

Of course, RE present other important advantages for society that are not considered in our analysis, such as industrial activity or technological development, which will as well bring large benefits in the longer term (in scenarios where energy efficiency potential is almost fully utilised and where renewables are therefore needed, e.g. to largely decarbonise energy sectors).

One element that muddles the analysis of the optimal policy that could have been followed is that the existing investment in new CCGT capacity in the period (21GW) is too large, according to the results. Indeed, without mandated CCGTs, the model installs between 2 and 11 GW (less than the actual 21GW), depending on the case, and total costs are lower. Combined cycles are being helpful in providing operating reserves to the system, but this does not justify the large existing volume of CCGT investment. This is nowadays reflected on the possible mothballing of some of these plants.

In fact, and interestingly, our study's main result is also contingent on the evolution of CCGT capacity. Although the main conclusion remains the same (DSM dominates RE for emissions reduction in both groups of scenarios), the extra cost of renewables for the system would be less, and the benefits of DSM would be greater, if the large investment in CCGTs had not occurred.

Despite the above-mentioned weaknesses of our study, we believe that our main conclusion (for curbing emissions in Spain, energy efficiency would have been cheaper than renewables) does hold for the short and medium term future. This will be true while inexpensive energy efficiency potential remains untapped and until renewable technologies become more competitive. Other institutions point at similar conclusions, such as Bloomberg New Energy Finance for the United States or the International Energy Agency at global level.

Therefore, a natural policy conclusion is that, from a short- and medium-term viewpoint and ignoring the need for supporting renewable technologies with a view to the longer term, energy efficiency policies should be prioritized well above renewable energy promotion ones in order to reduce emissions at a minimum cost. This conclusion may still hold under other circumstances, since energy efficiency can also contribute to economic development or technological advances.

IX.4. MAIN CONTRIBUTIONS

This section outlines our main contributions, in order of importance.

Our main contribution is centred around the development of MASTER_SO. It is a partial equilibrium static optimization model of the Spanish energy system, which: (i.) contains all energy subsectors and their interactions; (ii.) focuses on a disaggregated representation of the end-use sectors (based on the demand for energy services); and (iii.) very importantly, it is able to provide policy-useful insights about the *big picture* of the studied energy system (as advocated in this PhD thesis) because it fills the gap found in the literature, notably regarding transparency, trade-off analysis and direct policy-effect modelling. The existence of this gap is justified in a detailed and didactic review of the state of the art in energy modelling which also intends to be useful for future researchers starting in the field. It includes a discussion of the strong and weak points of the models, according to the seven features that we consider relevant for a useful sustainable energy policy analysis tool. This MASTER_SO model is the centre of a comprehensive methodological proposal that also includes: (i.) the outlining of a synergic partial equilibrium dynamic simulation model (only a prototype for now) which could be able to deal with the main drawback of most optimization models, that is, their assumption of perfect energy markets; and (ii.) the definition of how both models relate to each other and how they should be used, including their integration with possible energy sustainability indicators, which should be the maximised figure in a comprehensive sustainable energy policy assessment. This is complemented with the proposal for a specific approach to data and magnitudes and for a specific way to represent outputs (based on Sankey diagrams), both of which are novel for the case of Spain.

The above methodology is complemented with other issues in which the PhD candidate has been a key or the only researcher, forming a complete research package that goes beyond this specific PhD thesis document. Some of these issues are: (i.) the identification of the need for long term model-based energy prospective exercises in Spain and of the lack of publicly available and suitable tools to support a sound debate on the future of the Spanish energy sector; (ii.) the identification, elaboration, structuring and documentation of public data for the yearly Observatory of Energy and Sustainability in Spain (López-Peña et al., 2013), which has been also used for this PhD thesis; (iii.) the development, together with undergraduate engineering students, of a TIMES-based model of the Spanish energy system using the same data sources; (iv.) the definition of some possible energy sustainability indicators which could be used for policy analysis; (v.) adapting to Spain the methodology for energy sector representation based on Sankey diagrams, originally developed for the Observatory but which has also been used for the outputs of the models within this PhD thesis; and (vi.) making all this information publicly available through the present document, through the other publications of the BP Chair on Energy and Sustainability or, in the future, through possible research collaborations with the University where this thesis has been done.

The developed models have been applied to policy issues of special relevance to the case of Spain. The most important one assesses the cost of carbon emissions reduction through renewables or through energy efficiency, obtaining clear policy insights and conclusions about the big picture, and which has resulted in a publication in the Energy Policy journal. We have also applied MASTER_SO to other issues such as: (i.) the costs of the decarbonisation of private passengers transportation through electric mobility or biofuels in the 2030 horizon (presented in the International Energy Workshop 2012 in Cape Town, South Africa); (ii.) the needed deployment of renewables in 2030 to be in a path compatible with the European 2050 Energy Roadmap, also analysing if it is viable for the power system from the technical perspective (through a collaboration with other researchers developing a detailed model of the operation of the electric power system in Spain); or (iii.) to the assessment of the costs and benefits of different energy mixed for the 2030 horizon (presented at the International Conference of the International Association for Energy Economics 2011 in Stockholm). MASTER_DS has been applied to obtain possible evolutions of the Spanish energy system under four scenarios representing the stock of end use energy technologies.

Lastly, within the field of the energy and sustainability problem, a comprehensive, up-to-date, evidence-based, and didactic discussion, particularised to the case of Spain, has been done. It provides updated evidence and a graphical representation of some of the key variables by making use of Sankey diagrams. It also analyses such issues with a historical perspective and providing some insights about the future based on reputed forecasts.

Apart from the publications and conferences mentioned above, this research effort has resulted in the supervision of six engineering thesis, on the publication of four issues of the Observatory on Energy and Sustainability in Spain, on a technical report on the interactions between climate and development policies in Spain, on the publication of five working papers and on the participation on four other international workshops and conferences.

IX.5. FUTURE RESEARCH

Possible future research lines will be mentioned next. They are presented according to a structure similar to the one of the PhD thesis: (i.) aspects related to energy sustainability and the development of energy sustainability indicators; (ii.) issues regarding the representation of the energy system, with a special focus on Spain; (iii.) aspects regarding our methodological framework and how the models interact; (iv.) then issues regarding MASTER_SO; (v.) then MASTER_DS; (vi.) specific sustainable energy policy analyses; and (vii.) finally some other aspects.

These future research lines are presented in a schematic way. However, with the aim of being useful for future researchers aiming to continue along the lines proposed, one of the annexes of this PhD thesis provides a significantly higher level of detail about these future research lines, providing some ideas on how to address the proposed.

IX.5.1. Energy and sustainability. Energy sustainability indicators.

- A more comprehensive diagnostic of energy sustainability in Spain, including the yearly publication of specific quantitative statistics. A special focus on the demand side could be desirable, given the need to improve energy efficiency in Spain.
- Integration in our model of specific energy sustainability indicators, e.g. on issues such as (but not limited to) regional or local pollutants, security of supply, or energy access. These indicators could then be used to measure the effectiveness of the evaluated energy policies.

IX.5.2. Representation of the energy system, with a special focus on Spain

- Improvements in the representation of the demand for energy services: e.g. more realistic representation of the interactions with the rest of the economy (price elasticity, rebound effects, etc.).
- Enhance the temporal representation of final energy services' demands (key for electricity but can also be relevant for gas or oil products if intra yearly prices are introduced or if storage is modeled).
- Improve end use technological representation of the industrial sector, up to a level of detail such as the one in the transportation or residential sector. The commercial sector could also be improved, by including more services and technologies.
- Improve the representation of ESVMs, which have a great potential for energy demand reduction in Spain (e.g. to reduce motorised mobility, to reduce heating and cooling demand from buildings, etc.). Refer to Data annex for more details.

- Sensitivity analyses and greater validation on the data values used for all other technologies (as documented in the Data Documentation Annex).
- Model the energy losses in end use technologies, or realistic (i.e. lower) values for non served demand in different sectors and for different energy vectors, to actually represent the consumers' utility and allowing the model to leave unserved demand.
- Also for end use technologies, separate between investment and yearly O&M (non-energy) costs, and consider the initial stock of existing technologies, maybe as already amortized.
- Electricity sector: improve the representation of renewables' variability in the electricity sector, better representation of distributed power generation, its influence on the reliability of the complete electricity grid, a better representation of electricity interconnections, the inclusion of smart grids, smart appliances and other end-use technologies such as smart electric vehicles. Also, the power grid could be represented with a number of TE processes, as said above, if different zones want to be considered, maybe limiting the power flows between them (instead of single node, as done now). While doing this, keep a balance with transparency as advocated by this thesis.
- Gas system: better representation of the network, maybe also considering different TE processes as proposed for the power grid. Related, include gas storage (relevant especially if the intra-year variation of gas prices is modeled, or if storage capacity is used to compute security of supply indicators). Modeling of possible gas production or fugitive methane emissions.
- Oil products system: network and storage, strategic reserves/storage (maybe used to compute security of supply indicators). Technical restrictions in the network. Representation of oil refining, especially calibration and sensitivity analyses.
- Biofuels: second generation ones, improve the modeling of biofuels production, its costs, its technologies, the representation of imported or domestic supply of biofuels or feedstock, the international trade, etc.
- Solar energy: CSP plants with storage and/or hybridized with gas or biomass. Net balance and self-consumption with PV.
- Hydropower: model intermonthly water usage; daily, weekly, monthly or even intermonthly pumping storage cycles; representation of mixed plants with both pumping storage and hydro inflows.
- Biomass coupled with carbon capture and storage. Other renewables such as biogas, geothermal or sea energies. An improved modeling of combined heat and power and district heating/cooling (using TE processes) may also be interesting.
- Public engagement in the energy debate: translate all our units and results into easily-understandable units or implementing some type of online energy calculator/model, which uses Sankey representation and energy sustainability indicators.

IX.5.3. Methodological framework

- Relation between both models: how to represent the dynamic nature so that MASTER_DS takes the system to the point in the future prescribed by MASTER_SO: dynamic optimization approach, backcasting, or through the inclusion in the System Dynamics framework of some type of goal seeking algorithm within a loop (based for instance on control theory) which acts when certain variables depart from their prescribed values (which could represent a trend towards that point in the future).
- Development of an optimization-based dynamic model, to answer questions such as the optimal penetration paths for certain technologies. Such a tool would be very much in line with the objective of transparency and ease of understanding since it does not need to include internal parameters to quantify the level of imperfection in markets. It could be implemented as a forward-looking model, or as a model that optimizes over a set of possible futures. It would provide, as output, an optimal trajectory to reach the desired point in the future, or a set of dominant trajectories if the objective function was multiobjective (e.g. to account for different aspects of sustainability).
- Include a measure of sustainability after the last year of the studied period (e.g. post-2030), so that the trajectories are analyzed also considering how the energy system is positioned for the future (e.g. using an approach based on the residual value one).
- Include a more comprehensive energy sustainability indicator to be maximized.
- Include decision support techniques to understand issues such as the policies' sensitivity to uncertainties or the value of policy anticipation or wait-to-see (until more complete information is available, in an approach similar to *real options*). Also, it can be interesting to choose strategies that are robust and flexible to unexpected developments and that minimize the regret value (e.g. approaches such "minimax regret" or robust optimization).

IX.5.4. MASTER_SO

- Improve the "Constraints to avoid unrealistic solutions" (as referred to in Chapter 5), which can significantly affect the results of the model, for instance using penetration curves or exhaustive sensitivity analyses.
- Improvement of the representation of end use technologies through the conversion of the external parameters QACTESST2ES, TE2QACTESST, and PE2QACTESST to decision variables, e.g. to model flexifuel technologies or policies such as improving the occupation of cars, improving the efficiency of certain technologies, etc.
- Improving our representation of load shifting in final technologies, which may be especially interesting if coupled with an improved temporal resolution of issues such as demand for energy services, production of intermittent technologies, or international prices of imported energy carriers.

IX.5.5. MASTER_DS

- Completely model the consumers loop, building upon the already-proposed conceptual basis, dealing with not only economic but also psychological or sociological issues.
- Include the policymaker as an autonomous and active agent within the model, which makes its own decisions based on what she observes *during the model execution*.
- Deepen in the representation of realistic markets using the “collaborative modeling” ideas as supported by the System Dynamics community and as mentioned above. Different modules could be broken down into more detailed algorithms and different researchers could work in parallel in separate modules, to then integrate them. This would ultimately aim at using more realistic features of (imperfect) energy markets to provide more realistic trajectories while keeping transparency and trust in our internal parameters (thanks to the collaborative modeling approach).
- Improve the representation of utilities, to consider not only the energy transformation business, but also energy transportation and distribution or the upstream activities, considering how companies may have different business structures, how they act in different activities and how their decisions and results in one can affect the others.
- Related to the above, more research could be done to better model utilities investment, considering issues such as risk/portfolio management, strategic behaviors, hedging against regulatory risk, different degree of policy anticipation, etc. Also, the current calculation of net present value could be improved by adequately considering construction times, decommissioning costs and lead times, or using a more advanced calculation of the discount rate (e.g. considering the costs of capital).
- Other aspect related to investment decisions is how to minimize boom and bust investment cycles, maybe through the introduction of some type of capacity mechanism or other way of sending adequate investment signals. Also, some type of investment limits could be included, to account for instance for resources or financial limitations.
- Better model how capacity is phased out e.g. to represent step retirement when each plant finishes its life, or adding another loop which accounts for decommissioning decisions, which may also be very relevant for the case of consumers, where there are specific policies for these issues (e.g. scrappage programmes for cars).

IX.5.6. Sustainable energy policy analysis

- For instance, to analyse how the Spanish energy system could evolve towards the European 2050 objectives. In the case of very high penetration of intermittent generation, it may be useful to use our models together with other more detailed models of renewables’ variability and its impacts on the operation of the electric power system, along the lines of (Dietrich & López-Peña, 2013).

- Analyse the cost of emissions reduction in different sectors or which measures could be better for doing so (e.g. developing sectoral MAC curves).
- Study how the European renewables penetration objectives could be achieved (considering for instance the forecasted reduced costs of renewable technologies, which may not longer need subsidies).
- Once more complete sustainability indicators are included, perform studies using them.

IX.5.7. Others

- Represent the water-energy-land nexus, or the inclusion of technological evolution within our modeling approach.

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ANNEX 1.

“BACK OF THE ENVELOPE” EXAMPLES

This annex includes some "back of the envelope" calculations done with just a single Excel sheet, which allow us to show the possibilities of using uniform units and magnitudes.

We believe that, even without using overly detailed mathematical models of the studied energy system, the combination of uniform magnitudes, ballpark figures and basic "back of the envelope" mathematical operations is sometimes enough to gain some policy insights (however in most cases it is better to use mathematical models which allow for a more complete representation of all the existing effects and interactions).

Let's start with the first example. A large number of authors support that, in order to advance towards more sustainable energy systems, a further electrification of the economy needs to be pursued, where electricity is increasingly used in final energy uses (e.g. heat pumps, electric vehicles, etc.) and where this electricity is generated through rising shares of renewables. However, as we have seen before, electricity may be (at least in the case of Spain) more expensive and inefficient to transport throughout the country than gas and even more than liquid fuels (of course, it may also be a higher-quality energy vector). Hence a first policy insight that could be obtained is that a further electrification of the economy will require significant networks expenditure: this is for instance a key conclusion of the European 2050 Energy Roadmap (European Commission, 2011b). Let's assume for instance that 50% of the gasoline and diesel cars are fully electrified¹⁶¹, as reflected in Figure 111. The base case (left column) represents 100% gasoline/diesel cars, which (as seen above) demand around 0.5EJ, equivalent to 1.4×10^8 MWh. The case with 50% electrification (right column) would imply a reduction in gasoline and diesel demand in 0.25EJ, hence now being around 7×10^7 MWh. Considering that an electric car is much more energy efficient than its fossil-fuelled equivalent, only consuming 30% of the original energy (International Energy Agency, 2010e), the electricity consumption from these cars would only be 2.1×10^7 MWh. Given that (as seen above) the cost of transporting gasoline/diesel or electricity through the networks is around 1€/MWh and 21€/MWh respectively¹⁶², our cars' substitution policy would make the total cost of electricity networks for delivering energy to cars to jump more than threefold, from around 140M€/year to more than 500M€/year¹⁶³. It must be reminded that the used figures (1€/MWh and 21€/MWh) only include the costs of transporting and distributing each type of energy, not the costs of the energy itself. Of course, these figures are only approximations, since we are using average cost values for marginal changes, which may be overly simplistic from an economic perspective. In any case, this is just an example used for clarification: our models take this correctly into account.

¹⁶¹ Ignoring possible difficulties in this such as electric cars' greater costs or reduced range, and assuming that these electric cars are used in the same way as their fossil-fuel predecessors.

¹⁶² We will ignore losses here, for the sake of simplicity in this example, which is just an illustration of our methodology.

¹⁶³ Not to consider other possible costs from this policy, such as subsidies for the electric cars or increased needs for power generation. However this policy would also bring associated benefits, e.g. reduced emissions and fossil fuel imports.

Figure 111: cars' electrification example.
Source: own elaboration.

100% fossil cals	50% fossil, 50% elec
1.4E+08 MWh gsl/die @ 1 €/MWh	7E+07 MWh gsl/die @ 1 €/MWh 2.1E+07 MWh elec @ 21 €/MWh
Tot. TE cost = 139 M€	Tot. TE cost = 507 M€

Another example of our approach is presented in Figure 112. Let's assume a person commuting to work every day for 40 km, and let's assume that she drives her own car, alone. Let's look at three alternatives to supply that energy service demand of 40vkm: a gasoline car, a compressed natural gas (CNG) car¹⁶⁴, and a battery electric vehicle (BEV). We will try to answer the question of which alternative for her commuting is less expensive for the country (as said above, this PhD thesis adopts the view of the policymaker, hence the view of the whole country). Let's assume the wholesale prices of gasoline, natural gas and electricity to be 55€/MWh, 35€/MWh and 30€/MWh¹⁶⁵. Electricity is (in this case) the least expensive energy vector at wholesale level. If the losses and costs of transporting and distributing each energy vector to final consumers (through TE processes) are the ones seen above, the retail prices of these energy vectors would be 56.1€/MWh, 41.4€/MWh and 58€/MWh.¹⁶⁶ It can be seen here how gasoline wins significant advantage due to its lower transport and distribution costs and losses (it has only incremented its price 1.1€/MWh, vs. 6.4€/MWh for natural gas and 28€/MWh for electricity). Again, these figures are just for illustrative purposes: in reality, all the other costs for society should be taken into account, including externalities or possible distortions caused by taxes. The first ones could be potentially included within our models. Distortions by taxes would require a more complex general equilibrium approach, which is out of the scope of this thesis.

Figure 112: private commuting example.
Source: own elaboration.

Choice	TE wholes.p.	TE lf. (%)	TE cost	TE retail p.	Vehicle Efficiency	E. Serv.	Tot. E. (€)	Vehicle	Tot. E.+V. (€)
Gasoline	55 €/MWh gs	0.2%	1 €/MWh gs	56.1 €/MWh gs	0.74 kWh gs/vkm	40 vkm	1.7	0.16 €/vkm	7.9
CNG	35 €/MWh ng	1.0%	6 €/MWh ng	41.4 €/MWh ng	0.74 kWh ng/vkm		1.2	0.20 €/vkm	9.2
BEV	30 €/MWh el	12.0%	21 €/MWh el	58.0 €/MWh el	0.22 kWh el/vkm		0.5	0.40 €/vkm	16.5

However, the energy efficiency of each vehicle type comes into play now, making electricity the best alternative again (it was the least expensive energy vector at wholesale level, but it became less convenient when the losses and costs of transporting and distributing it for

¹⁶⁴ We will assume it only consumes natural gas, although in reality they are normally bi-fueled, combined with gasoline (International Energy Agency, 2010f).

¹⁶⁵ This electricity price may seem slightly low for Spanish standards, where CCGTs are normally the marginal technology. However it is not for periods of high renewable energy production, as has been seen during the first months of 2013, where many hours had null prices (this being also related to the low demand due to the economic crisis).

¹⁶⁶ In reality these are significantly higher due to taxes and other regulated costs. In our methodology we do not consider taxes. This is because we assume them: (i.) to produce no distortion in the economic activity, and (ii.) to be fully reused for providing other goods and services within the country, hence being pure wealth transfers. Therefore we assume taxes to be neutral from the perspective of the entire country.

final use came into play). The gasoline car consumes 0.74kWh of gasoline per kilometre (equivalent to 8litres/100km, a reasonable value for daily commuting with traffic jams, which make consumption higher); the CNG has the same energy consumption (International Energy Agency, 2010f), and the electric vehicle is significantly (70%) more efficient (International Energy Agency, 2010e). Hence for a trip of 40km with each of these cars, the total energy costs are 1.7€, 1.2€ and 0.5€. If only energy supply costs were taken into account, the electric car would be the best alternative. However this is unrealistic, because the cost of the end use technology (ESST, following with our terminology) has to be also taken into account. As said above, this allows considering the trade-off between: (i.) older, energy inefficient and (economically) less costly; and (ii.) modern, more efficient and (presumably) expensive technologies. The costs of the gasoline vehicle are 0.16€/vkm (i.e. a 15,000€ car running for 12,000 km per year during 8 years). The other costs have also been calculated using realistic values extracted from the same sources as above. It can be seen that the battery electric vehicle is significantly more expensive, what is mainly due to the cost of the battery. Finally, once these final costs are included, it can be seen that the best alternative is, still, the gasoline car. Of course, this could change if fossil fuel-fired cars were charged for the environmental externalities they create (e.g. emissions of CO₂ or local pollutants, as seen in Chapter 2), under significant price increases of oil products, or if batteries' costs drop significantly. If the government wanted to promote the use of electric cars, let's say until 5 million drivers like the one if our example use them for their daily commuting, this would (all else being equal), save 6M€ (i.e. 5 million x (1.7-0.5)) per day in energy to the country, which is 1.5 billion € per year (in a year with 250 working days). But the extra-cost of electric vehicles would be 8€ per driver each day, which is 10 billion € per year (i.e. 5 million drivers, 250 working days), hence the net cost of the measure would be 8.5 billion€/year. Once again, this example may be overly simplistic: it is shown here just for illustrative purposes.

ANNEX 2.

FUTURE RESEARCH LINES:

POTENTIALLY USEFUL DETAILS

This annex provides a significantly higher level of detail on future research lines than the schematic last section of Chapter 9. The aim is to serve as a useful basis for future researchers aiming to continue along the proposed lines. It follows the same structure as that last section.

Energy and sustainability. Energy sustainability indicators.

Following with the discussion in Chapter 2, and building on the work of the BP Observatory on Energy and Sustainability in Spain (López-Peña, Linares, Pérez-Arriaga, et al., 2013) and other sustainability assessments such as (Observatorio de la Sostenibilidad en España, 2012), a more comprehensive diagnostic of energy sustainability in Spain could be done, including the yearly publication of specific quantitative statistics. A special focus on the demand side could be desirable, given the need to improve energy efficiency in Spain. For this, interesting existing references are mentioned in Chapter 2.

From this, a natural continuation would be the integration in our model of specific energy sustainability indicators, along the lines described above in this PhD thesis (notably in Chapter 4). Some possible difficulties (also mentioned above) in this could be the use of different magnitudes for different indicators, or their possible aggregation. If aggregation is not desirable, a good approach could be some type of multicriteria assessment. Also, a more informal approach could be used, based on some type of multidimensional representation (e.g. using spider diagrams such as the ones in Figure 33), maybe with some minimum thresholds in some dimensions (following ideas from the *strong sustainability* approach as defined in Chapter 2), or with a color code such as the acidity indicators in chemistry. Special focus could be put in the aspects less addressed in the literature, such as those regarding natural, human and social capital, or equity.

Within natural capital, including the external costs not only for CO₂ emissions but also of other regional or local pollutants could be very interesting, since as said in Chapter 2, regional or local pollution associated to energy causes an important burden on human health. For this, key references are the ExternE project (European Commission, 2011a), or (NEEDS Project, 2008). We have also done something similar in our BP Observatory on Energy and Sustainability in Spain for CO₂, particulate matter; NO_x and SO₂ (see Chapter 2 for a brief overview). Also interestingly, if externalities want to be included for energy technologies, it may be interesting to do so not only for their operation phase but for their complete lifecycle, where a good reference could be the Swiss Centre for Life Cycle Inventories *Ecoinvent* or the studies by the Spanish research centre CIEMAT.

Also very interesting could be the development of indicators to include security of supply within economic or social capital, which can be of special relevance in European countries such as Spain where energy dependence is very large. This could be interesting from a double perspective. First, the physical security of supply one, which seems to have been more treated in the literature. Secondly, and this would be more original, from the perspective of the macroeconomic implications which could cause negative externalities due to the large quantities that importing countries spend in importing energy. Possible ideas for further research could be: (i.) to simply add a economic value (representing the externality) per unit of imported energy; (ii.) to estimate some indicator on energy security through the difference between the total

expenditure in energy by final consumers and the costs of energy imports in the country, as suggested in our BP Observatory of Energy and Sustainability in Spain (López-Peña, Linares, Pérez-Arriaga, et al., 2013); (iii.) following the ideas in (Task Force of the Monetary Policy Committee of the European System of Central Banks, 2010), an energy security indicator could be produced as the inverse of a combination of energy intensity, energy dependence and imports concentration.

Other interesting area of research (in this case mainly applied to developing countries) could be the development of indicators on energy access, for instance to analyze the level of access to modern sources of energy or the burden that inequality on energy access imposes on a society. Here, interesting references are the IEA's Energy Development Index and (Bazilian et al., 2010). Related, it could be interesting to analyze how different energy consumers support energy prices, and how possible cross subsidies could be helping or negatively affecting vulnerable consumers. An interesting reference for this could be a Special Section in the Energy Policy journal in October 2012 called *Fuel Poverty Comes of Age: Commemorating 21 Years of Research and Policy*.

Even if including a numeric value quantifying in economic terms some of the above-mentioned externalities could be an interesting first approach, it would be more original to develop comprehensive energy sustainability indicators. Important work on this has been done by some authors or international organizations such as the Commission for Sustainable Development of the United Nations, the World Bank, the OCDE or the International Atomic Energy Agency (with their Indicators for Sustainable Energy Development, ISED). Other interesting references on this could be researchers such as Afgan or Vera. It is also of great interest a Special Issue of the Natural Resources Forum journal (Volume 29, Issue 4, year 2005) where the IAEA's ISED methodology was applied to several countries. These indicators can be greatly related to interesting international research efforts (mentioned in Chapter 2) aiming to develop comprehensive sustainable development indicators (beyond GDP and similar measures).

If correctly included within our modeling framework, these energy sustainability indicators could be used to measure, under each policy, how sustainable the represented energy system under study is, and the effectiveness of any proposed policy.

Representation of the energy system, with a special focus on Spain

In this section, we will mention some enhancements that could be done in our representation of the different sectors and aspects of the energy system, keeping in mind that we have a special focus on Spain (although many of these issues would be useful for representing other countries).

A first issue would be in the representation of the demand for energy services. This could be improved to account for a more realistic representation of the interactions with the rest of the economy, including for instance some degree of price elasticity (although this could make the models non linear), or including the possibilities of having rebound effects if the efficiency of

end use technology is improved significantly. In any case, for this it may be required to use a CGE framework, which would then make the model much more complex.

Also, further research could be done to improve the temporal representation of final energy services' demands, what is key for electricity but can also be relevant for gas or oil products if intra yearly prices are introduced or if storage of some of these energy carriers is modeled (see below). For this, for instance demand profiles could be used, published for Spain by institutions such as ENAGAS, CORES or CNE.

Another interesting line would be to improve end use technological representation of the industrial sector, up to a level of detail such as the one in the transportation or residential sector. The commercial sector could also be improved, by including more services and technologies, as done in (Greenpeace, 2011). It would also be interesting to carry out sensitivity analyses and greater validation on the data values used for all other technologies (as documented in the Data Documentation Annex).

Other relevant line of future research would be to model the energy losses in end use energy technologies. Given that the energy services they provide are measured in different units (almost none being energy magnitudes, e.g. passengers-kilometers for mobility), this is not trivial, since it cannot be done with a single subtraction. It could be done by including, through data, the ideal energy services supply technologies (ESSTs), which represent the minimum needed energy to provide a unit of energy service (taking into account the physical principles of each technology, thermodynamic limitations, mechanic losses, etc.). All the energy consumed in excess of the one that the ideal ESST would consume could be considered to be lost energy (of course, considering a broad interpretation of energy losses from the physical perspective, as has been explained in previous chapters).

Still within the energy demand side, our representation would also allow, in further research, to include realistic (i.e. lower) values for non served demand in different sectors and/or ESSTs (e.g. between 200 and 5000 €/MWh in the electricity sector) and for different energy vectors, trying to actually represent the utility produced given to it by energy consumers. This would give the model the possibility of leaving unserved demand if the costs of supplying it are larger than the utility given to it by demand, and using different values for different sectors and/or energy types would allow the model to prioritize between them.

Regarding end energy use technologies, it may be interesting to separate between investment and yearly O&M (non-energy) costs, and to consider the initial stock of existing technologies, maybe as already amortized.

In the electricity sector, it could be interesting to improve the representation of renewables' variability, which for now are modeled through simple load factors. It could maybe be interesting to include some evolution towards some type of probabilistic representation (e.g. based on Monte Carlo scenarios), or the use of load factors with greater level of detail (e.g. monthly, weekly, daily or intra daily). This may be specially interesting if other short term aspects of power generators (such as start-ups, shut-downs, ramping, etc.) are included, maybe also considering how this may affect the adequacy and reserves requirements in the system, the emissions and costs, or other aspects (e.g. reduced lifetime of backup technologies ramping up

and down many times). However it should be noted that these technical issues may play against transparency and ease of use as advocated by this thesis.

It could also be relevant to analyze how distributed generation affects the reliability of the complete electricity grid, because for now we have assumed that only the centralized capacity is affected by our adequacy and reserves constraints. A better representation of electricity interconnections could also be interesting: for now our model does not allow for investment in new power interconnections (even if the costs have been assessed, as can be seen in the Data Documentation Annex): it could be relevant to assess how interconnections allow to export low cost electricity at moments of low demand or high renewable generation, but also to represent how a larger interconnection capacity can provide better reliability characteristics to the power system (e.g. somehow including interconnections within our adequacy and reserve constraints), as should be according to the latest European policies on the Internal Energy Market. This could also be linked to the development of security of supply indicators, as mentioned above. The interconnections with different markets could be also included, according to latest European infrastructure plans.

Another line of further work could be to include other aspects that may provide adequacy or reserves to the power system, such as interconnections (if cross-border solidarity is effective) or the inclusion of smart appliances and other end-use technologies such as smart electric vehicles. This would be specially relevant if coupled with a comprehensive representation of smart grids.

Also, the power grid could be represented with a number of TE processes, as said above, if different zones want to be considered, maybe limiting the power flows between them (instead of single node, as done now). With such an approach, future research could be also be used to improve the representation of power transmission and distribution grids, for instance using a TE process for the national transmission network and then a number of TE processes for specific regional distribution grids, allowing specific power flows to circulate among them (in specific directions, e.g. using TETEFLOWS double sets as described above), or allowing distributed generation to inject electricity in some of these distribution networks, etc. The costs of these TE processes could be approximated with econometric expressions depending on several decision variables, provided that the expressions are linear (to keep the mathematical properties of our representation), and considering that distributed generation can increase but also reduce costs (e.g. in some of our executions it seemed that our current econometric expressions for the costs of the centralized power network TE process may be over penalizing the installation of intermittent generation). The representations done in some MARKAL models (notably MARKAL-UK) or in the IEA's World Energy Model may be useful references. From another perspective, maybe it would be interesting to improve the calculation of the peak power demand in the system to make it endogenous, although this is complex because it depends on the demand for energy services, the share of its supply with electric technologies, the representation of the different power networks and its interrelations/connection, on the intrayear temporal representation of these issues, load shifting, etc.

In the gas system, a clear enhancement could be the better representation of the network, maybe also considering different TE processes as proposed for the power grid. Related, gas

storage has not been modeled, being also an interesting line for future research (especially if the intra-year variation of gas prices is modeled, or if storage capacity is used to compute security of supply indicators). Useful information on this could be found in ENAGAS, CNE and CORES. When modeling underground storage, attention should be paid at the injection/extraction profiles. Normally in Spain there is no gas passed between different years, so the balance equation in storage facilities could be yearly. When modeling storage it can also be interesting to consider the different costs and possibilities of storing gas as natural gas (e.g. in underground storages) or as LNG (e.g. in the storage facilities within regasification or discharge terminals). Some import/export limitations could be applied to LNG charges/discharges. Also interesting could be the modeling of possible gas production, such as the one using the *fracking* technique (which for the moment seems to not be approved by European authorities). Coupled with the representation of the natural gas system, the inclusion of methane emissions (an important greenhouse gas) could also be relevant, to account for instance for fugitive emissions.

Something similar could be said about the oil products network and storage, or the import/export capacities both for products and crude oil. Strategic reserves/storage could also be used to compute security of supply indicators. Useful information on this could be found in CLH, CNE and CORES. It may also be interesting to maybe include any type of technical restriction in oil products network (for now a simple energy balance has been used). The representation of oil refining in Spain could be further improved, especially issues regarding calibration and sensitivity analyses. In any case, as has happened within this research, data availability may be a difficult limitation. A useful reference could be the section “Representation of oil refining in MARKAL”, in (Loulou et al., 2005), which in any case has inspired our current modeling approach. It may also be interesting (and challenging) to model how specific investments in an existing refinery (e.g. a coker) could change the shares of output products.

Second generation biofuels have not been modeled, being an interesting line for future research. Also, further research could improve the modeling of biofuels production, its costs, its technologies, the representation of imported or domestic supply of biofuels or feedstock, the international trade, etc. Again, data availability here can be complex (e.g. we have not found good projections of the prices of biofuels).

Concerning solar energy, CSP plants with storage and/or hybridized with gas or biomass could be included, which could provide ancillary services and hence be better off in the reserves/adequacy constraints, and which could also present greater load factors. Net balance and self-consumption with PV (which represents an important potential in Spain) could also be included, in order to account for the potential benefits to the electric system in terms of reduced losses and costs in power grids. It should be done along with an adaptation in the parameters used to represent distributed electricity generation, as mentioned above.

Concerning hydro power generation, it could be relevant to model intermonthly water usage. Also, it would be interesting to further analyze if pumping storage cycles (represented through the energy balance constraint in this specific technology) are daily, weekly, monthly or even intermonthly. The higher the penetration of intermittent power generation, it seems reasonable to assume cycles closer to daily, according to experts at the Spanish Transmission

System Operator REE. Also, maybe consider the representation of mixed plants with both pumping storage and with hydro inflows (we have considered them separately).

Regarding biomass technologies, it may be interesting to model them coupled with carbon capture and storage, which may have the potential to achieve negative carbon emissions throughout their lifecycle and could be an interesting technology for climate change mitigation.

Other aspects that could be enhanced are the representation of other renewables such as biogas (also considering its possible injection in the gas network), geothermal energies (which could be interesting not only for power generation but also for domestic heat pumps), or sea energies. An improved modeling of combined heat and power and district heating/cooling (using TE processes) may also be interesting.

Concerning data and units, an easy-to-implement and interesting line of future work, with the motivation of engaging the wide public into the Spanish energy debate, would be to translate all our units and results into easily-understandable units, following similar approaches as in (MacKay, 2009), or implementing some type of online energy calculator/model, which also used our Sankey representation and some energy sustainability indicators as explained above.

Including other emissions such as NO_x, SO_x or particulate matter could also be relevant, especially if linked with a quantification of externalities or energy sustainability. Also interesting could be the inclusion of methane and specifically fugitive emissions from the gas system, given that natural gas is expected to play a large role in the medium term and that these emissions can be important for global warming. Including emissions constraints in some of these gasses, based for instance on the European regulation on emissions from large combustion installations, may be relevant.

Lastly, it could also be relevant to incorporate the investment costs of previously installed capacities, to be able to obtain better economic and financial indicators of the studied energy system, including the value of all assets.

Methodological framework

Regarding the modeling framework, we will in this section point out at some general issues, to then in the next two sections give more detailed further research options for both the MASTER_SO and the MASTER_DS models.

Concerning the relation between both models, the first issue is how to represent the dynamic nature so that MASTER_DS takes the system to the point in the future prescribed by MASTER_SO. It could be done though a dynamic optimization approach, through backwarding, or through the inclusion in the System Dynamics framework of some type of loop (based for instance on control theory) which acts when certain variables depart from their prescribed values (which could represent a trend towards that point in the future).

The development of a optimization-based dynamic model could have important value per se, as it would allow answering questions such as the optimal penetration paths for certain technologies or energy types (although it would not represent realistic evolutions of real and imperfect energy markets). Also, such a tool would be very much in line with the objective of

transparency and ease of understanding since it does not need to include internal parameters to quantify the level of imperfection in markets. It could be implemented as a forward-looking model where the optimization is done with perfect knowledge and information about the future, or as a model that optimizes over a set of possible futures. It would provide, as output, an optimal trajectory to reach the desired point in the future, or a set of dominant trajectories if the objective function was multiobjective (e.g. to account for different aspects of sustainability).

Within the representation of dynamic aspects in our methodology, it could be interesting to include a measure of sustainability after the last year of the studied period (e.g. post-2030), so that the trajectories are analyzed not only considering the studied period but also how the energy system is positioned for the future after the studied period. This could be done for instance using an approach similar to the residual value one (explained above).

Including within our models a more comprehensive energy sustainability indicator, which would be the main high-level policy objective to be maximized, would allow to assess how each policy is, indeed, maximizing sustainability.

From another perspective, it may also be interesting to include decision support techniques within our modeling framework. As said above, many uncertainties are present in analyzing the future of the energy sector. They affect not just utilities and consumers, but as well the policymaker. Hence it could be useful for her to understand issues such as the policies' sensitivity to uncertainties or the value of policy anticipation or wait-to-see (until more complete information is available, in an approach similar to *real options*). Also, it can be interesting to choose strategies that are robust and flexible to unexpected developments and that minimize the regret value (e.g. approaches such "minimax regret"). In this line, approaches that could be explored include portfolio analysis (Awerbuch, 2006), uncertainty and scenario analyses, multicriteria analysis and cost benefit analysis (Diakoulaki & Karangelis, 2007; Linares, 1999), robust optimization (Bertsimas & Sim, 2004) or real options theory (even if it seems that up to now it has been mostly applied for analysing the investment in specific projects instead of for policy analysis).

MASTER_SO

In this section we will mention the main aspects where MASTER_SO could be improved by further research. The first issue concerns what we have called, in Chapter 5, "Constraints to avoid unrealistic solutions". Some of these impose for instance a maximum or minimum share in the energy services demand supplied by certain end use technologies. If these constraints are active in the result of the optimization, it may be significantly affecting the results. What is more, this may be relevant when assessing certain policies (e.g. the maximum share of bikes may be an important limiting condition when assessing policies to improve the sustainability of urban passengers' transportation). Improving the way these "constraints to avoid unrealistic solutions" are implemented may be an important line of future work. This could be done for instance through penetration curves for certain technologies or through sensitivity analyses on the values used for these constraints, especially when assessing policies which could be related (like in the example just given about bikes).

Another very interesting future research line could be the improvement of the representation of end use technologies through the parameters QACTESST2ES, TE2QACTESST, and PE2QACTESST. These are, in the current version of MASTER_SO, fixed external parameters given through data per each end use technology (ESST). However, this does not allow to directly representing flexifuel technologies, or policies such as improving the occupation of cars (e.g. through car sharing or car pooling), improving the efficiency of certain technologies, etc. Currently, this can be done by creating another technology which has a modified value of these factors (e.g. creating a new ESST “car of high occupation” with QACTESST2ES of 3 passengers/vehicle, in addition to the normal ESST “car” with a QACTESST2ES of 1.5 passengers/vehicle). It could however be interesting to implement these three parameters as variables, to allow the model to do this internally. The main reason why this has not been done, however, is that this may make the model non-linear, because the multiplication or division of variables would appear (i.e. QACTESST2ES, QACTESST, TE2QACTESST and PE2QACTESST would all be variables, and they are multiplied/divided in certain constraints of the model). Possible mathematical solutions could be explored. For instance, the linearization through decomposition with Taylor series could be tried. This in any case would require the definition of the “reference point in these variables” around which the linearization is done, which may require some sort of calibration (also quite challenging). Even more, the approximation may lose mathematical validity if the approximated variables depart significantly from that reference point. Other possibility is to go along with the product of variables, but in this case the LP problem would become an NLP, losing some of its transparency and other mathematical properties (e.g. interpretation of shadow prices, etc.), and requiring some other modeling work, such as providing the optimization software with a suitable starting point.

Another interesting line of future research would be improving our representation of load shifting in final technologies, which may be especially interesting if it is coupled with an improved temporal resolution of issues such as demand for energy services, production of intermittent technologies, or international prices of imported energy carriers. More specifically, the load shifting costs (which, as said, represent the lost utility for consumers) could be better defined, for instance to account not only for the amount of shifted load but also how far it has been shifted (in terms of hours). This in any case could be challenging given our representation in non-chronological time slices.

Given that it is a static model, as said, the investment costs of each technology are considered through the annuity of the investment depreciation. This may be importantly influenced by the considered life of each technology. As said above, we have considered 20 years life for all CE technologies (i.e. the CECAPAMORTYEARS parameter). Assessing the influence of using the actual technical life of each technology in calculating the amortization could also be interesting. Even more, it may be relevant to include an amortization formula which considers working hours of each technology, although this may include a non-linear term in the objective function.

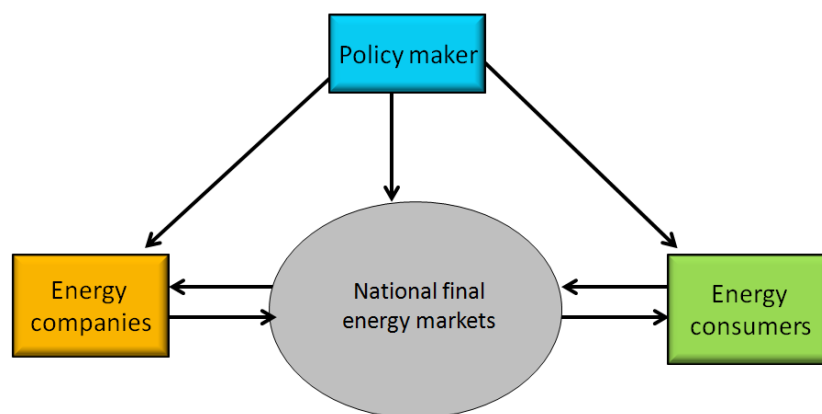
MASTER_DS

In this section we will provide some further work that could be done to improve MASTER_DS. First, one key element of future research could be to model the consumers loop. As

said, although its main conceptual basis is proposed, its full representation remained out of this PhD thesis scope, especially since some of its internal parameters can be subject of intensive research dealing with not only economic but also psychological or sociological issues. For this, the use of the five sectors that we propose (see Chapter 8) may be useful: they could replicate different levels of rationality in the decisions concerning energy usage equipment. We would consider industrial and professional transportation sectors (both of passengers and freight) to be the most rational ones, because energy could represent an important cost in their businesses. The residential consumers would be the least rational ones. The commercial sector and the private passengers transportation (i.e. mainly private cars) would be somewhere in the middle.

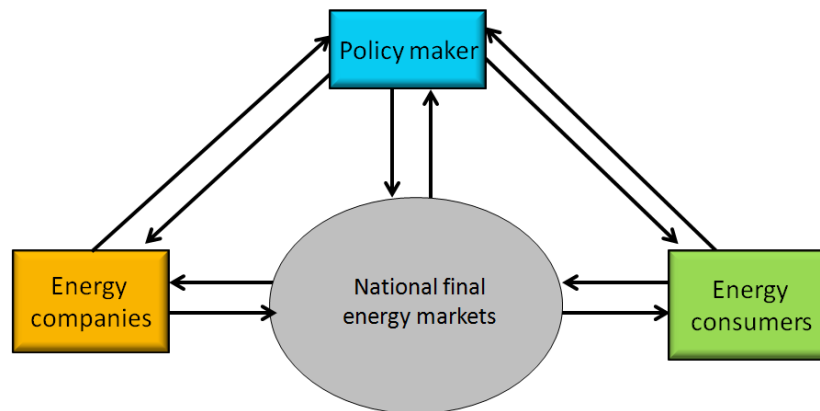
Another possible line for future research is explained now. Regarding the schematic figure in Chapter 7 which represents the way policy makers affects energy utilities, energy markets and energy consumers (reproduced here, slightly modified, in **¡Error! No se encuentra el origen de la referencia.** below), the policy maker is there assumed to act on these elements from a *unilateral* perspective (there are no arrows going *into* the policymaker). In other words, it is the model user who acts as the policymaker, deciding in each model run which is the value of renewable energy premiums or carbon prices, for instance, then observing the model results and finally carrying out other model runs with other values for these parameters. On the contrary, companies and consumers affect energy markets, and energy markets affect them (arrows in both senses).

Figure 113: representation of the main agents in our prototype model and their interaction.
Source: own elaboration.



An interesting line for future research could be to include the policymaker as an autonomous and active agent within the model, which makes its own decisions based on what she observes *during the model execution* (and not between consecutive model runs, as done now, where the model user acts as the policy maker). This would imply that there are information arrows going *into* the policymaker, as represented in **¡Error! No se encuentra el origen de la referencia..** This means that the policymaker would react during the execution of the model, changing her policies as a result of the observed variables.

Figure 114: representation of the possible future research regarding the main agents in our prototype model and their interaction.
Source: own elaboration.



Such an approach could be interesting for a key issue that has not been completely addressed within this PhD thesis: how to make the MASTER_DS model reach the future point (e.g. for 2030) that the static MASTER_SO model has prescribed. As said in Chapter 8, for now, our MASTER_DS model has an exploratory rationale (i.e. it allows to represent several future evolutions), but this does not guarantee that the prescribed future point will be reached. To make this happen, future research could for example explore the possibility of using a *backwarding* approach. Also, including the regulator as an autonomous and active agent within the model could be an interesting approach: following some ideas based on control theory (which lies in the foundations of System Dynamics), the policymaker could react to the distance between certain key observed variables and the values they should have for a smooth path towards the prescribed future objective. For example, a penetration path for a certain renewable technology could be calculated as a linear interpolation between the current value (e.g. in 2010) and the needed 2030 value (output of the MASTER_SO model). This path could be given to the dynamic model, and the policy maker would in each simulation step compute the distance between the actual penetration level and the desired one, and according to this she would increase/decrease the economic support for that technology (e.g. the biggest the deficit in installed capacity, the largest the premium). This is very similar to what the System Dynamics terminology calls a *goal seeking* algorithm.

Another area of future research could be to deepen in the representation of realistic markets using the “collaborative modeling” ideas as supported by the System Dynamics community and as mentioned above. Different modules could be broken down into more detailed algorithms and different researchers could work in parallel in separate modules (to then integrate them all). This would ultimately aim at using more realistic features of (imperfect) energy markets to provide more realistic trajectories while keeping transparency and trust in our internal parameters (thanks to the collaborative modeling approach). Some issues that could be improved are agents’ forecasting errors (e.g. using trend extrapolations, adaptative expectations, etc.), agents bounded rationality / complex utility functions (making decisions which do not necessarily respond to economic optimization behaviors), imperfect competition (e.g. somehow modifying the clearing process of the energy markets), etc.

Now, we will mention some issues regarding the representation of utilities. As said, we have only considered the energy transformation business, as represented by the investments and operation of energy transformation technologies (as represented by the CE set within this PhD thesis). We have considered energy transportation and distribution as fixed (through fixed parameters representing their costs and losses), what can be justified because some of them (notably in the case of electricity and natural gas) are natural monopolies. We have not modeled either the upstream activities (e.g. primary energy production). In reality, energy utilities can perform activities in several of these activities, or different ones. This depends, among other things, on the level of unbundling that the regulation of each country requires. Further research could aim at modeling how companies may have different business structures, act in different activities and how their decisions and results in one can affect the others.

Related to the above, more research could be done to better model utilities investment. For now we have mainly based it on the estimated net present value per technology calculated as the discounted cash flow. However, companies take into consideration other issues when assessing their investments, such as risk/portfolio management, strategic behaviors, hedging against regulatory risk, different degree of policy anticipation, etc. Considering some of these issues could be interesting future work. Also, the current calculation of net present value could be improved by adequately considering construction times, decommissioning costs and lead times, or using a more advanced calculation of the discount rate such as (Sanchez et al., 2008).

Other aspect related to investment decisions (and specially relevant after the results obtained in our model runs in chapter 8) is how to minimize boom and bust investment cycles, or in electricity terms, how to ensure adequacy. The introduction of some type of capacity mechanism or other way of sending adequate investment signals could be interesting research, as done in (López-Peña et al., 2009). Also, some type of investment limits could be included, to account for instance for resources or financial limitations, which could help in avoiding investment peaks as also seen in chapter 8.

Lastly, it would also of interest to better model how capacity is phased out. For now we are using lineal depreciation of capacity along the life time of each technology, but in the future it could be more realistic to represent step retirement when each plant finishes its life. For this, it would be needed to account for individual plants (what the literature sometimes calls *vintages*), that is, discrete capacities (now we have continuous capacity), and take into account the years of life in each individual one. Another interesting line for further research could be adding another loop which accounts for decommissioning decisions (allowing capacity to be retired early or later than its technical life, affected by company's decisions based on prices, forecasts, policies, business strategies, etc.). The decommissioning decisions may also be very relevant in the consumers' loop, where there are specific policies for these issues (e.g. scrappage programmes for cars).

Sustainable energy policy analysis

Other lines of future research could be actually using the developed models for policy analysis, after doing some adaptations to the model if needed. Some other researchers and student within Comillas University are already doing so by using MASTER SO to: (i.) to assess the

economic return of energy innovation in Spain, along the lines of (Conchado et al., 2013); (ii.) to analyze different policies for improving energy access in countries such as Kenya and Peru; (iii.) to gain insights in the water-energy linkages in Spain (after modifying the model to include water aspects); or (iv.) to assess energy efficiency policies in Spain, their potentials and costs.

Another policy assessment that could be performed includes the analysis of how the Spanish energy system could evolve towards the European 2050 objectives. In the case of very high penetration of intermittent generation, it may be useful to use our models together with other more detailed models of renewables' variability and its impacts on the operation of the electric power system, along the lines of (Dietrich & López-Peña, 2013).

It could also be interesting to see how costly emissions could be reduced in different sectors or which measures could be better for doing so (e.g. developing sectoral MAC curves), or how the European renewables penetration objectives could be achieved (considering for instance the forecasted reduced costs of renewable technologies, which may not longer need subsidies).

Once more complete sustainability indicators are included in our model, it may be interesting to perform studies using them. There are already some interesting references for this type of analysis in the literature.

Others

In this final section we just mention two other aspects in which the developed tools could be applied or improved. The first is the analysis of the water-energy-land nexus, which as said above is already ongoing research for the energy-water relation. The second is the inclusion of technological evolution within our modeling approach, which in any case may not make full sense if the studied country is too small so as to affect global technology evolution. Interesting references on this could be (Berglund & Söderholm, 2006; Kouvaritakis et al., 2000; Löschel, 2002).

ANNEX 3.

DATA DOCUMENTATION

As advocated in this PhD thesis, for transparency, this annex contains our data sources, hypothesis, previous calculations, etc. The aim is to have it all well documented and made public so that anyone could criticize the values or perform her own calculations with different ones.

1. Macro Assumptions

1.1 Dollar/Euro Rate in constant 2010 terms

Sources

<http://www.oanda.com/currency/average>

European Commission. (2010). EU Energy Trends to 2030. Update 2009. Brussels.

Previous calculations/hypothesis/explanations

Real values in 2010 and 2011. Long-run value (obtained from EU Energy Trends to 2030) is considered to be 1.25\$/€. It is considered to be reached lineally since 2011 and maintained over to 2030

Used values (Units: \$/€ rate)

	2010	2011	2015	2020	2025	2030
	1.32	1.39	1.33	1.25	1.25	1.25

1.2 Spanish Population

Sources

Own calculation based on Prevision 2012. National Statistics Institute (Instituto Nacional de Estadística)

Used values (Units: millions)

	2011	2015	2020	2025	2030
	46.8	46.8	46.9	46.9	47.0

1.3 Spanish GDP in real terms

Sources/Previous calculations/Hypothesis

For 2010 data: International Monetary Fund, World Economic Outlook Database.

For future values: short term: march 2012 previsions of the Spanish Economy Ministry (real GDP growth rate of 0.7% in 2011 and -1.7% in 2012); long term: 1% real GDP growth rate attained in 2020 and kept constant from 2020 to 2030. This 1% value, added to an estimated value of 2% in GDP deflator (in line with inflation objectives of the European Central Bank), yields a 3% nominal GDP growth rate, a reasonable value over the long term; medium term: linear aproximation from short-term values (economic crisis) to long term trend.

Used values (Units: million €2010)

	2010	2015	2020	2025	2030
	1,062,591	1,027,550	1,083,868	1,196,678	1,321,229

1.4 Private investor interest rate for investments' amortization

Sources

Own estimations in line with the most commonly used values in the literature.

Used value (Units: %)

All years
9%

Comments

Some specific technologies can present deviations from this value due to their specificities. For instance, nuclear power plants or private consumers' assets (normally higher interest rates due to risk premium or myopic decision-making) or government's investments (normally lower values)

1.4 Housing and building stock in Spain in the 2030 horizon

Sources

National Statistics Institute (2010). Indicadores sociales. Edición 2010
Ministerio de Fomento (2013). Housing statistics.
Economics for Energy. (2011). Potencial económico de reducción de la demanda de energía en España (transl. Economic Potential of Energy Demand Reduction in Spain).
García-Casals. (2011). Energía 3.0. Greenpeace Spain

Comments and values

Assumptions: Dwelling = first residences, houses = dwellings + empty houses (e.g. holiday residences). Using the values of inhabitants per dwelling (3.4 people/dwelling in 1991, 2.7 in 2009 and supposed 2.5 for 2030), divide by population = 18.8 million dwellings in 2030. From Ministerio de Fomento, we obtain the total housing stock (around 26 million in 2010). For the future we assume +150k new houses per year (reasonable after the current crisis) and in the longer run a growth rate of 0.82% per year (Economics for Energy, 2011). Around 30 million houses in 2030. Dwellings/Houses=18.8/30=63% -> 27% empty houses.

To obtain the total built space in km² of houses in Spain, we use the average size per house obtained from INE, and from García-Casals (2011), relation between GDP per capita and average dwelling in square meter per person. We obtain values of around 2700 km² in 2011 and around 3000 km² in 2030. Also from García-Casals (2011) we obtain the share of surface that is first residence, so we can calculate the km² of first residences.

Also from García-Casals (2011) we obtain the share of commercial and residential surface, around 32%. This implies around 890km² in 2011 and around 979 km² in 2030.

2. Time representation

2.1 Divisions of a year in load blocks

Sources

Own calculations

Previous calculations/hypothesis/explanations

When modelling large electricity systems, special attention must be paid to the precision in the representation of temporal variations in their operation, and to the requisites for technical reliability of the system. Concerning temporal variations, 96 load levels have been used to represent electricity demand throughout the year with enough precision: 12 months, two day types within each month (week day/weekend), and four load levels per day (including a super-peak one representing the 1% hours with the highest demand values in each day type). This time representation has been also useful to model seasonal variations in the demand of other final energy types such as oil products or natural gas.

Used values (Time divisions)

Periods: months		Subperiods: day type		Levels: type of hours	
JA	"January"	WD	"Week Day"	SP	"Super Peak"
FB	"February"	WE	"Weekend"	PK	"Peak"
MR	"March"			MD	"Medium"
AP	"April"			OP	"Off-Peak"
MY	"May"				
JN	"June"				
JL	"July"				
AG	"August"				
SP	"September"				
OC	"October"				
NV	"November"				
DC	"December"				

Used values (Durations expressed in hours)

	WD.SP	WD.PK	WD.MD	WD.OP	WE.SP	WE.PK	WE.MD	WE.OP	Total	%
JA	6	137	273	136	2	48	95	47	744	8.5%
FB	5	119	238	118	2	48	95	47	672	7.7%
MR	5	125	250	124	2	60	119	59	744	8.5%
AP	5	131	262	130	2	48	95	47	720	8.2%
MY	6	137	273	136	2	48	95	47	744	8.5%
JN	5	119	238	118	2	60	119	59	720	8.2%
JL	6	137	273	136	2	48	95	47	744	8.5%
AG	5	131	262	130	2	54	107	53	744	8.5%
SP	5	125	250	124	2	54	107	53	720	8.2%
OC	6	137	273	136	2	48	95	47	744	8.5%
NV	5	125	250	124	2	54	107	53	720	8.2%
DC	5	131	262	130	2	54	107	53	744	8.5%
Total	64	1554	3104	1542	24	624	1236	612	8760	100%
%	0.7%	17.7%	35.4%	17.6%	0.3%	7.1%	14.1%	7.0%	100%	

Comments

3. International Markets for Energy and Energy-Related Commodities

3.1 Cost of carbon emissions

Sources

For present ETS prices: BlueNext (<http://www.bluenext.fr/index.php>)

For projected ETS prices: International Energy Agency. (2011). *World Energy Outlook 2011*. Paris.

For external costs of carbon emissions: Tol, R. S. J. (2009). The Economic Effects of Climate Change. *The Journal of Economic Perspectives*, 23(2), 29–51.

Previous calculations/hypothesis/explanations

The value used has been either the expected carbon price in the european Emissions Trading Scheme (from IEA, 2011), or the estimated value of the external cost on society of carbon emissions (from Tol, 2009). In the MASTER_SO static model, where the evolution from 2010 to 2030 is represented in a single step, the average value in the 2010-2030 period is used.

Used values (Units: €2010/tCO₂)

	2010	2020	2030	Avg. 2010-2030
ETS price	14	24	32	23
	2010	2020	2030	Avg. 2010-2030
External cost	30	32	32	31

Comments

Spanish Government's predictions consider a central scenario price of 24 €2010/tCO₂ price in 2020 and 30 €2010/tCO₂ price in 2030. Source: Instituto para la Diversificación y Ahorro de la Energía. (2011). Plan de Energías Renovables 2011-2020 (transl. Renewable Energy Plan 2011-2020).

3.2 Price of crude oil

Sources

International Energy Agency. (2011). *World Energy Outlook 2011*. Paris.

Previous calculations/hypothesis/explanations

The value considered in the WEO's central scenario (*New Policies Scenario*) has been used no matter the Spanish energy system's evolution, given that the Spanish energy system is considered to be small and therefore to not affect world crude oil prices. In the WEO it is given in \$2010, and then we convert it to €2010/MWh using the average energy content of a crude oil barrel and the \$/€ rate. In the static model, where the evolution from 2010 to 2030 is represented in a single step, the average value in the 2010-2030 period is used.

Data values (Units: \$2010/bbl)

2010	2015	2020	2025	2030
78.1	102	108.60	113.6	117.3

Used values (Units: €2010/MWh)

2010	2015	2020	2025	2030	Avg. 2010-2030
39.44	51.13	57.92	60.59	62.56	54.33

Comments

Spanish Government's energy previsions estimate, for the base scenario, 110 \$2008/bbl in 2020 and 123 \$2008/bbl in 2030, which are similar values. Source: Instituto para la Diversificación y Ahorro de la Energía. (2011). Plan de Energías Renovables 2011-2020 (transl. Renewable Energy Plan 2011-2020).

3.3 Price of natural gas (pipeline gas)

Sources

International Energy Agency. (2011). *World Energy Outlook 2011*. Paris.

Previous calculations/hypothesis/explanations

The value considered for Europe in the WEO's central scenario (*New Policies Scenario*) has been used no matter the Spanish energy system's evolution, given that the Spanish energy system is considered to be small and therefore to not affect world natural gas prices. In the WEO it is given in \$2010/Mbtu, and then we convert it to €2010/MWh using the official conversion from Mbtu to MWh and the \$/€ rate. In the static model, where the evolution from 2010 to 2030 is represented in a single step, the average value in the 2010-2030 period is used.

Data values (Units: \$2010/Mbtu)

2010	2015	2020	2025	2030
7.5	9.6	10.40	11.1	11.7

Used values (Units: €2010/MWh)

2010	2015	2020	2025	2030	Avg. 2010-2030
19.39	24.63	28.39	30.30	31.94	26.93

Comments

Spanish Government's energy previsions estimate, for the base scenario, 27€2010/MWh in 2020 and 32€2010/MWh in 2030, which are similar values. Source: Instituto para la Diversificación y Ahorro de la Energía. (2011). Plan de Energías Renovables 2011-2020 (transl. Renewable Energy Plan 2011-2020). The same gas prices have been assumed for both Spanish' borders: Africa and rest of Europe. These values in 2010, according to Spanish foreign trade official statistics (COMEX), were 291 €/ton of gas from Africa and 334 €/ton of gas from Continental Europe. These values (using a calorific value of 50MJ/kg for natural gas as established by the IEA, and a conversion of 3600MJ/MWh) yield 21€/MWh and 24€/MWh. The used 2010 value is in line with the one reported in the BP Statistical Review 2011: gas prices in the European Union (CIF), where around 8 \$/Mbtu (19.7 €/MWh).

3.4 Price of liquefied natural gas (LNG)

Sources

Energy Information Administration (2012, 2003) and Petroleum Economist.

Previous calculations/hypothesis/explanations

We have not been able to find recent forecasts of LNG import prices to Europe that take into account the shale gas effect happening in the United States. Those forecasts found in the IEA's World Energy Outlook, or in European Commission's documents, do not seem to take it into account, as they do not seem to distinguish between pipeline gas imports and LNG. In addition, assuming gas prices' indexation to oil prices for the future does not seem valid anymore, as pointed in Moniz, E. J., Jacoby, H. D., et al. (2010). *The Future of Natural Gas. An Interdisciplinary MIT Study*. Cambridge MA: MIT. So we have constructed our own numbers: in the Early Release of EIA's Annual Energy Outlook 2012 and associated documents, they forecast natural gas prices at wellhead to be 4.59 \$2009/thousand cubic feet, in 2020 and 5.81 \$2009/thousand cubic feet in 2030. Converting from cubic feet to cubic meters, from \$ to €, and using an energy content for gas of 11730 GWh/billion cubic meter, these values yield 11.06 €2010/MWh in 2020 and 14.01 €2010/MWh in 2030, at wellhead. Then, we add 4€/MWh of pipeline transport to liquefaction plant and 2 €/MWh of liquefaction cost (equivalent to 0.8\$/Mbtu, estimated by EIA, 2003, *The Global Liquefied Natural Gas Market: Status and Outlook*). We add as well 1.77 €/MWh of shipping: 0.7 \$/Mbtu estimated by Petroleum Economist for a 10000 miles round trip from New Orleans to Cartagena (Spain), and back. This yields a LNG import price in Spain of around 18.8 €2010/MWh in 2020 and 21.8 €2010/MWh in 2030. Of course this is taking important hypothesis, such as that the marginal cost of world LNG markets is set by US exports from New Orleans produced at those wellhead prices and with those value chain costs.

But we have no better data at the moment. And we give all these details on the numbers so that, if the reader wants, she can use ours or produce her own numbers.

The real 2010 value has been obtained from Spanish foreign trade official statistics: average of import costs of gas from Middle East and Central America, as these were our main LNG import sources apart from Algeria and Nigeria, where trade statistics (referred to "Africa") do not allow us to separate LNG from pipeline gas. This value yields 266.8€/ton, which using energy density for LNG of 51.5 MJ/kg and 3600MJ/MWh, equals 18.6€/MWh. 2015 and 2025 values are just interpolated.

Used values (Units: €2010/MWh)

2010	2015	2020	2025	2030	Avg. 2010-2030
18.6	18.7	18.8	20.3	21.8	19.64

Comments

Spanish Government's energy previsions estimate a lower price of LNG imports of 17.7€/MWh, constant up to 2030. Our values are therefore in the right order of magnitude. Source: Instituto para la Diversificación y Ahorro de la Energía. (2011). *Plan de Energías Renovables 2011-2020* (transl. Renewable Energy Plan 2011-2020).

3.5 Price of steam coal

Sources

BP. (2011). *BP Statistical Review of World Energy 2011*.

International Energy Agency. (2011). *World Energy Outlook 2011*. Paris.

The values reported for Europe in 2010 in (BP, 2011) are the same ones as the ones used by the Spanish government in Ministerio de Industria, Turismo y Comercio. (2011). *La Energía en España 2010*. Madrid. In addition, these values are very similar to the ones from IEA's WEO. Hence we decide to use WEO's price forecast (OECD import price) for the future years.

Data values

	2010	2015	2020	2025	2030
(BP, 2011) Units: \$2010/t	92.5	--	--	--	--
(IEA, 2011). Units: \$2010/t	99.2	103.7	106.3	108.1	109.3
(BP, 2011) Units: \$2010/MWh	8.17	--	--	--	--

Used values (Units: €2010/MWh)

	2010	2015	2020	2025	2030	Avg. 2010-2030
(IEA, 2011). Units: \$2010/MWh	8.77	9.16	9.39	9.55	9.66	9.31

Comments

3.6 Price of oil products

Sources

BP. (2011). *BP Statistical Review of World Energy 2011*.

International Energy Agency. (2011a). *World Energy Outlook 2011*. Paris.

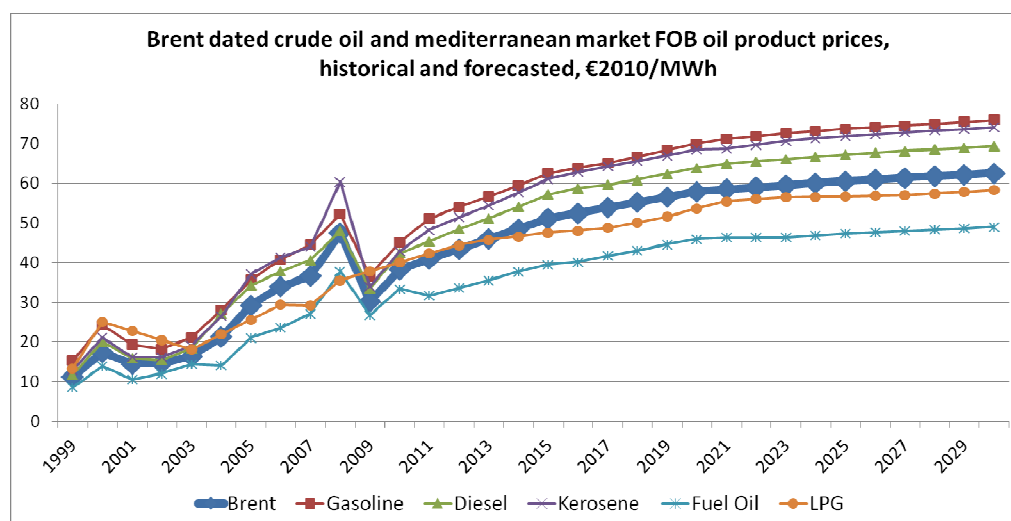
International Energy Agency. (2011b). *Oil Market Report. Annual Statistical Supplement, 2011 Edition with 2010 data*.

Previous

calculations/hypothesis/explanations

If it is difficult to forecast prices for world crude oil markets, it is even harder to do so for world oil products' markets, where not only crude oil prices affect, but as well other factors such as refining capacities, products supply and demand per region, technological developments (e.g. a breakthrough on transportation technologies), or regional legislations. We have not found any reliable forecast of cotizations in international oil products' markets. The only possible source was the EIA's *Annual Energy Outlook interactive table viewer*, but it provides forecasts for final products' prices in the US including taxes, whereas we are interested in international prices in the Mediterranean market, the reference for Spain.

Hence we have calculated our own projections for oil products' markets prices in the Mediterranean market up to 2030. First, the products' prices in this market for the 1999-2010 period (Free On Board prices in current \$/bbl) are obtained from (IEA, 2011b). Brent dated crude oil prices are also obtained from this source. Then, all of these values are converted to €2010/MWh, by using the historical US\$ inflation rate, the historical \$/€ exchange rate, the volumetric energy density of each oil product as defined by the IEA and the volume equivalence between bbl and litres. After doing this we compute, for each product, the historical (1999-2010) ratio between the prices of brent crude and the product (all previously expressed in €2010/MWh). The key hypothesis is introduced here: the historical behavior of these ratios is similar in the future. Of course we know that this is a very important assumption, as this implies that the market forces that have driven these markets in the past will continue driving them in the future (same refining structure, same products' supply and demand per region, etc). But we have not found any more appealing alternative. These ratios' extrapolations into the future have been done by assuming that each value is the 11-previous-years moving average. For instance, the Brent/gasoline ratio in 2025 is the mean of that ratio from year 2014 to 2024. Once these ratios are extrapolated, we apply them to the forecasted brent price and we estimate each product's price. This can be seen in the next figure, where the historical and forecasted prices, both for Brent and products, are represented.



More precisely, the used price ratios for each product (Brent dated/product) have been:

RATIOS	2005	2010	2015	2020	2025	2030
Gasoline	0.824	0.848	0.819	0.828	0.822	0.823
Diesel	0.854	0.903	0.893	0.907	0.901	0.902
Kerosene	0.791	0.893	0.837	0.845	0.843	0.844
Fuel Oil	1.393	1.146	1.294	1.261	1.282	1.276
LPG	1.142	0.956	1.075	1.079	1.068	1.072

Hence the obtained products' prices, in €/2010/MWh are the following ones. The product "others", which represents demand for other oil products of low value that are normally demanded on heavy industries, is assumed to be 20% below fuel oil price

Used values (Units: €/2010/MWh)

	2010	2015	2020	2025	2030	Avg. 2010- 2030
Gasoline	47.88	60.27	70.75	73.17	76.12	65.64
Diesel	46.19	56.61	64.83	66.77	69.46	60.77
Kerosene	49.89	57.23	69.16	71.68	74.22	64.44
Fuel Oil	28.32	44.60	44.77	48.04	48.81	42.91
LPG	34.55	53.50	53.87	56.15	58.58	51.33
Others	22.66	35.68	35.81	38.43	39.05	34.33

Comments

3.7 Price of electricity

Sources

European Commission (2012) SETIS Calculator of Energy Production Costs
<https://odin.jrc.ec.europa.eu/SETIS/SETIS1.html#>

European Energy Exchange EEX Homepage. <http://www.eex.com/en/>

Previous calculations/hypothesis/explanations

In our model, electricity trade has been modelled with the two regions that Spain is connected to: Europe (meaning Portugal and France) and Africa (meaning Morocco). For the European region, we have only modeled connections through the north (France). Portugal has not been modeled as it is considered to not affect the results in a significant way: since 2007 both systems are coupled, the interconnection is being reinforced, the prices are almost the same (number of hours with market splitting is decreasing very fast in the last years), demand patterns are similar due to similar climate and economic characteristics, supply will tend towards similar mixes (due to similar gas prices, similar policy constraints), renewable resources are very similar, and finally, Portuguese system is quite small compared to Spanish one (peak demand is around 20% and total demanded energy is around 19%). Hence we have used as import/export prices the wholesale electricity prices in France. For the African region, we have not managed to find any reliable data on electricity prices, so we have used a value of 180 €/MWh: it is high enough so that our model does not decide to import electricity from Morocco (normally Spain exports to Morocco). In any case, interconnection capacity with Morocco is quite small, so this value does not affect model's much. Concerning French electricity wholesale market prices, for 2010 we have used the reported price in EEX web page (52€/MWh). For 2020 and 2030 we have not found any good forecast of these prices. So we have calculated them supposing that the French electricity system is fully liberalised before 2020 and that the marginal technology establishing French spot prices (both in peak and off-peak hours) is combined cycle gas turbines. Their parameters (efficiency, emissions, costs) have been obtained from European Commission's SETIS calculator, and we have used the forecasted prices for natural gas (pipeline) and CO₂ emissions (ETS price) reported in this document. According to this source, a combined cycle gas turbine power plant will have efficiency of 63% in 2020 and 65% in 2030, emissions of 0.42 tCO₂/MWh, and the variable O&M costs reported in the table below. The 2015 and 2025 values are just interpolated.

Cost components (€/Mwhe)	2020	2030
Variable O&M costs	2.89	2.84
Fuel expenditure	45.06	49.13
CO2 expenditure	10.08	13.44
Total cost of electricity	58.03	65.41

Used values (Units: €2010/MWh)

	2010	2015	2020	2025	2030	Avg. 2010-2030
	52.0					
Europe	0	55.02	58.03	61.72	65.41	58.44
Africa	180	180	180	180	180	180

3.8 Price of biofuels

Sources

Comisión Nacional de Energía. (2012). Informe anual sobre el uso de biocarburantes correspondiente al ejercicio 2010 (transl. Annual Report on Biofuels Use 2010 Edition)

Energy Information Administration (2012) Annual Energy Outlook interactive table viewer

Previous calculations/hypothesis/explanations

For 2010 we have obtained the actual international cotizations of bioethanol and biodiesel from (CNE, 2012). The bioethanol value corresponds to the cotization of Ethanol T2 FOB Rotterdam. The biodiesel one corresponds to FAME OC CFPP NWE FOB Barges (Argus). They are expressed in \$2010/Tm and then we convert them to €2010/MWh by using the 2010 \$/€ exchange rate and the energy density of bioethanol (0.0273 TJ/t) and biodiesel (0.0371 TJ/t). Concerning future values, it has been very difficult to find reliable projections for cotizations in international biofuels markets. There are large uncertainties in these projectios due to the large regulatory and technological unknowns.

The only reliable projection has been (EIA, 2012), where a projection for bioethanol wholesale prices is done (2.49 \$2010/gallon in 2020 and 2.281 \$2010/gallon in 2030). Even if these prices are for the US, we have assumed that the ones for Europe and Spain are the same. No projections of biodiesel prices have been found, so we have assumed that the prices remain in the same levels, assuming that increased demand (due to increased support policies) is offset by improved manufacturing processes and increased supply. Those bioethanol wholesale prices are converted to €2010/MWh using the equivalence 1 gallon= 3.185 litres and an energy density for bioethanol of 24 MJ/litre, yielding 88.84 €2010/MWh (in 2020) and 81.38 €2010/MWh (in 2030)

	2010 average cotization (CNE, 2012)	Equivalent values for 2010
Bioethanol	898.00 \$2010/t	89.02 €2010/MWh
Biodiesel	1009.13 \$2010/t	73.72 €2010/MWh

Used values (Units: €2010/MWh)

Bioethanol

2010	2015	2020	2025	2030	Avg. 2010-2030
89.02	88.93	88.84	85.11	81.38	86.66

Biodiesel

2010	2015	2020	2025	2030	Avg. 2010-2030
73.72	73.72	73.72	73.72	73.72	73.72

3.9 Price of nuclear fuel

Sources

Deutch, J. M., Forsberg, C. W., Kadak, A. C., Kazimi, M. S., Moniz, E. J., & Parsons, J. E. (2009). *Future of Nuclear Power. 2009 Update*. Cambridge MA: MIT.

UNESA. (2007). *Prospectiva de generación eléctrica 2030 (transl. Electricity Generation Prospective to 2030)*

World Nuclear Association. (2011). *The Economics of Nuclear Power*.

Previous calculations/hypothesis/explanations

In this section we calculate the costs of nuclear fuel in €2010/MWht, that is, per unit of thermal energy contained in the fuel. This is the same as has been done with all the other fuels, where the costs are expressed per unit of thermal energy. In this particular case, however, a hypothesis must be made. Several references express the nuclear fuel costs per unit of electricity output (per MWhe). Hence, for converting it to MWht, we have used the efficiency of a nuclear power plant which in this research (following IEA's convention) has been considered to be 33%. For converting from \$ to €, as no precise year is given for cost values in the literature, we consider a 1.3 rate. We have used three sources: two international ones (MIT and World Nuclear Association) and a Spanish one (UNESA), all three yielding similar values (we have used the average). As many sources point out, nuclear fuel prices are quite stable and are forecasted to remain like that on the future. Hence we have supposed a very slight increase from 1.87 €2010/MWht (the average of the three sources) to 2.00 €2010/MWht in the future (a 7.5% increase). Note for Spanish readers: the value from UNESA takes into account as well the second cycle of nuclear fuel, as should be done in our opinion, i.e. the full fuel cost is the value we are seeking.

Source	Cost reported	Units	Converted costs	Units
MIT	6.97	\$/Mwhe	1.77	€2010/MWht
UNESA	5.6	€/MWhe	1.85	€2010/MWht
WNA	7.7	\$/Mwhe	1.95	€2010/MWht
	Average --->		1.86	€2010/MWht

Used values (Units: €2010/MWh)

2010	2015	2020	2025	2030	Avg. 2010-2030
1.86	1.89	1.93	1.96	2.00	1.93

3.10 Price of biofuels production inputs

Sources

Comisión Nacional de Energía. (2012). *Informe anual sobre el uso de biocarburantes correspondiente al ejercicio 2010 (transl. Annual Report on Biofuels Use 2010 Edition)*

Indexmundi (2012) Soybeans Daily Price

Instituto para la Diversificación y Ahorro de la Energía IDAE. (2011). *Plan de Energías Renovables 2011-2020 (transl. Renewable Energy Plan 2011-2020)*.

Previous calculations/hypothesis/explanations

According to (IDAE, 2011), we can assume that the inputs for biofuel production in Spain are and will be entirely imported. Hence, the marginal cost of these inputs will be their international cotization.

Spanish-produced bioethanol mainly comes from cereal (mainly wheat and corn, according to CNE, 2012), so the costs of bioethanol inputs will be the international cotization of wheat and corn. Following (CNE, 2012), we assume that bioethanol input cotizations, mainly corresponding to an average of corn values (FR Maize-EURONEXT) and wheat (FR Mill Wheat No2), have been and will be in the future years around 300 \$2010/t, which using an average \$/€ rate of 1.3, yields 230 €2010/t. Using a low calorific value for these cereals of 15.5 MJ/kg, and taking into

account that 3600 MJ=1 MWh, we obtain a cost of around 54 €/2010/MWh for bioethanol input, for 2010 and for the future. This entails the hypothesis of international cotizations remaining in the same levels and bioethanol in Spain being produced from the same combination of inputs in the future. We have not found any better alternative.

Concerning biodiesel, two main processes are involved in its fabrication: in the first one, palm or soybean or rapeseed oil is manufactured using the corresponding seeds/fruits as inputs; in the second one, these vegetables oils are converted into biodiesel in a chemical reaction (transesterification). This second step does not add much added value to the process, and that is why international cotizations of vegetable oils and biodiesel (FAME) follow a very close evolution. We have, hence, decided to consider "biodiesel production" as both steps together. This implies that the inputs for biodiesel production are, directly, the seeds and fruits. According to (CNE, 2012), the main inputs were soybean and palm. Concerning palm, we have only found the cotization of palm oil, not the palm fruits. We have, in turn, been able to find soybean prices in Indexmundi, 2012 (Soybeans, U.S. No. 2 Yellow, FOB Gulf of Mexico, U.S. price, US\$ per metric ton). We will consider as price, both for 2010 and the future, a value of 400\$/2010/t, which converted to € using a rate of 1.3, yields 308 €/2010/t. Using a low calorific value for these beans of 24 MJ/kg, and taking into account that 3600 MJ=1 MWh, we obtain a cost of around 46 €/2010/MWh for biodiesel input, for 2010 and for the future. This entails the hypothesis of international cotizations remaining in the same levels and biodiesel in Spain being produced from the same combination of inputs in the future. We have not found any better alternative.

Used values (Units: €/2010/MWh)

Bioethanol inputs

2010	2015	2020	2025	2030	Avg. 2010-2030
54.00	54.00	54.00	54.00	54.00	54.00

Biodiesel inputs

2010	2015	2020	2025	2030	Avg. 2010-2030
46.00	46.00	46.00	46.00	46.00	46.00

4. Domestic Energy Production

4.1 Domestic Coal Production Costs

Sources

Ministerio de Industria, Turismo y Comercio. (2011). La Energía en España 2010 (transl. The Energy in Spain 2010). Madrid.

Previous calculations/hypothesis/explanations

Spanish coal's quality is low, what makes it non-competitive for national electric utilities: for power generation, they rather use imported coal. However, coal mining is an important activity in northern Spain, so the government subsidizes national coal in order to keep mining jobs. According to the Spanish Ministry of Industry, the coal prices paid to coal producers were, from 2005-2010, between 7.8 €/MWh and 11 €/MWh (from 0.9 c€/thermia to 1.3c€/thermia, being 1 thermia=1.163kWh). These values were in similar orders of magnitude as imported coal, and would represent the opportunity cost for utilities to use national coal instead of imported coal. Then, the Spanish Ministry of Industry gives as well the statistics of subsidies given to national coal: in those same years, they were between 5.4 €/MWh and 7.2 €/MWh (from 0.6 c€/thermia to 0.8 c€/thermia). The precise values are given below. Supposing that the total production costs are the addition of the price and the subsidy, we can obtain the national coal production costs, which are around 16 €/MWh

Data values (Units: €2010/MWh)

	2005	2006	2007	2008	2009	2010
Price	7.8	8.4	8.6	10.1	11.0	9.7
Subsidy	5.7	6.5	6.7	6.5	5.4	7.2
Total cost	13.5	14.9	15.3	16.6	16.4	16.9

Used values (Units: €2010/MWh)

Cost of national coal production
16.9 €2010/MWh

Comments

In all years, as we have no estimates of the evolution of these costs in the future

These total production costs values are in line with the ones estimated in Europe Economics, Fraunhofer ISI, et al. (2006). Evaluation of State Aid for the Coal Industry. In this source they estimate costs around 130€/tec (for underground mines, the majority of Spanish production). Using a conversion factor of 0.1228 tec/MWh, this value yields 15.96€/MWh.

The costs of public aid to national coal production in 2010 accounted for around 320M€ (according to Ministerio de Industria, Turismo y Comercio, 2011).

4.2 Domestic Coal Production Capacity

Sources

BP. (2011). *BP Statistical Review of World Energy 2011*.

Previous calculations/hypothesis/explanations

According to (BP, 2011), in the 1981-2010 period, the year with maximum coal production in Spain was 1984, where 13.4 Mtoe (million tones of oil equivalent) of coal were produced. This value will be used as the upper bound of yearly coal production in Spain. It is equivalent to 155842 GWh

Data values (Units: GWh)

Maximum yearly national coal production
155842 GWh/year

Comments

If all this yearly production was to be subsidised (in order to create mining jobs, for instance) at the subsidy cost of 2010 (7.2 €/MWh), it would have a cost for Spain of over 1120 million €.

4.3 Biomass Production Potential

Sources

Instituto para la Diversificación y Ahorro de la Energía. (2011). Plan de Energías Renovables 2011-2020 (transl. Renewable Energy Plan 2011-2020).

Previous calculations/hypothesis/explanations

Looking at page 184 of (IDAE, 2011), in table 4.3.9, it can be seen that it makes sense to consider three types of biomass for Spain: agriculture waste, forestry waste and energy crops. In that same table, the potential of energy production of each kind of biomass in 2020 is expressed. We have considered that 2020 value as valid for our complete time horizon. The values of that table are in tons of oil equivalent, and then we convert them to GWh taking into account that 1ktoe=11.63GWh

	Potential (ktoe/year)
Agriculture Waste	6392.63
Forestry Waste	4050.43
Energy Crops	6843.79

Data values (Units: GWh)

Potential (GWh/year):	
Agriculture Waste	74346
Forestry Waste	47107
Energy Crops	79593

Comments

These values are in the same orders of magnitude as the ones in: Greenpeace (2005). Renovables 2050: el Potencial de las Renovables en la España Peninsular (transl. Renewables 2050: the Renewable Energy Potential in Peninsular Spain). Madrid.

4.4 Biomass Production Costs

Sources

Instituto para la Diversificación y Ahorro de la Energía. (2011). Plan de Energías Renovables 2011-2020 (transl. Renewable Energy Plan 2011-2020).

Previous calculations/hypothesis/explanations

In page 184 of (IDAE, 2011), in table 4.3.9, the biomass potential of each of the three biomass types seen above is given in energy units (tons of oil equivalent) per year and in tons per year. The mean costs (in €/ton) are given as well. These values are represented in the table below. With the two first columns, the energy content per mass unit of each biomass type (toe/t) can be calculated, and with it and the last column, the cost per energy unit (€/toe). Finally, these costs are converted to €/MWh with the factor 1toe=11.63MWh. We have considered the same biomass production costs along the complete time horizon, given that (IDAE, 2011) is a study up to 2020.

	Potent. (ktoe/year)	Potent. (kt/year)	Mean Cost (€/t)	Mean Cost (€/toe)
Agriculture Waste	6392.63	30552.79	40.52	193.65
Forestry Waste	4050.43	18715.36	19.98	92.32
Energy Crops	6843.79	39409.05	42.47	244.53

Data values (Units: €/2010/MWh)

Biomass costs (€/2010/MWh):	
Agriculture Waste	16.65
Forestry Waste	7.94
Energy Crops	21.03

Comments

These values are in the same orders of magnitude as the ones in: de Wit, M., & Faaij, A. (2008). Biomass Resources Potential and Related Costs. Assessment of the EU27, Switzerland, Norway and Ukraine. REFUEL Work Package 3 Final Report; and European Climate Foundation, Sveaskog, Södra, & Vattenfall. (2010). Biomass for heat and power. Opportunity and economics.

4.5 Biogas Production Potential

Sources

Instituto para la Diversificación y Ahorro de la Energía. (2011). Plan de Energías Renovables 2011-2020 (transl. Renewable Energy Plan 2011-2020).

Previous calculations/hypothesis/explanations

From page 149 of the above-mentioned source, and only considering available potential, the value for all types of biogas (we consider them all together within this category) is 1818.5 ktoe per year, which equals to 21149 GWh/year. We have considered the same value along the complete time horizon, given that (IDAE, 2011) refers to 2020.

Data values (Units: GWh)

Potential (GWh/year):	
Biogas	21149.16

Comments

4.6 Biogas Production Costs

Sources

Caldés, N., Lechón, Y., Labriet, M., Cabal, H., de la Rúa, C., Sáez, R., & Varela, M. (2008). *Description of the Energy System of Spain* (Informes Técnicos CIEMAT No. 1150). Madrid: CIEMAT.

Jalalzadeh-Azar, A. (2010). A Technoeconomic Analysis of Biomethane Production from Biogas and Pipeline Delivery. National Renewable Energy Laboratory NREL, USA.

U.S. Department of Agriculture. (2007). *An Analysis of Energy Production Costs from Anaerobic Digestion Systems on U.S. Livestock Production Facilities* (Technical Note No. 1). Natural Resources Conservation Service.

Previous calculations/hypothesis/explanations

According to (Caldés et al., 2008), the costs of biogas production in Spain in 2005 were 32.85 €/GJ, what is equivalent to 118.26 €/MWh (1MWh=3.6GJ). This value is on the upper range of the estimates for anaerobic digestors in (USDA, 2007), which are 80€/MWh (29 US\$/GJ, using 1.3 US\$=1€ and 1MWh=3.6GJ). We believe that this is due to the large difference in the Spanish and US agriculture industry. We will make the hypothesis that the biogas used in this research is already upgraded (converted into biomethane with more than 95% of CH₄, whereas biogas only has around 60% of CH₄). This upgrading process costs around 10€/MWh (Jalalzadeh-Azar, 2010). We suppose that the 80€/MWh value reported for the US is without upgrading, and that the 118.26€/MWh value for Spain is already upgraded. If the first one is added with the 10€/MWh of upgrading, it yields a value of 90€/MWh, closer to the 118€/MWh value found for Spain. We will use the mean between both values, that is, 104€/MWh. We have not found other reliable data, so this value is considered for the whole time horizon.

Data values (Units: €2010/MWh)

Costs (€2010/MWh):	
Biogas	104.00

4.7 Solid Waste Production Potential

Sources

Instituto para la Diversificación y Ahorro de la Energía. (2011). Plan de Energías Renovables 2011-2020 (transl. Renewable Energy Plan 2011-2020).

Previous calculations/hypothesis/explanations

We will consider, jointly within this category, urban and industrial solid waste. Of it, only its renewable share will be used. From page 385 of the above-mentioned source, the total amount of solid waste with energy-use potential, considering both urban and industrial solid waste and only its renewable fraction, adds up 4045 ktoe per year, which equals to 47043.35 GWh/year. This value has been obtained already subtracting biogas potential (already accounted for in the biogas section). We have considered the same value along the complete time horizon, given that (IDAE, 2011) refers to 2020.

Data values (Units: GWh)

Potential (GWh/year):	
Solid waste	47043.35

4.8 Solid Waste Production Costs

Sources

Caldés, N., Lechón, Y., Labriet, M., Cabal, H., de la Rúa, C., Sáez, R., & Varela, M. (2008). *Description of the Energy System of Spain* (Informes Técnicos CIEMAT No. 1150). Madrid: CIEMAT.

Previous calculations/hypothesis/explanations

We have not found much reliable data on the costs of producing solid waste which is ready to use for energetic purposes. The only source is (Caldés et al., 2008), where it says that this cost is 5.81€/GJ, equivalent to 20.92 €/MWh. This value will be used for the complete time horizon.

Data values (Units: €2010/MWh)

Costs (€2010/MWh):	
Solid waste	20.92

4.9 Large Hydro Energy Potential and Costs. Data also for pumping storage

Sources

Red Eléctrica de España. (2011). El Sistema Eléctrico Español 2010 (transl. The Spanish Electricity System 2010).

Previous calculations/hypothesis/explanations

In the graph on page 37 of (REE, 2011), the Spanish 2010 hydraulicity (the amount of water available each day for power generation) is compared to the historical average value. We will use this historical average value as a good estimation of the total available hydro energy for any year in the future. In this graph, the values are given, for each month, in GWh/day, so it is enough to multiply for the number of days in each

month to obtain the available monthly (and yearly) energy. This water is supposed to be used only in large hydro power plants (with reservoirs and run-off-the-river), i.e. those technologies that REE considers "Régimen Ordinario". The energy used by minihydro power plants (considered "Régimen Especial") by REE is accounted for separately. As it is a free renewable source, hydro energy is considered to have null cost. The installed capacity of large hydro power plants, both for run-off-the-river and reservoir plants, is already fully utilised. These values, after asking some experts, have been considered to be 6.42 GW for reservoir capacity plants and 4.88 GW for run-off-the-river. Costs of the primary energy per se are null: costs will be considered for the power generation technology itself, under the CE category.

PUMPING STORAGE: from the Spanish Renewable Energy Plan (PER, done by IDAE) there is a potential of pumping storage in Spain of 8811MW, and the actual one is actual 5347MW. According to Greenpeace it is around 8000MW. We use those values, and an efficiency of the pumping-releasing cycle of 70%

Month:	JA	FB	MR	AP	MY	JN	JL	AG	SP	OC	NV	DC
GWh/day:	125	146	110	101	91	72	30	15	20	46	72	99
Days/Month:	31	28	31	30	31	30	31	31	30	31	30	31

Data values (Units: GWh for energy and GW for power)

Mean historical hydraulicity (GWh/month) or (GWh/year)												
JA	FB	MR	AP	MY	JN	JL	AG	SP	OC	NV	DC	YEAR
3875	4088	3410	3030	2821	2160	930	465	600	1426	2160	3069	28034
Installed capacity of large reservoir power plants (=maximum potential):											6.42 GW	Effic. (%)
Installed capacity of large run-off-the-river power plants (=max. potential):											4.88 GW	100%

4.10 Onshore Wind Energy Potential and Costs

Sources

Frías, P., Linares, P., & Gómez, T. (2010). Análisis prospectivo general (transl. General Prospective Analysis). In F. Becker, L. M. Cazorla, & J. Martínez-Simancas (Eds.), *Tratado de Energías Renovables (transl. Renewable Energy Treaty)* (1ª ed., pp. 243–288). Cizur Menor (Navarra): Aranzadi.

Greenpeace. (2005). *Renovables 2050: el Potencial de las Renovables en la España Peninsular* (transl. Renewables 2050: the Renewable Energy Potential in Peninsular Spain). Madrid.

Instituto para la Diversificación y Ahorro de la Energía. (2011). *Plan de Energías Renovables 2011-2020* (transl. Renewable Energy Plan 2011-2020).

Previous calculations/hypothesis/explanations

Greenpeace (in 2005) performed a good evaluation of wind energy potential in Spain: was one of the first ones taking into account a key aspect of wind energy: land use. In addition, it considered environmentally protected areas: Red Natura 2000 and Espacios Naturales Protegidos were left out. With this, a total potential of onshore wind energy of 91.5 GW was identified (using only 10% of the real technological potential so that total land used was around 5.6%, a reasonable value according to them). According to Greenpeace, the equivalent functioning hours for that capacity would be 2080h/year, i.e. a capacity factor (CF) of 23.74%, calculated using data from the Spanish National Energy Commission from 2003. This value is similar to the current one: according to (IDAE, 2011), in Spain in 2010 a total of 20744 MW of wind power generated 43700 GWh, which yields a CF of 24.05% (i.e. 2106 equiv. hours). This slight increment is probably due to technological advances and repowering of windfarms between 2003 and 2010. In addition, (IDAE, 2011) estimates a CF of 23.36% (2048 equivalent hours) for a wind power objective of 35GW in 2020. Once considered all this, we will model wind energy in 3 steps of limited capacity and decreasing equivalent hours, in order to represent the decreasing potential in free wind spots as more and more power is installed (in other words, best spots are used first). The first step represents the situation at the end of 2010: 21GW and 2100 equivalent hours (aprox.). The second step represents the value that, in order to achieve 2047 equiv. hours for 35 GW, should have the remaining 14 GW (from 21GW in 2011 to 35GW in 2020). This value is 1970 hours (22.5% CF). For the last step, which represents capacity from 35GW to the total potential of 91.5GW, we will use a value of 1900 equiv. hours, in line with (Frias et al., 2010), even if they applied that factor to much less capacity, which may make our hypothesis a bit optimistic. This optimism, however, is justified by the fact that our analysis is up to 2030, whereas theirs was up to 2020, so in our case there are greater possibilities for technological advance. As it is applied only to the last 56.5 GW, it yields an equivalent (for all the 91.5GW) of 1957 total accumulated equivalent hours. As it is a free renewable source, wind energy is considered to have null cost. 100% efficiency is used, in line with IEA. Costs of the primary energy per se are null: costs will be considered for the power generation technology itself, under the CE category.

Data values (Units: GW for step limits, hours for equivalent hours, % for capacity factors and % for efficiency)

Step	lim.(GW)	Eq. h.	CF (%)	Energy(GWh)	Cap. , eq. hours & energy (accumulated)				
Step 1	21.0	2100	23.97%	44100	21.0	GW	2100	h	44100 GWh
Step 2	14.0	1970	22.49%	27580	35.0	GW	2048	h	71680 GWh
Step 3	56.5	1900	21.69%	107350	91.5	GW	1957	h	179030 GWh
Effic. (%)		100							
		%							

4.11 Offshore Wind Energy Potential and Costs

Sources

Frías, P., Linares, P., & Gómez, T. (2010). Análisis prospectivo general (transl. General Prospective Analysis). In F. Becker, L. M. Cazorla, & J. Martínez-Simancas (Eds.), *Tratado de Energías Renovables (transl. Renewable Energy Treaty)* (1ª ed., pp. 243–288). Cizur Menor (Navarra): Aranzadi.

Greenpeace. (2005). Renovables 2050: el Potencial de las Renovables en la España Peninsular (transl. Renewables 2050: the Renewable Energy Potential in Peninsular Spain). Madrid.

Instituto para la Diversificación y Ahorro de la Energía. (2011). Plan de Energías Renovables 2011-2020 (transl. Renewable Energy Plan 2011-2020).

Previous calculations/hypothesis/explanations

(Greenpeace, 2005) identifies a total potential of 165 GW (but proposes to not use more than 10%, that is, 16.5GW). For that potential, they established around 2030 equivalent hours (if the full potential is to be used), which we consider a small value. However, they identify as well another case of technoeconomic optimisation, which yields a maximum potential of 95GW (only 10% would be used) and 3325 equivalent hours. This case, we think, is a bit optimistic. More recently, (IDAE, 2011) establishes a 2020 objective of 0.75GW with 2460 equivalent hours. And (Frias et al., 2010) used 2500 equivalent hours. Considering these values, we will use 2700 equivalent hours and we will calculate the maximum potential as the interpolated value for 2700 hours in Greenpeace's figures (16.5GW with 2030 hours and 9.5GW with 3325hours), which yields 12.88GW. Only one step will be used, implying that offshore resources are more constant than onshore ones. As it is a free renewable source, wind energy is considered to have null cost. 100% efficiency is used, in line with IEA. Costs of the primary energy per se are null: costs will be considered for the power generation technology itself, under the CE category.

Data values (Units: GW for step limits, hours for equivalent hours, % for capacity factors and % for efficiency)

	Step lim.(GW)	Eq. h.	CF (%)	Energy(GWh)	Effic. (%)
Step 1	12.88	2700	30.82%	34776	100%

4.12 Human Energy Costs

Sources and calculations

In order to account for the costs of human powered energy types (such as bikes), which is needed to avoid knife-edge solutions in the LP model, we have used a value of 172 €/MWh, assuming that 0.5kg of spaghetti (= 1500 kcal) = costs 1€ of which 70% are supposed to be business margins and taxes. Hence $0.3€ = 1500kcal = 0.0017445000 \text{ MWh}$

4.13 Solar Photovoltaic Energy Potential and Costs

Sources

Frías, P., Linares, P., & Gómez, T. (2010). Análisis prospectivo general (transl. General Prospective Analysis). In F. Becker, L. M. Cazorla, & J. Martínez-Simancas (Eds.), *Tratado de Energías Renovables (transl. Renewable Energy Treaty)* (1ª ed., pp. 243–288). Cizur Menor (Navarra): Aranzadi.

Greenpeace. (2005). Renovables 2050: el Potencial de las Renovables en la España Peninsular (transl. Renewables 2050: the Renewable Energy Potential in Peninsular Spain). Madrid.

Instituto para la Diversificación y Ahorro de la Energía. (2011). Plan de Energías Renovables 2011-2020 (transl. Renewable Energy Plan 2011-2020).

Previous calculations/hypothesis/explanations

Concerning solar PV (photovoltaics), (Greenpeace, 2005) differentiates between fixed panels and those with solar tracking devices, and as expected, the latter have better capacity factors (CF). We will use this differentiation as well: for "centralised" solar farms, where large capacities are installed in the countryside, we will consider tracking devices and higher capacity factors; whereas for "distributed" solar panels (on roofs, for instance), we will consider static instalations with lower CFs. Greenpeace estimates total technological potentials of 495 GW (distributed PV without tracking) and 708 GW (centralised PV with tracking). But then they use a realistic maximum utilisation of 10% of these technological potentials. Regarding capacity factors (CF) and equivalent functioning hours, Greenpeace considers 1150h (CF=13.13%) for the former, and 1950h (CF=22.26%) for the latter. These values are compatible, in our opinion, with (Frias et al., 2010) and (IDAE, 2011), where they do not distinguish between PV with and without tracking, and use, as equivalent hours, values of 1500h and 1700h. We will, then, use Greenpeace's values considering the 10% bound on technological potentials as a realistic one. Only one step will be used for each type of PV, which implies that we

are not differentiating geographically, for instance between northern and southern Spain. As it is a free renewable source, solar PV energy is considered to have null cost. 100% efficiency is used, in line with IEA. Costs of the primary energy per se are null: costs will be considered for the power generation technology itself, under the CE category.

Data values (Units: GW for step limits, hours for equivalent hours, % for capacity factors and % for efficiency)

	Step lim.(GW)	Eq. h.	CF (%)	Energy(GWh)	Effic. (%)
Centralised PV with tracking	70.8	1950	22.26%	138060	100%
Distributed PV w/o tracking	49.5	1150	13.13%	56925	

4.14 Solar Thermoelectric Energy Potential, Costs and Efficiency

Sources

Greenpeace. (2005). Renovables 2050: el Potencial de las Renovables en la España Peninsular (transl. Renewables 2050: the Renewable Energy Potential in Peninsular Spain). Madrid.

International Energy Agency. (2011). IEA ETSAP Technology Brief E10. Concentrating Solar Power.

Instituto para la Diversificación y Ahorro de la Energía. (2011). Plan de Energías Renovables 2011-2020 (transl. Renewable Energy Plan 2011-2020).

Previous calculations/hypothesis/explanations

In line with (IDAE, 2011), where it says that cilindroparabolic (CP, called as well Parabolic Trough) systems with thermal storage are the ones that are being mainly built nowadays in Spain, we will suppose that all thermoelectric potential is exploited with CP systems containing 6 hours thermal storage systems. This is consistent with these systems representing the most mature technology (IEA, 2011). For this technology, according to (IDAE, 2011), there is a total potential of 1281GW producing 4037 TWh/year, i.e. 3152 equivalent hours. But this would use almost 58000 square kilometers, i.e. around 12% of Spanish surface. Greenpeace seems to be more optimistic, considering that with similar land occupation, 2740GW could produce 9897 TWh/year, i.e. 3612 equivalent hours, but then they propose a scenario for 2050 where only around 2% of the land is used. Given that (IDAE, 2011) is a more recent study, we will use its values as maximum potential, and suppose a maximum land use of 3%. With this, the maximum potential (of CP technology with 6h storage) is 320GW, producing 3152 equivalent hours (capacity factor of 35.98%), i.e. 1008.64 TWh/year. As it is a free renewable source, solar PV energy is considered to have null cost. Following (IEA, 2011), we will suppose a 20% efficiency between primary and final energy as a reasonable value for the period up to 2030. Costs of the primary energy per se are null: costs will be considered for the power generation technology itself, under the CE category.

Data values (Units: GW for step limits, hours for equivalent hours, % for capacity factors and % for efficiency)

	Step lim.(GW)	Eq. h.	CF (%)	Energy(GWh)	Efficiency (%)
Step 1	320.00	3152	35.98%	1008640	20%

4.15 Minihydro Energy Potential and Costs

Sources

Greenpeace. (2005). Renovables 2050: el Potencial de las Renovables en la España Peninsular (transl. Renewables 2050: the Renewable Energy Potential in Peninsular Spain). Madrid.

Instituto para la Diversificación y Ahorro de la Energía. (2011). Plan de Energías Renovables 2011-2020 (transl. Renewable Energy Plan 2011-2020).

Red Eléctrica de España. (2011). El Sistema Eléctrico Español 2010 (transl. The Spanish Electricity System 2010).

Previous calculations/hypothesis/explanations

In this category we will consider the small hydro power plants accounted by the Spanish regulation

under the category "Régimen Especial". This category includes, in Spanish regulation (Royal Decree 661/2007) the power plants of less than 50MW, but for data availability considerations we only will consider here those smaller than 10MW. In addition, establishing the limit in 10 MW is done as well in (Greenpeace, 2005) and (IDAE, 2011). We believe that this simplification does not significantly affect results. According to (IDAE, 2011), in Spain currently there is an installed power of around 1922 MW of these power plants, which in 2010 produced 6234 GWh (3244 equivalent hours). But 2010 was a very humid year (129% of the historical mean hydraulicity, according to REE) so that capacity in an average year would have produced around 2515 equivalent hours. Given that minihydro power plants are normally run-off-the-river plants, we will model them as a capacity producing a constant amount of electric power according to a capacity factor which corresponds to this average value of 2515 equivalent hours per year (28.71%). In other words, the model can not optimise minihydro water utilisation, as it does with large hydro power plants with reservoir capacity. In order to account for different hydro availability in each month, this capacity factor will be modified (in the previous calculations within the model) so that, even if the yearly mean remains the same, the monthly value is proportional to the hydraulicity introduced as data (see "Mean historical hydraulicity" above). As it is a free renewable source, hydro energy is considered to have null cost. And following IEA's convention, it will be supposed to have 100% efficiency. According to (IDAE, 2011) around 1000 MW of untapped potential remains available in Spain (the total available capacity is 2922 MW). Costs of the primary energy per se are null: costs will be considered for the power generation technology itself, under the CE category.

Data values (Units: GW for step limits, hours for equivalent hours, % for capacity factors and % for efficiency)

	Step lim.(GW)	Eq. h.	CF (%)	Energy(GWh)	Efficiency (%)
Step 1	2.92	2515	28.71%	7349	100%

4.15 Solar Thermal Energy Potential and Costs

Sources

Instituto para la Diversificación y Ahorro de la Energía. (2011a). Plan de Energías Renovables 2011-2020 (transl. Renewable Energy Plan 2011-2020).

Instituto para la Diversificación y Ahorro de la Energía. (2011b). *Evaluación del potencial de energía solar térmica y fotovoltaica derivado del cumplimiento del Código Técnico de Edificación. Estudio Técnico PER 2011-2020* (transl. *Evaluation of the Solar Thermal and Solar Photovoltaics Potential Derived from the Technical Building Code. Technical Study PER 2011-2020*). Madrid.

Instituto para la Diversificación y Ahorro de la Energía. (2011c). *Evaluación del potencial de la energía solar térmica en el sector industrial. Estudio Técnico PER 2011-2020* (transl. *Evaluation of the Solar Thermal Potential in the Industrial Sector. Technical Study PER 2011-2020*). Madrid.

Weiss, W., & Biermayr, P. (2009). Potential of Solar Thermal in Europe. This report was prepared within the framework of the EU-funded project RESTMAC, TREN/05/FP6EN/S07.58365/020185. European Solar Thermal Industry Federation Federation (ESTIF).

Previous calculations/hypothesis/explanations

According to the sources used here, the potential for solar thermal energy use in Spain is not derived from a physical limit in the use of this energy, as happens with hydro, wind or electricity-production solar technologies, where, for instance, land use constraints are critical. The limitation is just derived from the surface of roofs and buildings where solar thermal collectors can be installed, and the demand for heat that could be supplied with this technology. Hence, we will not suppose any limitation of the potential due to land use but, instead, due to the availability of surfaces and heat demand. We will study this for two sectors: industry and other uses (which includes residential and services). First, concerning industrial uses, in (IDAE, 2011a) a total useful surface of 319 million m² is identified. However, given that solar thermal can only supply low and medium temperature heat, the study has to be based on the industrial demand for this type of heat. The industrial demand of this type of heat that could be covered with solar thermal is around 60TWh (per year), what would require around 68GW of solar thermal panels (883 equivalent hours), covering around 97.4 million m² (so the limiting factor is not the available surface but the demand that could be supplied with solar thermal). Even if (IDAE, 2011a) looks until 2020, we will use the same values for 2030. The same source establishes, for 2020, an installed capacity of 10 MW in a favourable case, and 1.7 MW in an unfavourable case. With this, we will suppose the installed capacity in our base case for 2030 to be 7MW. Second, concerning other uses sectors, we will suppose that the current solar thermal installed capacity in Spain was all in this sector (none in industry). According to (IDAE, 2011a), it was 2.36 million m², what equals 1.657GW producing 2128 GWh (1284 equivalent hours). And according to the same source, due to the Buildings Technical Code (CTE, in Spanish), between now and 2020 around 3.4 million m² will be installed and, between 2020 and 2030, 0.35 million m² per year. This gives a total amount of 9.26 million m² in 2030, what is 6.5 GW, producing 8346 GWh (1284 equivalent hours). Concerning the maximum limit for solar thermal, it can be obtained from the comparison of figures 17 and 34 of (IDAE, 2011b), given that the first one represents theoretical potential, and the second one, real potential. Considering that actual real capacity is around 2.36 million m², but which could have been one extra million in 2007, around 0.83 extra million in 2008 and around 0.4 extra million in 2009, and that the value from 2010 to 2020 (3.4 million) could be increased by 40% and by 25% between 2020 and 2030, we obtain a maximum theoretical potential of 13.75 million m² by 2030. This equals 9.65GW producing 12390 GWh (1284 equivalent hours). In line with (IDAE, 2011c), we will suppose an efficiency of around 55% between primary and final energy (solar radiation and heat). As it is a free renewable source, solar thermal energy is considered to have null cost. Costs of the primary energy per se are null: costs will be considered for the technology itself, under the CE category.

Data values (Units: GW for step limits, hours for equivalent hours, % for capacity factors and % for efficiency)

Sector:	GW inst. in 2030 (base case)	Potential (GW)	Eq. h.	CF (%)	Energy(GWh)
Industrial	7	68.00	883	10.1%	60044
Other uses	6.5	9.65	1284	14.7%	12391
Sector:	Efficiency (%)				
Industrial	55%				
Other uses	55%				

5. Energy Trading Capacities and Energy Network/Transport Modelling

5.1 Electricity Interconnections Capacities

Sources

Ministerio de Industria, Turismo y Comercio. (2011). Planificación de los Sectores de electricidad y gas 2012-2020. Desarrollo de las redes de transporte. Primer borrador (transl. Electricity and Gas Sectors Plan 2012-2020. Transport Networks Development. First Draft).

European Commission. (2010). Energy infrastructure priorities for 2020 and beyond - A Blueprint for an integrated European energy network. Communication (2010) 677/4.

Red Eléctrica de España. (2011). El Sistema Eléctrico Español 2010 (transl. The Spanish Electricity System 2010).

Previous calculations/hypothesis/explanations

As explained in this document when justifying the used prices of electricity trading, the "Europe" region is considered to be France (french prices are used). When considering interconnections, the same has been done. According to (REE, 2011) and (EC, 2010), in 2010 the interconnection capacity with France was about 1.4GW, and with Morocco, 1.4GW. For the future, we have used the plans for future interconnections recommended in (EC, 2010): Spain-Morocco of 2.1GW (starting from 2015) and remaining in that level up to 2030; Spain-France of 4.0GW (reached lineally in 2020) and reaching lineally 6.6GW in 2030 (assuming similar increase in each decade).

Used values (Units: GW)

From/to:	2010	2015	2020	2025	2030	Avg. 2010-2030
Europe	1.4	2.7	4.0	5.3	6.6	4.00
Africa	1.4	2.1	2.1	2.1	2.1	1.96

Comments

According to (MITYC, 2011), other possible connection in the long term would be between the systems of Spain and UK (between the Basque Country and Indian Queens). It is apparently feasible and profitable, for an underwater connector of between 1 GW to 2 GW working in "merchant line" regime. However, this possibility has not been considered in this research, unless explicitly said.

5.2 Electricity Interconnections Costs

Sources

Ministerio de Industria, Turismo y Comercio. (2011). Planificación de los Sectores de electricidad y gas 2012-2020. Desarrollo de las redes de transporte. Primer borrador (transl. Electricity and Gas Sectors Plan 2012-2020. Transport Networks Development. First Draft).

de Joode, J., Ozdemir, O., Veum, K., van der Welle, A., Miglavacca, G., Zani, A., & L'Abbate, A. (2011). SUSPLAN Project. Deliverable Number D3.1. Trans-National Infrastructure Developments on the Electricity and Gas Market.

Previous calculations/hypothesis/explanations

In (Ministerio de Industria, Turismo y Comercio, 2011), it says that the cost of the interconnection reinforcement with France (from 1.4 to 2.7 GW) is expected to be 1200 million € (i.e. 923 €/kW). However, this cost is quite high because due to environmental constraints, an underground High Voltage DC (HVDC) solution has been used. According to (de Joode et al., 2011), overhead AC lines are much less expensive: taking into account the annualized costs they report in page 38 (which include CAPEX, O&M and compensation costs, and are calculated at 8% interest rate over 40 years), obtained values are 87.31€/kW (80km overhead AC line) and 574.65 €/kW (130km HVDC). We will use the mean of all three values: 528.1€/kW. We will suppose that this cost is lineally reduced by 65% in 2030 due to technological advances, i.e. 184.83 €/kW. Only half the cost is born by Spain, the other half belonging to the neighbouring country.

Used values (Units: €/2010/kW)

From/to:	2010	2015	2020	2025	2030	Avg. 2010-2030
Europe	264.05	221.1	178.2	135.3	92.4	178.2
Africa	264.05	221.1	178.2	135.3	92.4	178.2

Comments

Even if the the geology is different, same values have been supposed for France and Africa

5.3 Gas Interconnections Capacities

Sources

Ministerio de Industria, Turismo y Comercio. (2011). Planificación de los Sectores de electricidad y gas 2012-2020. Desarrollo de las redes de transporte. Primer borrador (transl. Electricity and Gas Sectors Plan 2012-2020. Transport Networks Development. First Draft).

ENAGAS. (2011). El Sistema Gasista Español 2010 (transl. The Spanish Gas System, 2010).

de Joode, J., Ozdemir, O., Veum, K., van der Welle, A., Miglavacca, G., Zani, A., & L'Abbate, A. (2011). SUSPLAN Project. Deliverable Number D3.1. Trans-National Infrastructure Developments on the Electricity and Gas Market.

Previous calculations/hypothesis/explanations

Like it has been done for electricity, for natural gas trading the "Europe" region has been supposed to be just France, so the gas interconnection capacities with Europe have been considered to be only the interconnections with France (those with Portugal have not been considered). In (ENAGAS, 2011), the 2010 capacities in GWh/day are provided for both interconnections with France (Larrau and Irún) and with Africa (Tarifa and Almería, this last one corresponding to the MEDGAZ pipeline). Given that GWh is already an energetic unit, just dividing by 24 (1day=24h) is enough to obtain power units in GW. If different, the average of the summer and winter value has been used. In (Ministerio de Industria, Turismo y Comercio, 2011), the estimated capacities with Europe for 2015 can be found. For the rest of estimations, values from table A.18 in (de Joode et al., 2011) are used (for 2030, four storylines mean).

	(GW)	2010	2015		(GW)	2010	2015
Spain->France	Larrau	3.3	6.9	Spain->Africa	Tarifa	---	---
	Irún	0.6	5.2		Almeria	---	---
France->Spain	Larrau	4.2	6.9	Africa->Spain	Tarifa	14.792	14.79
	Irún	0.4	5.2		Almeria	11.083	11.08

Used values (Units: GW)

From:	2010	2015	2020	2025	2030	Avg. 2010-2030
Europe	4.6	12.1	12.1	12.1	12.1	10.6
Africa	25.9	25.9	25.9	30.0	34.1	28.4
To:	2010	2015	2020	2025	2030	Avg. 2010-2030
Europe	3.9	12.1	16.8	16.8	16.8	13.3
Africa	0.0	0.0	0.0	0.0	0.0	0.0

Comments

5.4 Gas Interconnections Costs

Sources

de Joode, J., Ozdemir, O., Veum, K., van der Welle, A., Miglavacca, G., Zani, A., & L'Abbate, A. (2011). SUSPLAN Project. Deliverable Number D3.1. Trans-National Infrastructure Developments on the Electricity and Gas Market.

MEDGAZ web page (www.medgaz.com)

Previous calculations/hypothesis/explanations

From (MEDGAZ, 2007) and some press sources, we obtain that the MEDGAZ Algeria-Spain pipeline cost was around 1000 million €. Its capacity, as seen above, is around 11.1 GW, what yields a value of 90.09 €/kW for the overnight investment cost. According to (de Joode et al., 2011), in page 156, the marginal cost of an onshore european pipeline is smaller in the order of magnitude of 12/27 (respect to an offshore mediterranean one). Hence, we will consider a cost of 40 €/kW for a Europe-Spain pipeline. We will suppose a 40% cost reduction from 2010 to 2030, and that only 50% of the cost is born by Spain (being the other 50% born by the neighbouring country).

Used values (Units: €2010/kW)

From/to:	2010	2015	2020	2025	2030	Avg. 2010-2030
Europe	20.0	18.0	16.0	14.0	12.0	16.0
Africa	45.0	40.5	36.0	31.5	27.0	36.0

5.5 Liquefied Natural Gas (LNG) trading capacity and costs

Previous calculations/hypothesis/explanations

It has been supposed that the LNG import capacity is ilimited. This is equivalent to supposing that no limit of ships can discharge this product in Spanish' ports. Hence, the costs have been supposed to be null. However, a limitation will be set when establishing the LNG regasification capacity, which is indeed bounded (but the model can increase it by investing in regasification terminals).

5.6 Oil and oil products trading capacity and costs

Previous calculations/hypothesis/explanations

It has been supposed that the crude oil and oil products import and export capacity is ilimited. This is equivalent to supposing that no limit of ships can charge/discharge these products in Spanish' ports. Hence, the costs have been supposed to be null.

5.7 Biofuels and biofuels inputs' trading capacity and costs

Previous calculations/hypothesis/explanations

It has been supposed that the biofuels and biofuels' inputs (e.g. cereals or vegetable oil) import and export capacity is ilimited. This is equivalent to supposing that no limit of ships can charge/discharge these products in Spanish' ports. Hence, the costs have been supposed to be null.

5.8 Imported coal trading capacity and costs

Previous calculations/hypothesis/explanations

It has been supposed that the coal import capacity is ilimited. This is equivalent to supposing that no limit of ships can discharge this product in Spanish' ports. Hence, the costs have been supposed to be null. Null export capacity has been supposed because Spain does not export this kind of energy and this is not likely to happen in the future.

5.9 Nuclear energy trading capacity and costs

Previous calculations/hypothesis/explanations

It has been supposed that the nuclear energy import capacity is ilimited. Hence, the costs have been supposed to be null. Null export capacity has been supposed because Spain does not export this kind of energy and this is not likely to happen in the future.

5.10 Spanish Electricity network: losses

Sources

Ministerio de Industria, Turismo y Comercio. (2011). La Energía en España 2010 (transl. The Energy in Spain 2010). Madrid.

Previous calculations/hypothesis/explanations

For a complete explanation of electricity network modelling, refer to the main document describing this research. Here, we will just explain the calculated values for the losses factors. Concerning losses, for centralized networks some experts gave as an approximate value of 3% losses in transmission and 6% in distribution, adding up a 9% value. However, we have compared this to official statistics. In the annexes of (MITYC, 2011), the total electricity consumption in Spain for the last years is provided in ktoe (final demand). Taking the values from 2001 to 2010 and converting them to TWh (1ktoe=11.63TWh), we obtain the values reported below. In the same reference (and analog ones for previous years, given that it is a yearly publication), we can obtain the "demanda en barras de central" (transl. *demand in power plants' busbar*). This value represents the value of demand once expressed in power plants' busbar, i.e. once network losses have been taken into account (but not taking anything else into consideration, such as power consumption for pumping storage units or electricity exports). It is, hence, obtained subtracting the energy consumed in pumping storage plants and the net exports from the total net electricity generation in all power plants (*net* means once subtracted their own consumptions). In other words, demand in power plants's busbar + pumping storage consumptions + net exports = net generation. Once these values are obtained, the network losses are calculated as (demand in power plants' busbar - final demand)/demand in power plants' busbar. It can be seen that network losses have followed a decreasing trend over the last ten years. For the future, we will suppose that the tendency is maintained, implying that (i.) more investment in networks is produced; (ii.) localisation signals for generators and loads are improved; and (iii.) system operation continues improving. Extrapolating the tendency up to 2030, the 9% value is reached after 2020: we obtain a 9.9% in 2015, a 9.2% in 2020, a 8.5% in 2025 and a 7.7% in 2030.

For distributed networks, it is important to remember that high-voltage transmission lines only present a 2-3% of losses, and that these distributed networks are normally in medium- and low-voltage. Hence, if the total value for centralised grid is between 12% and 8%, a value of 9% to 5% would be expected for distributed grids. However, distributed grids as we have defined them are in local areas so distances are smaller, and as well they try to somehow represent the tendency of smart grids for the future. After speaking with some distribution and smart grids experts, a value of 4% is going to be used for industrial distributed networks and 4.5% for industrial distributed networks. The difference is due to the fact that networks in industrial areas are normally in higher voltages. To represent the improvements in these networks' operation up to 2030, mainly due to the penetration of smart grids, we will suppose a 2% and 2.5 values in 2030.

Calculation of losses in centralised network for the past 10 years:

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Demand in PP's busbar (TWh)	227.53	233.7	250.45	261.05	274.5	282.64	290.1	290.3	273.77	278
Final Demand (TWh)	200.77	206.4	220.55	231.02	242.3	250.51	257.8	258.8	243.83	249
Network losses (%)	11.8%	11.7%	11.9%	11.5%	11.7%	11.4%	11.1%	10.9%	10.9%	10.4%

Used values (Units: %)

Losses in each electric grid	2010	2015	2020	2025	2030	Avg. 2010-2030
Centralised network	10.4%	9.9%	9.2%	8.5%	7.7%	9.2%
Distributed network industrial	4.0%	3.5%	3.0%	2.5%	2.0%	3.0%
Distributed network residential/commercial	4.5%	4.0%	3.5%	3.0%	2.5%	3.5%

Comments

These values are in similar orders of magnitude as the used in the UK MARKAL model as reported in Kannan, R., Strachan, N., Pye, S., Anandarajah, G., & Balta-Ozkan, N. (2007). UK MARKAL Model Documentation. Retrieved from www.ukerc.ac.uk

5.11 Spanish Electricity network: costs

Sources

Comisión Nacional de Energía. (2011). *Boletín Mensual de Indicadores Eléctricos y Económicos. Enero 2011 (transl. Mensual Bulletin of Energetic and Economic Indicators. January 2011).*

Ministerio de Industria, Turismo y Comercio. (2011). Planificación Energética Indicativa, según lo dispuesto por la Ley 2/2011, de 4 de marzo, de Economía Sostenible (transl. Indicative Energy Planning, as required in Law 2/2011 of Sustainable Economy).

Red Eléctrica de España. (2011). El Sistema Eléctrico Español 2010 (transl. The Spanish Electricity System 2010).

Previous calculations/hypothesis/explanations

As explained in this research's main document, the electricity network has been divided in three types: centralised network, distributed network in industrial areas and distributed network in residential/commercial areas. Concerning centralised grid, its costs for the future are calculated using an econometric relation which explains those costs by two of the model's variables. With it, the grid's costs can be computed as a function of those two variables. Within these costs, we have only considered transmission costs, distribution costs and system operator's remuneration. The first two are supposed to fully include investments' amortization and operation and maintenance costs. Of the costs reported by CNE, we have not included in these econometrically-explained network costs: (i) the costs of power interruptions to large energy consumers which have signed specific contracts that allow the System Operator to not supply them in scarcity moments in exchange for a monetary payment if it occurs ; (ii) the electricity market operator's remuneration; (iii) the CNE's remuneration born by electricity consumers. The explanatory variables are chosen so that two main factors are taken into account: increment in demand and increment in intermittent generation. These drivers could take the form of several variables in our model. For instance, even if they are not the same exact magnitudes, demand could be represented both by energy delivered to final sectors, or by energy injected into the grid. Both are different variables in our model and both could be used as explanatory factors.

After running some tests on the statistical significance of each adjustment, the used explanatory factors have been the net electricity generation (electricity generation after discounting power plants' own consumption) and the installed capacity of intermittent generation connected to the main national grid. This category includes wind energy (onshore and offshore), run-off-the-river large hydro (4.88 GW), large (centralised) solar photovoltaic and solar thermoelectric power plants, and (with a marginal contribution) sea energy. Combined heat and power plants are as well considered to be intermittent (we suppose their operation to be driven by the demand for heat, so they are intermittent from the electricity point of view). However, we suppose that they are connected to the distributed grids, so actual CHP capacity is not used as an explanatory factor for centralized grid costs. The equation used in the regression is, therefore, the following one:

$$TotYearCostCEGrid_y = \alpha_1 \cdot NetElectrGen_y + \alpha_2 \cdot InstCapIntermittent_y$$

The explained costs are reported below under the category "Total", which includes the three previous costs. The explanatory variables are below these costs, and last, the parameters and goodness of the regression analysis are given.

Concerning distributed grids' costs, the main source of information have been experts. As explained in this research's main document, we will suppose that the only driver of distributed grids' costs is total generation capacity connected to each grid, both dispatchable and intermittent generation. According to the consulted experts, the UK regulator OFGEM considers as very high a cost value for distribution of 200 pounds per kW of connected generation capacity. This value is equivalent to 260€/kW (using 1.3€/pound). As this is a high value, we will suppose an average value of 80€/kW for residential/commercial distributed grids and 120€/kW for industrial distributed grids. The latter is higher because connection's voltage is normally higher. These values are referred to overnight investment costs (investments needed in the grid per unit of installed capacity). As we are here calculating annualised costs, we will compute the annuity of these values. Given that distribution is a natural monopoly and, hence, a regulated business, we will use a 7% interest rate. And we will use an economic life of 30 years for networks' equipment. With these, we obtain annual cost values per unit of connected (intermittent and dispatchable) generation capacity of 6.4469 €/kW for distributed grids in residential/commercial areas, and 9.6703 €/kW for distributed grids in residential/commercial areas.

Centralised grid:

Explained costs (M€):

Year	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Transmiss.	507	521	550	582	603	633	834	937	1013	1090	1246	1344	1397
Distrib.	2788	2813	2824	2899	2918	2961	2981	3113	3192	4033	4055	4552	4656
System Op.	4.78	6.24	6.31	8.47	9.18	10.3	33.1	34	35.3	34.6	36.8	37.5	38.3
Total	3300	3341	3380	3489	3530	3605	3848	4084	4240	5157	5338	5934	6091

Explanatory factors: 1. Net Electricity Generation (TWh); 2. Installed Intermittent Capacity (GW)

(source: REE, 2011)

Year	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
1. (TWh)	181.4	192.3	206.2	228.2	235.3	253.9	268.8	282.3	291.4	300.2	305.1	285.7	290.8
1. (GW)	6.7	7.1	8.2	9.3	10.7	11.9	14.8	16.7	18.5	22.3	26.3	29.5	31.4

Regression results:

Parameter	Estimated value	Units	Estimation Standard Error	Units
ALFA1	11.4811	M€/TWh	1.36	M€/TWh
ALFA2	78.1218	M€/GW	19.14	M€/GW
Coefficient of determination R2 =		0.992107939		

Distributed grid in residential/commercial areas:

Explanatory factor: yearly grid costs due to connected dispatchable and intermittent generation capacity:	6.4469	€/kW

Distributed grid in industrial areas:

Explanatory factor: yearly grid costs due to connected dispatchable and intermittent generation capacity:	9.6703	€/kW

Comments

The same values have been used throughout the complete time horizon (even if this is a simplification). We have tested the values we are using for centralised network's costs. In (MITYC, 2011) there are official forecasts of electricity net generation, installed intermittent generation capacity, and electricity grid costs. As a test for our regression, we have applied our ALFA1 and ALFA2 values to the official forecasts of net generation and installed intermittent capacity, and then we have compared the cost values yielded by our equation to the official forecasted costs. There is an average difference of 11% between 2011 and 2020, which we consider acceptable for an approach as simplified as ours. In other words, our simplified approach yields cost values for the future which differ around 11% to the official forecasts, which we consider acceptable.

5.11 Spanish gas network: costs and losses

Sources

Comisión Nacional de Energía. (2011). Boletín Mensual de Indicadores Eléctricos y Económicos. Enero 2011 (transl. Mensual Bulletin of Energetic and Economic Indicators. January 2011).

Comisión Nacional de Energía, yearly Proposals for Access Tariffs in the Gas Network
 ENAGAS yearly reports

Calculations/hypothesis/explanations/values

Total yearly costs of the Spanish gas network around 2.2 billion € per year, including transport (0.8billion€), distribution (1.2billion€), and around 11M€ yearly (0.011billion) for the system operator (Enagas). We do not consider here the costs of regasification (it is a CE) nor underground storage (not modelled yet).

From Enagas (gas system operator in Spain) yearly reports, we obtain values for the total gas moved in each year (we assume it to be the same as "Entradas", i.e. inputs) of around 425 TWh per year.

$2.2 \text{ billion} / 425 \text{ TWh} = \text{around } 5.3 \text{ €} / \text{MWh}$

For the losses, we use values of around 1%, which is according to Enagas the outputs (entregas) / inputs (entradas). These values are similar to the ones recognised by CNE in the tariffs proposals (under the term "Merma y autoconsumos")

5.12 Spanish oil products network: costs and losses

Sources

CNE (2008) Estudio sobre los costes de comercialización del GLP canalizado
 International Energy Agency (2009) Energy Policies of IEA Countries. Spain.

2009 Review

CLH (2011) Presentación Corporativa

Calculations/hypothesis/explanations/values

COSTS:

For liquids (gasoline, diesel, etc.), from a technical session with experts at the Spanish Royal Academy of engineering, I wrote that transporting oil products per mode was: through pipeline 7.5 €/ton, ship 14 €/ton, truck 15 €/ton and train 25 €/ton. Using an average energy density of 0.044 TJ/ton (average of diesel, gasoline and kerosene), and considering that in Spain 80% is done through pipeline (International Energy Agency (2009), we obtain a value of around 0.73€/MWh. This value is similar that the obtained one from CLH (2011) where it says that the cost of basic logistics is 0.78 centimes of €/l (and then using the volumetric energy density). It is also similar to other presentations from CLH saying costs of 7.83€/m3 and then using the respective volumetric energy densities for the different

products.

For liquefied petroleum gases (GLP), from CNE (2008), we only consider primary transport (0.0158 €/kg), storage (0.0191 €/kg) and secondary transport (0.0394 €/kg), which yields a total of 0.0743 €/kg. Then considering an energy density for GLP of 0.0473 GJ/kg and changing units we obtain 5.65€/MWh, which seems ok as it is a similar order of magnitude than natural gas, other gas.

LOSSES: we have not found good estimations, but looking at the (low) values for natural gas (around 1%), we have supposed 0.2% losses for all oil products.

5.13 Spanish biomass transportation: costs and losses

Sources

European Climate Foundation et al (2010) Biomass for heat and power.
Opportunity and economics

Calculations/hypothesis/explanations/values

COST: biomass is generally expensive due to its normally low volumetric energy density. Looking at European Climate Foundation et al (2010) we use a value of 8€/MWh, but this can be certainly improved. LOSSES: we assume 0% losses

5.14 Spanish coal transportation: costs and losses

Sources

Edgar, T. F. (1983). Coal Processing and Pollution Control. Gulf Publishing Co.
Chapter 4

Calculations/hypothesis/explanations/values

COST: in US, train = 1.8 c\$1983/mile*t and en truck = 10.5 c\$1983/mile*t. Considering the inflation between 1983 and current times, the \$/€ conversion, the energy density of coal (even if there are different types), the km/mile conversion and assuming that in Spain we transport 80% of our coal by train and for an average distance of 300km we obtain 0.5760 €2008/MWh. LOSSES: we assume 0% losses

5.15 Spanish biofuels transportation: costs and losses

Sources

Varela, M., Lago, C., Jungmeier, G., Könighofer, K., & others. (2005). Environmental and Economic Performance of Biofuels. VIEWLS Project. Volume I (Main report) & Volume II (Appendices).

Calculations/hypothesis/explanations/values

COSTS: biofuels are more expensive to transport through the country than diesel or gasoline because of specific technological requirements due to their chemical characteristics. From Varela et al. (2005) we obtain for Bioethanol (in Volume I pag. 57) transport value of 3.7€/GJ, which with is 13.32 €/MWh. For biodiesel (in Volume I pag. 135) it is 1.7€/GJ = 6.12 €/MWh.

LOSSES: we have not found good estimations, but we have supposed 0.2% losses like for oil products.

6. Energy conversions: power generation, oil refining, LNG regasification, and biofuels production.

6.1 Power generation capacities, efficiencies, costs, emissions, capacity and flexibility factors

Sources

International Energy Agency. (2010). Projected Costs of Generating Electricity. 2010 Edition.
International Energy Agency. (2010). Energy Technology Perspectives 2010. Scenarios & Strategies to 2050. Paris.
European Commission. (2011). Energy Roadmap 2050. Communication (2011) 885/2. Annex with the data used for the PRIMES model
European Commission. (2006). World Energy Technology Outlook - 2050 WETO - H2. Brussels.
EIA U.S. Department of Energy. (2010). Assumptions to the Annual Energy Outlook 2010. Washington DC.
International Energy Agency. (2012). World Energy Outlook 2012. Paris.

Calculations/hypothesis/explanations/values

For installed capacities we have used the values from the yearly reports by REE, considering both the peninsular and extrapeninsular systems, making a hypothesis of how much of it will still be there in 2030. Just as a reminder, these capacities are considered as already amortised.

For efficiencies we have used 33% for nuclear (IEA convention), 33% for old Spanish coal power plants, 52% for new imported coal IGCC, 50% for new imported coal SCPC (both values from IEA coal ETSAP technology briefs), the same values with a 8% less efficiency for the cases of those technologies with CCS (according to IEA CCS technology brief), 64% for CCGT, 55% for open cycle gas turbines, the same values with a 10% less efficiency for the cases of those technologies (CCGT and OCGT) with CCS (according to IEA CCS technology brief), 37% for old Spanish fuel oil plants, 100% for hydro, wind, and solar PV and 32% for the three types of biomass power generation (IEA Energy Technology Essentials. Biomass for Power Generation and CHP).

Emissions, in tCO₂/MWh of electricity produced: 0.93 for national coal old plants, 0.91 for imported coal old plants, 0.725 for new imported coal IGCC, 0.79 for new imported coal SCPC, 0.4 for CCGT, 0.75 for OCGT, a 90% reduction versus these four last values, both new coals + CCGT + OCGT for CCS technologies (IEA CCS Technology Brief), 0.77 for old Spanish fueloil plants and 0.85 for solid waste.

Capacity and flexibility factors (for adequacy and reserves constraints) have been obtained from discussions with experts and own assumptions. Respectively: 95% and 0% for nuclear, 95% and 10% for coals, 95% and 80% for CCGTs, 95% and 100% for OCGTs, 95% and 60% for fueloil, 30% and 0% for hydro run off the river and minihydro, 30% and 100% for hydro manageable (hydro in Spain is nowadays 40% for adequacy, but we suppose 30% for the future due to climate change-derived draught as said in Németh et al. 2009)), 90% and 100% for hydro pumping storage, 7.5% and 0% for wind onshore, 9% and 0% for wind offshore, 50% and 0% for solar PV, 70% and 15% solar thermoelectric, and 80% and 80% for all biomass technologies.

For costs (and their projected evolution, see below), there is a wide range of estimates in the literature, many of them having a certain bias (e.g. pro nuclear sources may underestimate the costs of nuclear, the same for pro renewable sources, etc). Hence we have used only reputable sources, obtained their values and estimations for 2010, 2020 and 2030, put them all in uniform units (e.g. converting from \$ to € when needed) and for each technology (of the ones we consider) we have considered the median value between the values from the different sources. We have only considered cost evolutions in the investment costs. For CCS technologies we have experienced that the below values could be too optimistic.

Technology	Overnight investment costs (€2010/kW)			Fixed O&M costs (€2010/kW)	Variable O&M costs (€2010/MWh)
	2010	2020	2030	Cosntant	Cosntant
Nuclear	3578.79	3680.00	2849.50	67.2	1.5
Nat. Coal Trad.	2315.62	1745.00	1741.00	27.3	3.2
Imp. Coal Trad.	2315.62	1745.00	1741.00	27.3	3.2
Imp. Coal IGCC	2021.09	2057.50	1724.00	44.9	5.2
Imp. Coal SCPC	1628.79	1600.00	1220.00	22.5	3.2
Imp. Coal SCPC + CCS	2663.64	3064.00	1997.50	47.9	6.9

CCGT	759.85	720.00	581.00	11.1	2.4
CCGT + CCS	1460.61	1125.00	937.50	22.9	4.9
Gas Turbine	681.82	680.00	640.00	5.3	11.1
Gas Turbine + CCS	1818.18	1540.00	1160.00	10.0	15.2
Fuel Gas Trad.	1144.32	909.69	856.18	17.7	2.5
Hydro Run-Off-River	2330.30	1880.00	1840.00	10.2	0.0
Hydro Reservoir	2330.30	1880.00	1840.00	10.2	0.0
Hydro Pumping Storage	4013.26	3800.00	3600.00	9.9	0.0
Mini Hydro	2776.52	3200.00	2880.00	10.2	0.0
CHP Industrial	2244.70	2370.40	2370.40		
CHP Comm/Resid.	2244.70	2370.40	2370.40		
Wind Onshore	1382.58	1104.00	922.50	21.3	0.0
Wind Onshore	1382.58	1104.00	922.50	21.3	0.0
Wind Onshore	1382.58	1104.00	922.50	21.3	0.0
Wind Offshore	2537.88	1414.50	1295.00	40.4	0.0
Solar PV centralised with Tracking	3602.27	2499.00	1831.50	12.7	0.0
Solar PV distributed without tracking, industrial	4166.67	2899.00	1991.50	19.7	0.0
Solar PV distributed without tracking, commercial/residential	4169.00	2899.00	1991.50	19.7	0.0
Solar Thermoelectric CSP	4168.56	4450.00	2959.00	48.5	0.0
Solar Thermal Industry	909.09	768.00	672.00	22.7	0.0
Solar Thermal Commercial/Resid.	984.85	832.00	728.00	30.3	0.0
Biomass Electricity, Energy Crops	2871.21	2480.00	2200.00	76.1	3.8
Biomass Electricity, Agriculture Waste	2871.21	2480.00	2200.00	76.1	3.8
Biomass Electricity, Forestry Waste	2871.21	2480.00	2200.00	76.1	3.8
Solid Waste Electricity	6236.36	5444.10	4829.44	283.2	6.3

6.2 Oil refineries

Sources

Ministerio Medio Ambiente (2004) Guía de Mejores Técnicas Disponibles en España del Sector de Refino de Petróleo, apdo 1.4

Favennec, J.-P. (2001). Petroleum Refining: Refinery Operation and Management. Editions TECHNIP

Previous calculations/hypothesis/explanations

Important note: it has been very challenging finding data for oil refineries: it has been done mainly through informal conversations with experts and with the above-cited references, some of them are not for Spain. Hence these values should all be improved by further research. We have supposed three types of refineries according to their complexity, as explained above.

Efficiencies: in oil refining, there are almost no losses, and the self consumptions are kept small. We assume total outputs (all useful products)/input(crude) = 95% for low complexity, 92% for high and 89% for very high complexity.

Current capacity: we have used the total refining capacity as reported by MMA (2004) in Mt/year, differentiating between complexities according to each refineries' characteristics, and converting it to MW by using the energy density of crude oil and some units change. This provides a total refining capacity per refinery type and per unit of crude oil (input), but we need it for the output: we convert based on the efficiencies above. Obtained values: low complexity = 62.20GW, high complexity = 24.27GW, very high complexity = 0. Main doubt: how much of it will still be there in 2030? We have assumed it all to be there in 2030.

Investment costs: some experts said, very roughly, that a low complexity refinery has an overnight investment cost of around 2000M€2010 (2 billion) per each 100k bbl per day of refining capacity, a high complexity one a cost of 3000 M€2010/(100k bbl/day) and a very high complexity one around 4000M€2010/(100k bbl/day). Converting from bbl crude oil per day to MW of output product (using crude oil energy density and the above efficiencies) we obtain 305.73 €2008/kWprod, 473.55€2008/kWprod and 652.68 €2008/kWprod. These same values, with an amortization in 10 years at 8% interest rate yield values of around 12-24 \$/bbl of crude, which is the correct order of magnitude (given the current prices of oil and the refining margins reported by the industry associations). If instead of these experts' opinion we look at Favennec (2001) page 149, we see investment values of 580 M\$1999 for a simple refinery of 5 Mt/a, 1475M\$1999 for a more complex one of 8 Mt/a and 2455 M\$1999 for a very complex one of 8 Mt/a (consider that this book is 12 years old so the complexity measure may not be realistic now). Doing similar conversions as above (considering also inflation and \$/€) we obtain 113.67 €2008/kWproducto, 186.56 €2008/kWproducto and 320.98 €2008/kWproducto, and with the 8% amortization in 10 years, values between 4.6 and 12 \$/bbl. We have in the end use the following values, in the same orders of magnitude: 113.67 €2008/kWproducto, 330.06 €2008/kWproducto and 652.68 €2008/kWproducto.

Fixed O&M costs: also from Favennec (2001), page 154, and doing similar conversions we obtain 6.86 €2008/kWproducto (1.86 \$2008/bblcrudo), 8.60 €2008/kWproducto (2.26 \$2008/bblcrudo) and 16.74 €2008/kWproducto (4.25 \$2008/bblcrudo).

Variable O&M costs: from the same source, and excluding utilities (we assume they are fully covered by self consumption) and doing similar conversions we obtain for the lowest complexity 0.34 €2008/MWhProducto (0.84 \$2008/bblCrudo), 0.40 €2008/MWhProducto (1.01 \$2008/bblCrudo) and, for the highest complexity, 0.48 €2008/MWhProducto (1.19 \$2008/bblCrudo). These values are reasonable given the refining margins reported for instance in AOP (2009) Impacto en la Competitividad Internacional del Refino Español de la Directiva y Ley de Comercio de Emisiones.

Emissions: from discussions with experts we assume values of 0.2, 0.24 and 0.24 tCO₂/tCrudeProcessed for low, high and very high complexity, that then (with energy densities of crude oil and average efficiencies) yield 0.01776, 0.02201 and 0.02655 tCO₂/MWhProduct.

Shares: the values used for shares have been estimated very roughly based on discussions with experts. Basically, for a same crude, the highest the complexity the highest the share of high added value products. Values used:

	Share in total output	Gasoline	Diesel	Fueloil	LPG	Kerosene	Others
Low Complex	Max	33%	55%	60%	5%	10%	50%
Low Complex	Min	27%	45%	50%	4%	5%	0%
High Complex	Max	35%	50%	30%	15%	15%	45%
High Complex	Min	15%	30%	10%	0%	0%	0%
Vhigh Complex	Max	19%	83%	16%	17%	39%	16%
Vhigh Complex	Min	0%	53%	0%	0%	9%	0%

6.2 LNG regasification terminals

Sources

ENAGAS. (2010). El Sistema Gasista Español 2009. Pag 48 a 53. Nominal Total (A)
CNE (2013) Documentos proponiendo las tarifas del sistema gasista
ENAGAS (2010) Rangos admisibles 2011. Aplicación del PD-09 de las NGTS.pdf. Página 30

Previous calculations/hypothesis/explanations/values

Efficiencies: in the CNE documents establishing tariffs, the losses in LNG regasification (“mermas”) are assumed to be very low, around 0.3%. We use this value, so efficiency = 99.7%.

Current capacity: from ENAGAS (2010): around 1913 GWh/day for all plants in Spain (together), which is 79.71GW (=1913/24). Doubt is how much of this will be still be there in 2030?

Investment costs: they seem to vary a lot, depending on the site-specific characteristics. Values from USA or Argentina seem to vary a lot (EIA U.S. Department of Energy. (2003). The Global Liquefied Natural Gas Market: Status & Outlook (No. DOE/EIA-0637 (2003)). Washington DC for the USA yielding values of around 20€/kW of output (gas) and for Argentina Chimale, N. D., & Acosta, G. F. (2008). LNG in Argentina. A Regasification Plant Feasibility Study yielding around 70€/kw). From the documents in CNE (there is a specific one on regasification, Comisión Nacional de Energía. (2011). Plantas de Regasificación. 2011. Madrid.), and Enagas and assuming the average values between MUSEL and PALOS de la FRONTERA we will use 35€/kW.

Fixed O&M costs: same CNE references, Musel fixed costs of around 11M€/year (applying the formulas to its characteristics on Tanques de almacenamiento, Cargaderos, Instalaciones de regasificación and Obra civil y portuaria and adding them all up) for a regasification capacity of 9.67GW = 1.12€/kW

Variable O&M costs: from CNE, and adding Coste por kWh regasificado + Coste variable por kWh cargado en cisternas + Coste por trasvases /puestas en frío = 5.7E-6 €/MWh (value very small when compared to other variable O&M costs of other types of CE processes)

Emissions: since we do not consider methane emissions, LNG regasification terminals are assumed 0 emissions.

Technical minimum: as explained, we assume a technical minimum of 25% of the capacity in LNG regasification terminals. This is calculated from ENAGAS (2011) El Sistema Gasista Español 2010, which is around 500GWh/day = 20.833GW which is around 25% of the capacity. Similar values are obtained from adding the values (in m3N/h) for the different terminals in the document with the Rangos Admisibles and then converting with 10E9 m3N = 11730 GWh, of natural gas (gas, not liquefied).

6.3 Biofuel production plants

Sources

Instituto para la Diversificación y Ahorro de la Energía. (2011). Plan de Energías Renovables 2011-2020 (transl. Renewable Energy Plan 2011-2020).
Sanz, A. (2011). Estudio de viabilidad energética y medioambiental del bioetanol a partir de cereales de invierno en España (transl. Study on the Energetic and Environmental Feasibility of Bioethanol from Winter Cereal in Spain) (Proyecto Fin de Carrera (MSc Engineering Thesis)). Universidad Pontificia Comillas, Madrid. Page 134 (anexo)

Previous calculations/hypothesis/explanations/values

We have supposed only two types of biofuels: bioethanol and biofuels, and both of first generation. More research could be done here. In general, the biofuels modelling could be improved since data gathering has been complex.

Efficiencies: from Sanz (2011) considering the output of ethanol per unit of grain (both in kg, being around $0.2857=1/3.5$) and converting this to energy (to have energy-based efficiency) with calorific values of 26.75 MJ/kg bioethanol and 15.5 MJ/kg grain we obtain around 49% efficiency. For biodiesel we assume 60%.

Current capacities: from IDAE (2011), in Spain in 2010 there was an installed capacity of 464 kt/year of bioethanol, and 4318.4 kt/ year of biodiesel. Using energy densities of 7.585 kWh/kg for bioethanol and 10.292 kWh/kg for biodiesel, and performing some units change, this is equivalent to 393.6 MW of bioethanol and 5142.7MW of biodiesel. Doubt is how much of this will be still be there in 2030?

Investment costs: from IDAE (2011) the typical investment cost is 180 M€ for a bioethanol plant of capacity of 200 kt/year, which doing similar calculations as above yields 1039.6€/kW. Similar calculations with the data on biodiesel from the same source (60M€ for a capacity of 200kt/y) provide 255€/kW. However we are not sure about this value because it may seem that it is only for the manufacturing of biodiesel from the vegetable oil, but not for the oil itself (from the plant). Both processes should be aggregated if our feedstock is the plant and not the oil.

Fixed O&M costs: we have not found data on this.

Variable O&M costs: from IDAE (2011) page 125, it says variable costs of around 702€/ton bioethanol, of which 500 are for feedstock (that we consider separately). In the table there is also the amortization of the investment costs, that we assume to be 100€/t (i.e. a 200kt/year plant costs 180M€, amortised in 20years at 9% interest rate = 19.72 M€/year divided by production of 200kt/year = aprox. 100€/t). Hence variable O&M costs = $702€/t - 500 = 102€/t = 13.45€/MWh$. For biodiesel we do similar calculations ($1030€/t - 800 = 190€/ton$ biodiesel) obtaining 18.44€/MWh.

Emissions: we assume them to be null (i.e. we suppose sustainable biofuels with null lifecycle emissions) which of course may not be true (it is not nowadays). More research is needed here.

7. End use energy services and technologies in industry, transport and other uses sectors.

7.1 Industry and agriculture

Sources

Economics for Energy. (2011). Potencial económico de reducción de la demanda de energía en España (transl. Economic Potential of Energy Demand Reduction in Spain).
Greenpeace. (2011). Energía 3.0. Un sistema energético basado en inteligencia, eficiencia y renovables 100%. Madrid.
Ministerio de Medio Ambiente y Medio Rural y Marino. (2011). Inventario de Emisiones de Gases de Efecto Invernadero de España. Años 1990-2009 (transl. Greenhouse Effect Gasses Emissions Inventory for Spain. Years 1990-2009). Madrid.

Previous calculations/hypothesis/explanations/values

We have not modelled end use technologies in the industrial sector, as this sector is less interesting from the energy efficiency point of view because energy is an important element in the costs of industries so the potential for energy efficiency is normally smaller. In addition, it was hugely data intensive and would require a significant amount of technical work to understand the different production technologies to produce each unit of energy service output which in the case of industry should be the actual produced output (e.g. per ton of steel, per kg of paper, etc). A good reference on this could be the analysis behind Economics for Energy. (2011) or Greenpeace (2011).

Our modelling is simply to assume an energy mix per each industry subdivision and then consider for each industrial subdivision (MCM, CHE and OTH) two technologies, ELEDGD and OTNRGD. The first one is the electricity consumption and has a load curve, while the second one is the consumption of other energy types and is assumed to be flat. In the ESDMY table we give how many GWh are consumed by each industrial technology (which is the assumption we make for energy service "production", in other words as if each industry was "producing" those GWh). QACTESST2ES is 1 because both the activity and the output are measured in GWh. Then in TE2QACTESST we provide the GWh of each final energy type that are consumed per unit of GWh of activity (which is the same as GWh of output because QACTESST2ES is 1). The inverse of these values are the % consumption of each final energy type by that industry (e.g. ESST_DSIND_MCM_OTNRGD consumes a 63% of natural gas = $1/1.59$)

For the emissions (FEUEMISSFTE and/or FEUEMISSFPE) we simply use the specific emissions value for industry per each type of fuel as reported by Ministerio de Medio Ambiente y Medio Rural y Marino (2011).

We assume the non-energy costs per activity unit to be null. This is a strong hypothesis which should be refined. The same modeling is done for the primary sector. Energy mix assumed:

Energy Demand (PJ)	Industry: Mining, Constructions and Materials	Industry: Chemical	Industry: Other	Other Uses: Primary Sector	TOTAL
Electricity	371.5	119.7	200.5	20.0	711.6
Heat	71.4	29.7	170.4	0.0	271.5
Coal	11.1	5.0	0.0	0.0	16.0
Natural Gas	214.8	237.4	106.0	11.4	569.6
Gasoline	0.0	0.0	0.0	0.0	0.0
Diesel	13.8	3.7	20.9	104.3	142.6
Fueloil	4.5	2.3	6.9	0.0	13.7
LPGs	0.0	0.0	0.0	0.0	0.0
Kerosene	0.0	0.0	0.0	0.0	0.0
Other Oil Prods	10.4	0.0	0.0	0.0	10.4
Bioethanol	0.0	0.0	0.0	0.0	0.0
Biodiesel	0.0	0.0	0.0	0.0	0.0
Biomass	10.6	1.0	95.9	2.0	109.5
TOTAL	707.9	398.8	600.5	137.8	1845.0

7.2 Transportation sector: mobility estimates for all modes

Sources

Mendiluce, M., & Schipper, L. (2011). Trends in Passenger Transport and Freight Energy Use in Spain. *Energy Policy*, 39(10), 6466–6475. doi:10.1016/j.enpol.2011.07.048

Greenpeace. (2011). *Energía 3.0. Un sistema energético basado en inteligencia, eficiencia y renovables 100%*. Madrid.

Ministerio de Fomento. (2011). *Observatorio del transporte intermodal terrestre y marítimo. Documento Final. 3 de Junio de 2011*. Madrid.

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Ministerio de Fomento. (2007). *Encuesta de Movilidad de las Personas Residentes en España. Movilia 2006/2007*.

Pérez, M., López-Peña, Á., & Pérez-Arriaga, I. (2012). *Análisis de sostenibilidad del modelo energético español hasta 2030* (transl. Sustainability Analysis of the Spanish Energy System until 2030) (Proyecto Fin de Carrera (MSc Engineering Thesis)). BP Chain on Energy and Sustainability, Universidad Pontificia Comillas, Madrid.

Previous calculations/hypothesis/explanations/values

From the above references, plus estimates on GDP and population (see above), comparing values in the different sources and using some assumptions on the modal shares, we come out with the following values for energy services demand (i.e. mobility) in the transportation sector.

MOBILITY PASSENGERS k Mpkm	PASSENGERS k Mpkm	2010	2030
Land (national+international, in Spain)	Land. Urban (<10km)	110	118
Land (national+international, in Spain)	Land. Metropolitan Not Urban (10-50)	166	179
Land (national+international, in Spain)	Land. Interurban G50	23	25
Land (national+international, in Spain)	Land. G100	74	80
Land (national+international, in Spain)	Land. G500	51	54
Air (national+international, in Spain)	Air	229	377
Sea (national+international, in Spain)	Sea	2	4
MOBILITY FREIGHT k Mtkm	FREIGHT	2010	2030
Land (national+international, in Spain)	Urban (<10km)	70	94
Land (national+international, in Spain)	Metropolitan Not Urban (10-50)	129	172
Land (national+international, in Spain)	G50	64	86
Land (national+international, in Spain)	G100	99	132
Land (national+international, in Spain)	G500	137	184
Air (national+international, in Spain)	Air	2	4
Sea (national+international, in Spain)	Sea	81	158

7.3 Transportation sector: mobility reduction measures (ESVMs)

Sources

De la Villa, A. (2010). Propuestas sectoriales de políticas de eficiencia energética en el sector del transporte (transl. Proposals of Energy Efficiency Policies in the Transportation Sector) (Proyecto Fin de Carrera (MSc Engineering Thesis)). Universidad Pontificia Comillas, Madrid.

Previous calculations/hypothesis/explanations/values

We have assumed only one, which is the promotion of teleconferences for business purposes, with a yearly cost of 3.7M€ and an effect of reducing certain types of mobility:

ES_DSTRA_L NP_URBN	ES_DSTRA_ LNP_L50	ES_DSTRA_ LNP_G50	ES_DSTRA_L NP_G100	ES_DSTRA_L NP_G500	ES_DST RA_AIP
-1%	-1%	-2%	-2%	-3%	-3%

While at the same time increasing the demand for lighting and electronic appliances in the services sector:

ES_DSOTH_SRV_LIGH	ES_DSOTH_SRV_OEAP
+2%	+3%

We have assumed this effect to be equally distributed along all the time slices of the year: that is why the ESVMLOADC parameter has a % in each time slice which is the same as the duration of that time slice on the total year. It could for instance change this to make it impact more on working days.

7.4 Transportation sector technologies (ESSTs): passengers and freight

Sources

Ministerio de Agricultura, Alimentación y Medio Ambiente. (2013). Inventario de Emisiones de Gases de Efecto Invernadero de España. Años 1990-2011 (transl. Greenhouse Effect Gasses Emissions Inventory for Spain. Years 1990-2011). Madrid.

International Energy Agency. (2010). IEA ETSAP Technology Brief. Automotive LPG and Natural Gas Engines. Retrieved from <http://www.iea-etsap.org/web/E-TechDS.asp>

International Energy Agency. (2010). IEA ETSAP Technology Brief. Ethanol Internal Combustion Engines. Retrieved from <http://www.iea-etsap.org/web/E-TechDS.asp>

International Energy Agency. (2010a). IEA ETSAP Technology Brief. Electric and Plug-in Hybrid Vehicles. Retrieved from <http://www.iea-etsap.org/web/E-TechDS.asp>

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Ayuntamiento de Madrid. (2012). Plan de calidad del aire de la Ciudad de Madrid 2011 – 2015 (transl. Madrid Air Quality Plan 2011-2015).

Economics for Energy. (2011). Potencial económico de reducción de la demanda de energía en España (transl. Economic Potential of Energy Demand Reduction in Spain).

Ministerio de Medio Ambiente y Medio Rural y Marino, Ministerio de Fomento, & TRANSyT Centro de Investigación del Transporte Universidad Politécnica de Madrid. (2011). Observatorio de la Movilidad Metropolitana 2009 (transl. Observatory of Metropolitan Mobility 2009). Retrieved from <http://www.observatoriomovilidad.es/>

Barnitt, R. (2008). In-Use Performance Comparison of Hybrid Electric, CNG, and Diesel Buses at New York City Transit. SAE Technical Paper, 01–1556.

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Fundación de los Ferrocarriles Españoles, & Ministerio de Fomento. (2011). Observatorio del Ferrocarril en España 2010 (transl. Railways Observatory in Spain 2010).

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Ferropedia.es. (2012a). Canon de uso de infraestructura de Adif. Retrieved from http://www.ferropedia.es/wiki/Canon_de_uso_de_infraestructura_de_Adif

Ferropedia.es. (2012b). Consumo de energía del tren y de otros medios de transporte. Retrieved from http://www.ferropedia.es/wiki/Consumo_de_energ%C3%ADa_del_tren_y_de_otros_medios_de_transporte

García, A., & Martín, M. P. (2009). La electrificación ferroviaria cada vez más necesaria y eficiente. Anales de Mecánica y Electricidad.

SENASA. (2011). Observatorio de la Sostenibilidad en la Aviación en España (transl. Observatory on Aviation Sustainability in Spain).

Wikipedia.org (2012) Energy efficiency in transportation

Instituto para la Diversificación y Ahorro de la Energía. (2011). Informe Anual de Consumos Energéticos Año 2010.

Previous calculations/hypothesis/explanations/values

This sector is modelled through disaggregated end use technologies. For each technology we first identify its output energy service and its units and then its internal activity and its units. This allows us to then obtain the needed data: non-energy yearly cost per unit of activity (ESSTCOSTPACTUY, in €/activity unit), the conversion factors from activity to energy services (QACTESST2ES), the amount of final or primary energy (not power!) consumed per unit of activity (TE2QACTESST and/or PE2QACTESST, which together with the QACTESST2ES factor are a estimation of the efficiency of the technology) and the emissions factors per unit of input energy either TE or PE (FEUEMISSFTE or FEUEMISSFPE)

TECHNOLOGY: STANDARD GASOLINE CARS:

Output service = each car subtechnology (e.g. LNPURBN, LNPL50, LNPG100) provides its respective mobility type, for passengers by land (i.e. LNP), which is measured in passengers-kilometer (pkm);

Internal activity = vehicle-kilometer (vkm);

ESSTCOSTPACTUY=cost of the vehicle assumed 16k€ with a 9% depreciation in 12 years, + 3% yearly maintenance cost (usual in the literature), which provides a yearly cost of around 2700€, which is then divided by an assumed yearly activity of 16000km (=vkm) obtaining a (non-energy!) use cost of around 0.17€/km (=M€/Mvkm).

QACTESST2ES = $\text{pkm/vkm} = \text{p/v} = \text{occupancy rate}$ = assumed to be 1.2 passengers/vehicle in urban, 1.5 metropolitan, 2 interurban, 2.5 greater than 100 km ; and 3 p/v greater than 500km (long trips);
TE2QACTESST and/or PE2QACTESST = we obtain the energy use considering for each service provided its corresponding consumption (for each car doing 100km, hence for each 100vkm), assuming urban cons = 8 l/100vkm, mixed cons = 7 l/100vkm, highway cons = 6 l/100vkm, the volumetric energy density of gasoline and some energy units change. Results: urban=1.36 Mvkm/GWh of gasoline, metropolitan =1.55 Mvkm/GWh and the rest=1.81 Mvkm/GWh.
Emission factors = we use the value of road transportation (converted to our units i.e. tCO₂/MWh) sector for the corresponding liquid (gasoline, diesel, etc.) provided in MAGRAMA (2013) Table1.A(a)s3, which in this case is 0.256 tCO₂/MWh of consumed gasoline.

TECHNOLOGY: EFFICIENT GASOLINE CARS:

Output service = each car subtechnology (e.g. LNPURBN, LNPL50, LNPG100) provides its respective mobility type, for passengers by land (i.e. LNP), which is measured in passengers-kilometer (pkm);
Internal activity = vehicle-kilometer (vkm);
ESSTCOSTPACTUY=cost of the vehicle assumed 17.5k€ with a 9% depreciation in 12 years, + 3% yearly maintenance cost (usual in the literature), which provides a yearly cost of around 2970€, which is then divided by an assumed yearly activity of 16000km (=vkm) obtaining a (non-energy!) use cost of around 0.1856€/km (=M€/Mvkm).
QACTESST2ES = $\text{pkm/vkm} = \text{p/v} = \text{occupancy rate}$ = assumed to be 1.2 passengers/vehicle in urban, 1.5 metropolitan, 2 interurban, 2.5 greater than 100 km ; and 3 p/v greater than 500km (long trips);
TE2QACTESST and/or PE2QACTESST = we obtain the energy use considering for each service provided its corresponding consumption (for each car doing 100km, hence for each 100vkm), assuming urban cons = 6 l/100vkm, mixed cons = 5.5 l/100vkm, highway cons = 5 l/100vkm, the volumetric energy density of its fuel and some energy units change. Results: urban=1.64 Mvkm/GWh of gasoline, metropolitan =1.79 Mvkm/GWh and the rest=1.97 Mvkm/GWh.
Emission factors = we use the value of road transportation (converted to our units i.e. tCO₂/MWh) sector for the corresponding liquid (gasoline, diesel, etc.) provided in MAGRAMA (2013) Table1.A(a)s3, which in this case is 0.256 tCO₂/MWh of consumed fuel.

TECHNOLOGY: STANDARD DIESEL CARS:

Output service = each car subtechnology (e.g. LNPURBN, LNPL50, LNPG100) provides its respective mobility type, for passengers by land (i.e. LNP), which is measured in passengers-kilometer (pkm);
Internal activity = vehicle-kilometer (vkm);
ESSTCOSTPACTUY=cost of the vehicle assumed 18k€ with a 9% depreciation in 12 years, + 3% yearly maintenance cost (usual in the literature), which provides a yearly cost of around 3054€, which is then divided by an assumed yearly activity of 16000km (=vkm) obtaining a (non-energy!) use cost of around 0.1908€/km (=M€/Mvkm).
QACTESST2ES = $\text{pkm/vkm} = \text{p/v} = \text{occupancy rate}$ = assumed to be 1.2 passengers/vehicle in urban, 1.5 metropolitan, 2 interurban, 2.5 greater than 100 km ; and 3 p/v greater than 500km (long trips);
TE2QACTESST and/or PE2QACTESST = we obtain the energy use considering for each service provided its corresponding consumption (for each car doing 100km, hence for each 100vkm), assuming urban cons = 7 l/100vkm, mixed cons = 6.25 l/100vkm, highway cons = 5.5 l/100vkm, the volumetric energy density of its fuel and some energy units change. Results: urban=1.55 Mvkm/GWh of gasoline, metropolitan =1.74 Mvkm/GWh and the rest=1.97 Mvkm/GWh.
Emission factors = we use the value of road transportation (converted to our units i.e. tCO₂/MWh) sector for the corresponding liquid (gasoline, diesel, etc.) provided in MAGRAMA (2013) Table1.A(a)s3, which in this case is 0.261 tCO₂/MWh of consumed diesel.

TECHNOLOGY: EFFICIENT DIESEL CARS:

Output service = each car subtechnology (e.g. LNPURBN, LNPL50, LNPG100) provides its respective mobility type, for passengers by land (i.e. LNP), which is measured in passengers-kilometer (pkm);
Internal activity = vehicle-kilometer (vkm);
ESSTCOSTPACTUY=cost of the vehicle assumed 19.5k€ with a 9% depreciation in 12 years, + 3% yearly maintenance cost (usual in the literature), which provides a yearly cost of around 3308€, which is then divided by an assumed yearly activity of 16000km (=vkm) obtaining a (non-energy!) use cost of around 0.2067€/km (=M€/Mvkm).
QACTESST2ES = $\text{pkm/vkm} = \text{p/v} = \text{occupancy rate}$ = assumed to be 1.2 passengers/vehicle in urban, 1.5 metropolitan, 2 interurban, 2.5 greater than 100 km ; and 3 p/v greater than 500km (long trips);
TE2QACTESST and/or PE2QACTESST = we obtain the energy use considering for each service provided its corresponding consumption (for each car doing 100km, hence for each 100vkm), assuming urban

cons = 5 l/100vkm, mixed cons = 4.75 l/100vkm, highway cons = 4.5 l/100vkm, the volumetric energy density of its fuel and some energy units change. Results: urban=1.97 Mvkm/GWh of gasoline, metropolitan=2.07 Mvkm/GWh and the rest=2.19 Mvkm/GWh.

Emission factors = we use the value of road transportation (converted to our units i.e. tCO₂/MWh) sector for the corresponding liquid (gasoline, diesel, etc.) provided in MAGRAMA (2013) Table1.A(a)s3, which in this case is 0.261 tCO₂/MWh of consumed diesel.

TECHNOLOGY: EFFICIENT DIESEL CARS:

Output service = each car subtechnology (e.g. LNPURBN, LNPL50, LNP100) provides its respective mobility type, for passengers by land (i.e. LNP), which is measured in passengers-kilometer (pkm);

Internal activity = vehicle-kilometer (vkm);

ESSTCOSTPACTUY=cost of the vehicle assumed 19.5k€ with a 9% depreciation in 12 years, + 3% yearly maintenance cost (usual in the literature), which provides a yearly cost of around 3308€, which is then divided by an assumed yearly activity of 16000km (=vkm) obtaining a (non-energy!) use cost of around 0.2067€/km (=M€/Mvkm).

QACTESST2ES = pkm/vkm=p/v=occupancy rate=assumed to be 1.2passengers/vehicle in urban, 1.5 metropolitan, 2 interurban, 2.5 greater than 100 km ; and 3 p/v greater than 500km (long trips);

TE2QACTESST and/or PE2QACTESST = we obtain the energy use considering for each service provided its corresponding consumption (for each car doing 100km, hence for each 100vkm), assuming urban cons = 5 l/100vkm, mixed cons = 4.75 l/100vkm, highway cons = 4.5 l/100vkm, the volumetric energy density of its fuel and some energy units change. Results: urban=1.97 Mvkm/GWh of gasoline, metropolitan=2.07 Mvkm/GWh and the rest=2.19 Mvkm/GWh.

Emission factors = we use the value of road transportation (converted to our units i.e. tCO₂/MWh) sector for the corresponding liquid (gasoline, diesel, etc.) provided in MAGRAMA (2013) Table1.A(a)s3, which in this case is 0.261 tCO₂/MWh of consumed diesel.

TECHNOLOGY: CNG AND LPG CARS: similar approach than for the previous, assuming a 2000€ extra cost (adaptation) vs the gasoline standard car. According to the IEA ETSAP technology brief, these cars are less efficient than their baseline gasoline technology, and we assume them to consume in equal parts gasoline and CNG or LPG. Emissions factor 0.204tCO₂/MWh for natural gas, 0.242 for LPG and 0.256 for gasoline.

TECHNOLOGY: BIOFUEL CARS: similar approach than for the previous, assuming same cost as the gasoline or diesel standard technology (we assume that those cars will be flexifuel by them, able to consume E85 and D85). According to the IEA ETSAP technology brief, these cars are slightly more efficient (in energy terms, not in volume terms) than their baseline technology, and we assume them to consume in equal 15% and 85% gasoline/diesel and bioethanol/biodiesel. Emissions factor the same ones as above for gasoline and diesel, and 0 for bios.

TECHNOLOGY: HYBRID GASOLINE AND DIESEL CARS: similar approach than for the previous, assuming extracost vs the gasoline or diesel standard technology (mainly due to the battery), that is 21k and 22.5k€. For the rest, they are simply more efficient gasoline or diesel cars (5 and 4l/100km). Emissions factor the same ones as above for gasoline and diesel (but they consume less).

TECHNOLOGY: PLUG-IN-HYBRID GASOLINE AND DIESEL CARS: similar approach than for the previous, assuming even more extracost vs the gasoline or diesel standard technology (mainly due to the battery), that is 28k and 29k€. For the rest, they are even more efficient gasoline or diesel cars, which consume only electricity in short distance trips and 50%/50% (with gasoline or diesel) starting in the G100 service. Emissions factor the same ones as above for gasoline and diesel (but they consume less).

TECHNOLOGY: BATTERY ELECTRIC CARS: similar approach than for the previous, assuming a cost of 38k, 100% electricity consumption, that it does not provide long distance mobility (over 100km), and values of between 2.24 Mvkm/GWh and 2.98Mvkm/GWh of power, depending on the distance of the service (more consumption in urban). Emissions factor = 0.

TECHNOLOGY: MOTORCYCLES: similar approach than for the previous, assuming only urban and metropolitan services, less occupancy (1 and 1.1 p/v), smaller cost (4.5k), smaller amortization period (6years), shorter yearly distance (10900km/year) to calculate unity cost, and higher energy efficiencies (5.2. and 5 l/100km). Emissions factor = the gasoline one.

TECHNOLOGY: BICYCLES: similar approach than for the previous, assuming only urban services, less occupancy (1 p/v), smaller cost (0.2k€), smaller amortization period (6years), shorter yearly distance (4600km/year) to calculate unity cost. We have assumed an energy efficiency (from human energy) of 3.1kWh/100km, which is equivalent to 0.321 litres of gasoline/100 km

(http://en.wikipedia.org/wiki/Energy_efficiency_in_transportation). The energy consumption is hence human, which is a type of PE in our model, with a cost of around 170€/MWh as reported above. Emissions factor = 0.

TECHNOLOGY: BUSES:

Output service = each bus subtechnology provides its respective mobility type, for passengers by land (i.e. LNP), which is measured in passengers-kilometer (pkm). Urban busses present more technological detail, such as CNG, EUROIV, EUROV or hybrid. The rest of categories are conventional, efficient (both diesel) and biodiesel (i.e. CNG, EURO IV, EURO V or hybrid busses assumed to only provide urban transport).

Internal activity = vehicle-kilometer (vkm);

ESSTCOSTPACTUY=cost of the vehicle assumed 210k€ (= 300k\$, http://publictransport.about.com/od/Transit_Vehicles/a/How-Much-Does-A-Bus-Cost-To-Purchase-And-Operate.htm) for a conventional one, 220k€ for EUROIV, 230k for EUROIV, 250k for bio, 339,7k€ for the CNG ones (average between Economics for Energy and Ayuntamiento de Madrid), 385k for urban hybrid, 275k€ for interurban efficient and 290k€ for interurban biodiesel. We assume a 9% depreciation in 6 years, + 3% yearly maintenance cost (usual in the literature), which an assumed yearly activity of 50000km (=vkm) for urban busses (Observatory of Metropolitan Mobility 2009) and 96600km/year for interurban buses.

QACTESST2ES = pkm/vkm=p/v=occupancy rate=assumed to be 17.5passengers/vehicle in urban, 25 metropolitan, 50 interurban, 50 greater than 100 km ; and 50 p/v greater than 500km (long trips);

TE2QACTESST and/or PE2QACTESST = we obtain the energy use considering for each service provided its corresponding consumption, around 30l/100vkm for urban conventional or 20l/100km urban EUROV. For the rest, Barnitt (2008). Hybrid is just a more efficient bus and bio is assumed to run 85% on biodiesel and 15% on diesel.

Emission factors = we use the value of road transportation (converted to our units i.e. tCO₂/MWh) sector for the corresponding liquid (gasoline, diesel, etc.) provided in MAGRAMA (2013) Table1.A(a)s3, 0 for bios, and the corresponding value for CNG.

TECHNOLOGY: METRO, ONLY FOR URBAN MOBILITY:

Output service =urban mobility.

Internal activity = vehicle-kilometer (vkm);

ESSTCOSTPACTUY= from the yearly reports of Metro de Madrid: cost of one train (=vehicle) around 9M€, and we assume that they amortize it at 9% in 20 years. This gives an annuity of investment cost of 986k€/year. O&M costs are 36€/vkm (Metro anual report, pag. 77, operational costs do not include energy (but I assume they do include the cost of the tunnels) and they are 6€/wagon-km, x 6 wagons/train = 6*6=36€/vkm). Each vehicle (=train) runs around 90,000km/year (from the report, “production” = 200 Mwagons x km each year, and they have around 2281 wagons). This adds up to a total cost of around 47€/vkm. Much of this is due to the huge cost of the tunnels, accounted for in our O&M costs, which are very high.

QACTESST2ES = pkm/vkm=p/v=occupancy rate=assumed to be 165 p/v (Observatory of Metropolitan Mobility 2009), where a vehicle is the whole train, not just one wagon, and even if occupancy may significantly vary from peak to offpeak hours. Indeed this 165 value is a 16.5% occupancy rate vs a total capacity of around 1000 passengers/vehicle.

TE2QACTESST and/or PE2QACTESST = from Metro annual report we can have how much energy is consumed for traction in each year (760GWh in 2009), and dividing by the “production” and considering the 6 wagons per vehicle (=train) we obtain 0.04 Mvkm/GWh.

Emission factors = 0, it is electricity.

TECHNOLOGY: TRAINS

Output service = we consider train metropolitan electric, interurban electric, interurban diesel, interurban biodiesel, and the same 3 for regional (up to 100km). High speed train (only electric) provides G500km services.

Internal activity = vehicle-kilometer (vkm). 1 vehículo=1train=“n” coches;

ESSTCOSTPACTUY= from Railways Observatory in Spain 2010 and Ferropedia (very useful references, both) we obtain from the EBITDA tables in Ferropedia.es. (2012). Costes del ferrocarril: servicios the operational costs. Subtracting the % of this that corresponds to electricity, we obtain 13.95 €/vkm for high speed 7.36€/vkm for regional and metropolitan and 9.46 for freight (will be used later). For electric regional trains, on top of the 7.36 we add the cost of fully electrifying the rest of non electrified railways in Spain, although more research is needed for this. These values have been estimated using an electrification cost of 400k€/km (would add up to around 2144M€ for all the 5361 km unelectrified), amortized at 5% in 20 years (paid by Government), and spreading this over an estimate of the electric trains (both passengers and freight) in Spain. This is done because electric trains are the cause of electrifying.

QACTESST2ES = pkm/vkm=p/v=occupancy rate=assumed to be 123 p/v for interurban, 80 for regional, and 177 p/v for high speed. 296tkm/vkm for freight.

TE2QACTESST and/or PE2QACTESST = from the last pages of Railways Observatory in Spain 2010, there is the energy consumption. For freight (will be used later) we assume 0.05kWh/tkm and 300t/v. Looking at the different tables we assume that electric is 2.5. times more efficient than diesel.

TE2QACTESST (Mvkm/GWh)

High speed	0.0625
Reg elec	0.16666667
Reg non elec	0.06666667
Metrop	0.16666667
Freight elec	0.06666667
Freight non elec	0.02666667

Emission factors = 0 or the diesel one, depending.

TECHNOLOGY: PLANES:

Output service = long distance land (!) passenger services (to simulate competition) and air passenger services;

Internal activity = vehicle-kilometers, 1 vehicle=1plane;

ESSTCOSTPACTUY=From

http://wiki.answers.com/Q/What_is_the_average_life_expectancy_for_a_commercial_Aircraft in 20 years of life of a plane it does 50,000 flying hours = 2500h/year. At an average of 800km/h = 2E6 km/year. For the cost we consider 1. the amortization cost of the plane + 2. the O&M cost + 3. the cost of airports: 1. Airplane costs assumed to be 200M€, amortized at 9% during 20 years at 9% = 219k€/year; 2. O&M approx 1000USD/hour flying (http://www.iata.org/workgroups/Documents/MCTF/AMC_ExecComment_FY09.pdf), and in 1 year we assume it is 2500h flying so 1.92M€/year considering 1€=1.3USD; 3. In a year we assume 2500 hours flying and average of 3h/flight, we get 833 flights/year=833landings/year, x 1500€/landing (airport use, obtained from the AENA income reported by Ministerio de Fomento and from http://www.ub.edu/graap/JRE_BELFAGEDA.pdf) = 1.25M€/year. Hence cost of the plane + the O&M cost + the cost of airports = (219k€/year + 1.92M€/year + 1.25M€/year) all divided by 2E6 km/year = 1.7 €/vkm.

QACTESST2ES = 212 passengers/vehicle or 100t/vehicle;

TE2QACTESST and/or PE2QACTESST = we will assume 0.0381 litres/km-seat (average of Wikipedia.org (2012), SENASA 2010 and Ferropedia.es. (2012b). Consumo de energía del tren y de...), and assuming 257 seats/vehicle and the fuel's energy density we get 94.68 GWh kerosene/Mvkm. Biofuel plane I assume 50% bio and 50% kerosene.

Emission factors = the one for kerosene from the Emissions Inventory.

TECHNOLOGY: SHIPS FREIGHT AND PASSENGERS: it is not very much and data has been very challenging to obtain, maybe only from Ministerio de Fomento 2011

Output service = sea transport;

Internal activity = vkm;

ESSTCOSTPACTUY= from http://en.wikipedia.org/wiki/Bulk_carrier = 20k€/vehicle and day, assuming an average speed of 30km/h and doing the numbers = 27€/vkm. Of this I suppose 50% is fuel, which seems reasonable according to http://www3.weforum.org/docs/GETR/2012/GETR_Chapter1.8.pdf. To those almost 14€/km I add the cost of ports (from Fomento) which I assume to be around 11€/km (once assigned to each km), to come with a total value of 24.7 M€/Mvkm. We assume biodiesel are 10% more and LNG, 20% more.

QACTESST2ES = passenger 18.31 pkm/vkm and freight 814.6 tkm/vkm, obtained from Ministerio de Fomento but these data are very weak;

TE2QACTESST and/or PE2QACTESST = 121 GWh/Mvkm (assuming the total fuel consumption from ships by IDAE and assuming 100Mvkm in each year);

Emission factors = depending on the fuel (LPG, diesel or bio=0)

TECHNOLOGY: VANS AND TRUCKS FOR FREIGHT.

Output service = land transport;

Internal activity = vkm;

ESSTCOSTPACTUY= the values in table below, assuming also a 3% O&M, amortized in 15 years at 9%, and doing 15000km/year, not all technologies doing all services (vans more urban, trucks more long

distance).

QACTESST2ES = values in table below in t/v = tkm/vkm

	€/vehicle	t/v
Van Small Diesel	15000	0.5
Van Small Hybrid	18000	0.5
Van Small Electrical	30000	0.5
Van Small Biodiesel	15000	0.5
Van Small CNG	18000	0.5
Van Small LPG	17000	0.5
Van Medium Diesel	18000	1
Van Medium Hybrid	21600	1
Van Medium Biodiesel	18000	1
Van Medium CNG	21600	1
Van Medium LPG	20000	1
Van Big Diesel	30000	1.5
Van Big Hybrid	36000	1.5
Van Big Biodiesel	30000	1.5
Van Big CNG	36000	1.5
Truck Medium Diesel	65000	15
Truck Medium Hybrid	65000	15
Truck Medium Biodiesel	65000	15
Truck Big Diesel	85000	30
Truck Big Hybrid	85000	30
Truck Big Biodiesel	85000	30

7.5 Residential and commercial: estimates for demand of energy services

Sources

Greenpeace. (2011). Energía 3.0. Un sistema energético basado en inteligencia, eficiencia y renovables 100%. Madrid.

Economics for Energy. (2011). Potencial económico de reducción de la demanda de energía en España (transl. Economic Potential of Energy Demand Reduction in Spain).

IDAE "Informe Annual de Consumos energeticos"

Instituto para la Diversificación y Ahorro de la Energía. (2011). PROYECTO SECH-SPAHOUSEC. Análisis del consumo energético del sector residencial en España. INFORME FINAL (transl. SECH-SPAHOUSEC Project, Analysis of the Energy Consumption in the Residential Sector in Spain, Final Report).

Perez-Arriaga 2007 "La gestión de la demanda de energía en los sectores de la edificación y del transporte", Fundacion Alternativas, Madrid

Ecofys, E3Mlab of ICCS/NTUA, Institute for Prospective Technological Studies JRC European Commission, AEA Energy and Environment, & CE Delft. (2009). SERPEC-CC Project. Residential Buildings and Service Sector. Retrieved from <http://www.ecofys.com/en/publications/133/>

WWF Spain. (2010). Potencial de ahorro energético y de reducción de emisiones de CO2 del parque residencial existente en España en 2020 (transl. Potential for Energy Savings and CO2 Emissions Reduction in the Existing Dwellings Stock in Spain in 2020).

Lorenzo, J. (2010). Propuestas sectoriales de políticas de eficiencia energética en el sector residencial (transl. Proposals of Energy Efficiency Policies in the Residential Sector) (Proyecto Fin de Carrera (MSc Engineering Thesis)). Universidad Pontificia Comillas, Madrid.

Ministerio de Fomento. (2011). Plan de Ahorro, Eficiencia Energética y Reducción de Emisiones en el Transporte y la Vivienda (transl. Plan for Energy Efficiency, Savings and Emissions Reduction in the Transportation and Residential Sectors). Gobierno de España (Spanish Government).

Ministerio de Industria, Turismo y Comercio. (2011). Plan de Acción de Ahorro y Eficiencia Energética 2011-2020 (transl. Energy Efficiency and Savings Plan 2011-2020).

Sebastián, J. A. (2011). Análisis de políticas de eficiencia energética (transl. Energy Efficiency Policies Analysis) (Proyecto Fin de Carrera (MSc Engineering Thesis)). Universidad Pontificia Comillas, Madrid.

Important note: for this section on residential and commercial energy demand, I have done important and complex calculations (for instance based on the thermal conductivity of walls and roofs, their surfaces, etc), for different types of buildings, etc. Very inspired in the Greenpeace. (2011). Energía 3.0. report. Fully explaining these calculations is out of the scope of this annex. Please refer to my file "Modelado 5ª Columna.xls" within the folder of my PhD thesis that I have left to my advisors and colleagues of the BP Chair at Comillas University, Madrid.

Previous calculations/hypothesis/explanations/values

We have done them following a bottom-up approach starting with our macro-estimations on issues such as population, GDP, housing or residential surface, number of homes, etc.

Energy service code	Description	Residential sector	Commercial sector	Units	Details
ES_DSOTH_RES_HEAT	Space heating	65103		GWhHEAT	Space heating in homes + second houses in 2030 in GWh/año. Calculated as TOTAL surface 2030*demand BAU (23 kWh/m2 in surface built pre-2011 and 13 kWh/m2 (CTE levels) in the surface built after 2011). Source Greenpeace Energia 3.0
ES_DSOTH_RES_COOL	Space cooling	5661		GWhCOLD	Demand A/C homes 2030 GWh/year: surface homes 2030 * 30% penetration A/C in surface * demand BAU (6.83kWh/m2) surface pre-2011 and CTE (5.9kWh/m2) surface post-2011
ES_DSOTH_RES_HTWA	Hot water	46783		GWhACS	Energy in the form of hot water (Agua Caliente Sanitaria ACS). 1556.7 kWhACS/house x 30M houses (also empty ones)
ES_DSOTH_RES_LIGH	Lighting	353027		Giga Lumens-Hour (Glmh):	Calculated with the lighting demand curve (lmh/person) as a function of GDP/capita, plus GDP per cápita, home numbers and people per homes, similar to Greenpeace Energia 3.0. Value in 2010: around 179462 Glmh
ES_DSOTH_RES_FRID	Fridges	18.8		Million Dwellings (= number of families, since it is homes, NOT empty houses).	I assume that there is ONE working appliance per dwelling
ES_DSOTH_RES_OVEN	Ovens	18.8		Million Dwellings (= number of families, since it is homes, NOT empty houses).	I assume that there is ONE working appliance per dwelling
ES_DSOTH_RES_WAMA	Washing machines	18.8		Million Dwellings (= number of families, since it is homes, NOT empty houses).	I assume that there is ONE working appliance per dwelling
ES_DSOTH_RES_DIWA	Dishwashers	18.8		Million Dwellings (= number of families, since it is homes, NOT empty houses).	I assume that there is ONE working appliance per dwelling

ES_DSOTH_RES_COOK	Cooking facilities	18.8		Million Dwellings (= number of families, since it is homes, NOT empty houses).	I assume that there is ONE working appliance per dwelling
ES_DSOTH_RES_OEAP	Other electric appliances	18.8		Million Dwellings (= number of families, since it is homes, NOT empty houses).	I assume that there is ONE equivalent (see "Modelado 5ª Columna.xls") working appliance per dwelling. It is an aggregation of all other appliances
ES_DSOTH_SRV_HEAT	Space heating		50957	GWhHEAT	Space heating in homes + second houses in 2030 in GWh/año. Calculated as TOTAL surface 2030*demand BAU (54 kWh/m2 in surface built pre-2011 and 30 kWh/m2 (CTE levels) in the surface built after 2011). Source based on calculations from Greenpeace Energia 3.0
ES_DSOTH_SRV_COOL	Space cooling		28744	GWhCOLD	Demand A/C commercial surface 2030 GWh/year: surface 2030 * 100% penetration A/C in surface * demand BAU (29.9kWh/m2) surface pre-2011 and CTE (23.5kWh/m2) surface post-2011
ES_DSOTH_SRV_HTWA	Hot water		10054	GWhACS	10.27 kWhACS/m2comerc
ES_DSOTH_SRV_LIGH	Lighting		978.34	Commercial surface: km2	Directly the unit is the surface
ES_DSOTH_SRV_OEAP	Other electric appliances		978.34	Commercial surface: km2	Directly the unit is the surface

7.6 Residential and commercial: energy services demand reduction measures (ESVMs)

Sources

Greenpeace. (2011). Energía 3.0. Un sistema energético basado en inteligencia, eficiencia y renovables 100%. Madrid.

Economics for Energy. (2011). Potencial económico de reducción de la demanda de energía en España (transl. Economic Potential of Energy Demand Reduction in Spain).

And also same sources as above.

These calculations are very complex (e.g. cost and savings if we improve the thermal insulation of buildings in Spain) and need further research, I am not very confident on them. Hence I do not use them (for now) in the model (ESVMs disabled), and I do not include the here. In any case I do include the results (below), just for informative purposes. For more details please refer to my file "Modelado 5ª Columna.xls" within the folder of my PhD thesis that I have left to my advisors and colleagues of the BP Chair at Comillas University, Madrid.

Energy service VM code	Description	Cost per year (M€)	Effect on the energy service ES_DS OTH_R ES_HEAT	Effect on the energy service ES_DS OTH_R ES_COOL	Effect on the energy service ES_DS OTH_S RV_HEAT	Effect on the energy service ES_DS OTH_S RV_COOL
ESVARM_DSOTH_RES_InsOpaqDtch dUCTE0p8	"Improve insulation of opaque elements in detached dwellings built prior to 2011 to a U value of 0.8W/m2K (CTE standar)"	635.61				
ESVARM_DSOTH_RES_InsOpaqDtch dUPsvH0p2	"Improve insulation of opaque elements in detached dwellings built prior to 2011 to a U value of 0.2W/m2K (almost Passiv House)"	2363.55	-6.8%	-1.0%		
ESVARM_DSOTH_RES_WindowsDtch dUCTE0p8	"Improve windows in detached dwellings built prior to 2011 to a U value of 0.8W/m2K (CTE standar)"	417.14	-15.6%	-3.4%		
ESVARM_DSOTH_RES_WindowsDtch dUPsvH0p2	"Improve windows in detached dwellings built prior to 2011 to a U value of 0.2W/m2K (almost Passiv House)"	1551.14	-2.6%	-0.3%		
ESVARM_DSOTH_RES_InsOpaqBlock UCTE0p8	"Improve insulation of opaque elements in block dwellings built prior to 2011 to a U value of 0.8W/m2K (CTE standar)"	646.58	-8.0%	-1.2%		
ESVARM_DSOTH_RES_InsOpaqBlock UPsvH0p2	"Improve insulation of opaque elements in block dwellings built prior to 2011 to a U value of 0.2W/m2K (almost Passiv House)"	2404.36	-15.3%	-2.2%		
ESVARM_DSOTH_RES_WindowsBloc kUCTE0p8	"Improve windows in block dwellings built prior to 2011 to a U value of 0.8W/m2K (CTE standar)"	424.34	-35.2%	-7.8%		
ESVARM_DSOTH_RES_WindowsBloc kUPsvH0p2	"Improve windows in block dwellings built prior to 2011 to a U value of 0.2W/m2K (almost Passiv House)"	1577.92	-0.7%	-0.8%		
ESVARM_DSOTH_RES_ImprInsNewB UCTE0p8toUPsvH0p2	"Improve insulation of dwellings built between 2011 and 2030 from CTE Estándar (U=0.8W/m2k) to almost Passiv House	30.97	-2.3%	-2.8%		

	Estándar (U=0.2W/m2k)"					
ESVARM_DSOTH_RES_Thermostatic Valves	"Install thermostatic valves in dwellings in roughest climatic areas (in 600k dwellings in 2030)"	27.97	-0.4%	-0.2%		
ESVARM_DSOTH_SRV_InsUPsvH0p8	"Improve insulation of commercial buildings built prior to 2011 to a U value of 0.8W/m2K (CTE standar)"	2925.26	-0.4%		-41.7%	-20.1%
ESVARM_DSOTH_SRV_InsUCTE0p2	"Improve insulation of commercial buildings built prior to 2011 to a U value of 0.2W/m2K (almost Passiv House)"	8288.23			-83.3%	-74.6%
ESVARM_DSOTH_SRV_ImprInsNewB UCTE0p8toUPsvH0p2	"Improve insulation of commercial buildings built between 2011 and 2030 from CTE Estándar (U=0.8W/m2k) to almost Passiv House Estándar (U=0.2W/m2k)"	145.08			-4.1%	-5.4%

7.7 Residential and commercial technologies (ESSTs)

Sources

Greenpeace. (2011). Energía 3.0. Un sistema energético basado en inteligencia, eficiencia y renovables 100%. Madrid.

Economics for Energy. (2011). Potencial económico de reducción de la demanda de energía en España (transl. Economic Potential of Energy Demand Reduction in Spain).

Ministerio de Medio Ambiente y Medio Rural y Marino. (2011). Inventario de Emisiones de Gases de Efecto Invernadero de España. Años 1990-2009 (transl. Greenhouse Effect Gasses Emissions Inventory for Spain. Years 1990-2009). Madrid.

Previous calculations/hypothesis/explanations/values

Please see values below. Calculations follow a similar approach as for other technologies:

Efficiencies: based on literature, they determine the relation between input final energy and the internal activities (i.e. the factor TE2QACTESST). Those activities are already in the same units as the outputs (e.g. kWh of hot water) and hence the QACTESST2ES factor is 1.

We assume an investment cost (based on literature, internet, etc), a life period (15 years for many technologies), and an investment rate (9%). This allows us to calculate the annualised investment cost. Then we assume a yearly O&M cost (non energy), which in most cases is a % of the overnight investment cost (most time either 10% or 5%). The annuity + annual O&M cost = total (non energy) yearly cost. Then, we also assume a maximum capacity for each technology (per unit of the technology, i.e. which corresponds to the investment cost mentioned before), and a number of equivalent working hours (at full output) per year. Multiplying both we obtain the yearly activity. Finally we divide the (total) yearly cost by this total activity, obtaining the cost per activity unit, which is the ESSTCOSTPACTUY parameter.

For appliances we have simply basic consumptions (e.g. from manufacturers web pages), made ome assumptions (e.g. the most efficient one is a 20% more efficient than the baseline one)

The detailed calculations can be seen in the excel file mentioned above, where it is all well documented

Emissions: depending on the consumed fuel, the values from the National Emissions Inventory for the corresponding sector.

DOMESTIC BOILERS	Effic. (%): GWh _{heat} /GWh _{input}	Inv. Cost (€/unit)	Life (years)	Interest	Yearly O&M costs NO ENERGY (€/year)	Annual Inv Cost (€/year)	Total Cost NO ENERGY (€/year)	Unit power (kW):	Working Hours	Yearly Activity (GWh _{out} /year)	Cost Per Act Unit TOTAL (M€/GWh _{out})	TE2ACT_HEAT (GWh _{out} /GWh _{in})
Assumptions: Activity measured in GWh _{out} , and that GWh _{out} is converted to heat (factor 1) if it is a boiler or to heat and electricity (0.6, 0.4) if it is a CHP, etc. To create that activity, the efficiency is used. For the unit power we assume 25 kW each, which makes sense since private ones are in the range 30-35, and in 20 house- communities they are 350kW that is 17.5 kWh/house).												
"ESST Residential Heat. Diesel Boiler"	65%	600	15	9%	60	74	134	25	1680	0.042	0.003	0.65
"ESST Residential Heat. Natural Gas Boiler Conventional"	70%	700	15	9%	70	87	157	25	1680	0.042	0.004	0.70
"ESST Residential Heat. Natural Gas Boiler Low Temperature"	80%	889	15	9%	88.9	110	199	25	1680	0.042	0.005	0.80
"ESST Residential Heat. Natural Gas Boiler Condensation"	90%	1050	15	9%	105	130	235	25	1680	0.042	0.006	0.90
"ESST Residential Heat. Liquefied Petroleum Gas Boiler Conventional"	70%	700	15	9%	70	87	157	25	1680	0.042	0.004	0.70
"ESST Residential Heat. Liquefied Petroleum Gas Boiler Low Temperature"	80%	889	15	9%	88.9	110	199	25	1680	0.042	0.005	0.80
"ESST Residential Heat. Liquefied Petroleum Gas Boiler Condensation"	90%	1050	15	9%	105	130	235	25	1680	0.042	0.006	0.90

ion"												
"ESST Residential Heat. Electric Resistive Heating"	100%	300	15	9%	15	37	52	25	1680	0.042	0.001	1.00
"ESST Residential Heat. Heat Pump COP3"	300%	7000	15	9%	350	868	1218	25	1680	0.042	0.029	3.00
"ESST Residential Heat. Heat Pump COP6"	600%	8000	15	9%	400	992	1392	25	1680	0.042	0.033	6.00
"ESST Residential Heat. Biomass Furnace"	85%	2000	15	9%	200	248	448	25	1680	0.042	0.011	0.85
"ESST Residential Heat. Micro CHP"	75%	1800	15	9%	180	223	403	25	1680	0.042	0.010	0.75
"ESST Residential Heat. District Heating"	100%	23800	15	9%	1190	2953	4143	25	1680	0.042	0.099	1.00

DOMESTIC A/C and WATER HEATING	Effic. (%): GWhOut/GWh Input	Inv. Cost (€/unit)	Lif e (yrs)	Inter est	YearlyO&Mcosts_NO ENERGY (€/year)	Annu al InvCost (€/year)	Total Cost_NO ENERGY (€/year)	Unit power (kW):	Worki ng Hours	Yearly Activit y (GWh out/year)	Cost Per Act Unit_TOT AL (M€/GWh out)	TE2AC T (GWh out/G Wh in)
ACTIVITY: GWhout, and that GWhout is converted to A/C with a factor of 1, To create the activity, efficiency is used												
"ESST Residential Cooling. Air Conditioni ng COP 2"	200%	300	15	9%	15	37	52	3.5	960	0.003	0.016	2.00
"ESST Residential Cooling. Air Conditioni ng COP 6"	600%	600	15	9%	30	74	104	3.5	960	0.003	0.031	6.00
"ESST Residential Hot Water. Diesel Boiler"	65%	600	15	9%	60	74	134	15.0	548	0.01	0.02	0.65

"ESST Residential Hot Water. Natural Gas Boiler Conventional"	70%	700	15	9%	70	87	157	15.0	548	0.01	0.02	0.70
"ESST Residential Hot Water. Natural Gas Boiler Low Temperature"	80%	889	15	9%	88.9	110	199	15.0	548	0.01	0.02	0.80
"ESST Residential Hot Water. Natural Gas Boiler Condensation"	90%	1050	15	9%	105	130	235	15.0	548	0.01	0.03	0.90
"ESST Residential Hot Water. Liquefied Petroleum Gas Boiler Conventional"	70%	700	15	9%	70	87	157	15.0	548	0.01	0.02	0.70
"ESST Residential Hot Water. Liquefied Petroleum Gas Boiler Low Temperature"	80%	889	15	9%	88.9	110	199	15.0	548	0.01	0.02	0.80
"ESST Residential Hot Water. Liquefied Petroleum Gas Boiler Condensation"	90%	1050	15	9%	105	130	235	15.0	548	0.01	0.03	0.90
"ESST Residential Hot Water. Electric Resistive. Consuming centralised electricity"	100%	300	15	9%	15	37	52	15.0	548	0.01	0.01	1.00
"ESST Residential Hot Water. Electric Resistive. Consuming"	100%	300	15	9%	15	37	52	15.0	548	0.01	0.01	1.00

distributed electricity"												
"ESST Residential Hot Water. Biomass"	85%	2000	15	9%	200	248	448	15.0	548	0.01	0.05	0.85
"ESST Residential Hot Water. Solar Thermal"	70%	6421.23	15	9%	128	797	925	Ver abajo	Ver abajo	0.01	0.11	0.70

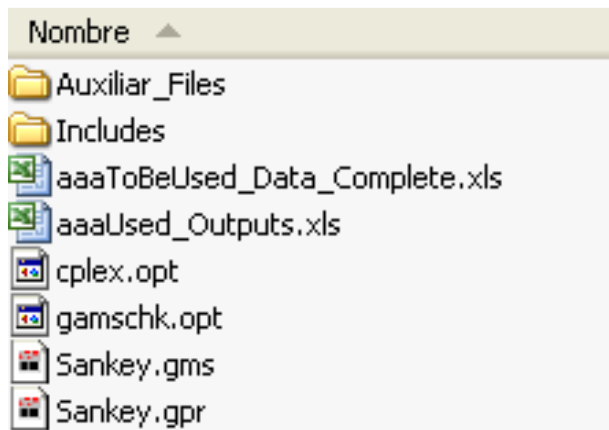
ANNEX 4.

REFERENCE GUIDE FOR THE MASTER_SO AND MASTER_DS MODELS

This annex contains information on how to use both MASTER SO and MASTER DS models from the computational point of view: files needed, software, etc.

MASTER SO

This part will tell you how to make MASTER_SO work in your computer. In addition to GAMS and a valid GAMS Licence (for CPLEX solver), the only things needed to run the MASTER_SO model are:



“Auxiliar_Files” can be empty: GAMS will generate the files. “Includes” needs to have all the include files, which are the following (next page):

(I think the only really needed ones are the INC and the GMS ones, the TMP and those with the ~ are generated by GAMS and not needed I think):

Nombre	Fecha de modificación	Tamaño	Tipo ▲
 a_FEllosses.~gm	12/06/2012 20:59	46 KB	Archivo ~GM
 a_InitialCalculations.~gm	07/06/2012 20:49	7 KB	Archivo ~GM
 a_Outputs.~gm	14/11/2012 13:37	46 KB	Archivo ~GM
 a_SetsModification.~gm	22/12/2012 16:03	7 KB	Archivo ~GM
 b_CaseSpecificNeeds.~gm	09/07/2012 21:05	5 KB	Archivo ~GM
 b_DStechCalibrBounds.~gm	09/07/2012 21:12	2 KB	Archivo ~GM
 b_ESSTCALIB.~gm	26/12/2012 21:37	14 KB	Archivo ~GM
 a_InputsUnitsConversion.~in	05/06/2012 18:21	19 KB	Archivo ~IN
 a_Parameters.~in	18/12/2012 12:51	12 KB	Archivo ~IN
 a_Scalars.~in	06/04/2011 19:22	5 KB	Archivo ~IN
 a_Sets.~in	18/12/2012 12:51	8 KB	Archivo ~IN
 a_SetsModification.~in	14/11/2012 13:26	5 KB	Archivo ~IN
 a_Tables.~in	18/12/2012 12:51	9 KB	Archivo ~IN
 a_VerifyData.~in	08/06/2012 10:25	13 KB	Archivo ~IN
 a_InputsUnitsConversion.inc	05/06/2012 20:22	19 KB	Archivo INC
 a_InternalConstants.inc	30/03/2011 19:37	4 KB	Archivo INC
 a_Parameters.inc	18/12/2012 17:04	12 KB	Archivo INC
 a_Scalars.inc	09/07/2013 11:27	5 KB	Archivo INC
 a_Sets.inc	18/12/2012 17:05	8 KB	Archivo INC
 a_Tables.inc	18/12/2012 17:05	9 KB	Archivo INC
 a_VerifyData.inc	08/06/2012 10:41	12 KB	Archivo INC
 a_P36A.tmp	01/06/2012 16:37	11 KB	Archivo TMP
 a_SCA.tmp	15/05/2012 18:13	7 KB	Archivo TMP
 a_FEllosses.gms	12/06/2012 21:08	4 KB	GAMS IDE file
 a_InitialCalculations.gms	23/01/2013 12:18	7 KB	GAMS IDE file
 a_Outputs.gms	14/11/2012 13:38	46 KB	GAMS IDE file
 a_SetsModification.gms	22/12/2012 17:30	7 KB	GAMS IDE file
 b_CaseSpecificNeeds.gms	15/11/2012 20:38	7 KB	GAMS IDE file
 b_ESSTCALIB.gms	28/12/2012 13:26	14 KB	GAMS IDE file

Normally these folders have everything needed, all the files needed to execute the model. However, if you see that there's something missing (a file or something), go look for them in the DVD/CD that I have left at IIT in Madrid with my PhD advisors Ignacio and Pedro, with the BP Chair colleagues, and in electronic format. Inside the DVD go look in:

TESIS\My_Model\Sankey\vCurrent

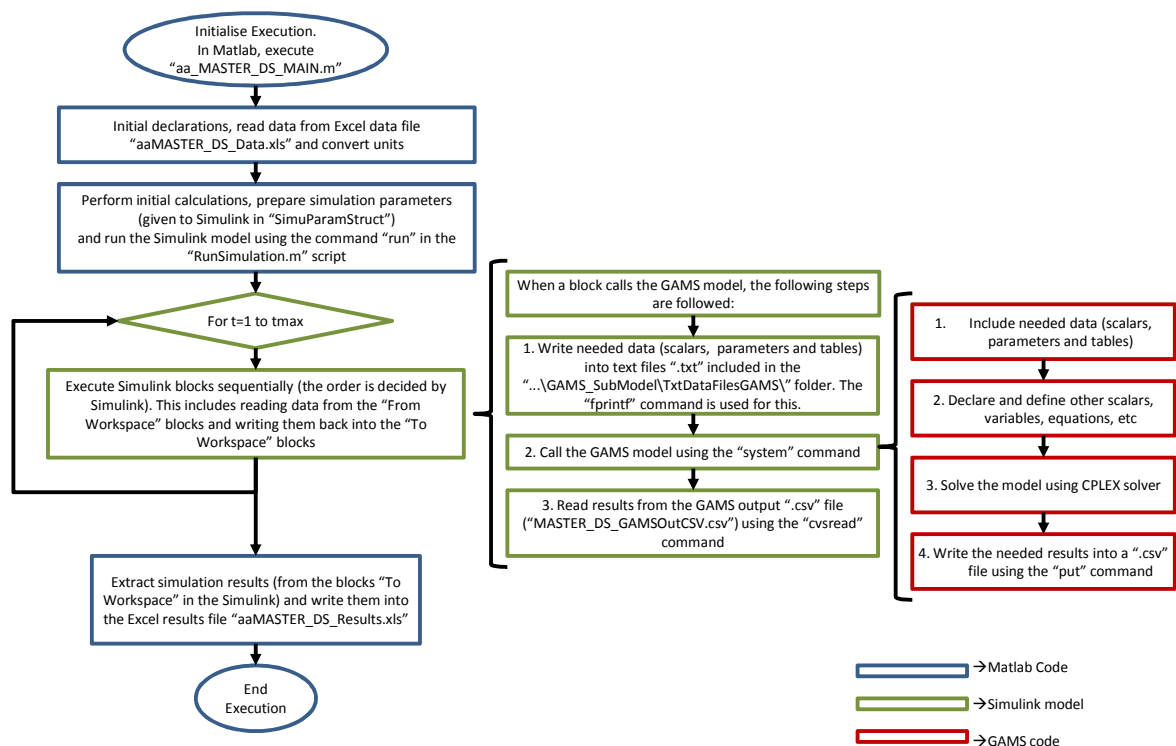
HOW TO BUILD SANKEY DIAGRAMS? What I did is paste the needed flows in an external excel file (either 1. copy and paste from the GDX viewer or 2. use the outputs gams code and outputs file, in a sheet with the energy flows). Then I copied these energy flows into an intermediate excel file "Flows4Sankey.xls" (in the left column) where I have some formulas (in the right column) calculating the needed flows aggregation (you should figure this out depending on the topology of your system), and the Sankey software (eSankey, with a valid licence) then reads from there.

MASTER_DS

This part will tell you how to make MASTER_DS work in your computer. It has two parts: a long and a short installation guide: the short one was written by Renato Rodrigues (thanks!!) when we tried the installation in his computer.

LONG INSTALLATION GUIDE

How to make MASTER_DS work in your computer? This may be a bit complex at the beginning because MASTER_DS is modeled using a set of software and programmes that interact between them. Mainly three tools are used: Matlab code (".m" files), a Simulink model, and a GAMS model, which are logically related as can be seen in the next diagram.



Matlab is only used to read data, write results, and control the main execution flow (which is done in the Main function called "aa_MASTER_DS_MAIN.m"). The principal model structure is done in Simulink. GAMS is used to represent the yearly optimization of the energy market.

The Simulink model uses discrete time steps (5 steps per year, in other words, $t=1, 1.2, 1.4, 1.6, \dots$, being years 2010=1, 2011=2, ..., 2030=21...). It uses mainly discrete blocks, arrows and “Matlab Function Blocks” (previously called Embedded MATLAB Function Block, I think). These “Matlab Function blocks” are a way of being able to write my own Matlab code within a Simulink model. The main issue to consider is that Simulink does not run this code line by line (as if it was just interpreting commands) but instead (I guess for execution speed), it compiles it into C code. A compiler will be needed for this (see below). This also affects the Matlab code you can use within the blocks: it is actually not all the Matlab code, but a subset of it called “Embedded Matlab” which is specifically designed for code generation. The main differences that I have been able to see between Embedded Matlab and normal Matlab code are:

1. In order to allocate memory, the compiler needs to know a priori the sizes of all variables, hence variable-sized matrixes are not allowed. These are very commonly used in Matlab for example when matrixes grow inside your code, normally done using subscripting like “:”. Instead you will have to assign matrixes a fixed size (if you are not sure of the size you will need, just declare a big-enough matrix), and initializing them (e.g “Matriz=zeros(n,m)”)
2. You will have to add at the beginning of each block the following instruction, telling the compiler to generate code with this block: “%#codegen”
3. Some of the Matlab instructions that you will use are not supported by the “Embedded Matlab” subset. Do not worry, this does not mean that you cannot use them. It just means that you have to tell the model to not compile them, instead, to interpret this as it was normal Matlab. You do this declaring that command at the beginning of the block where you use it using “coder.extrinsic(‘name_of_the_command’). Example: “coder.extrinsic(‘fprintf’);”

But this is not all: for the blocks which call the optimization model programmed in GAMS, we need to pass the data to GAMS and obtain back its results. This can be efficiently done between Matlab and GAMS using GDX files and the GDXMRW tools. However, I was obtaining some strange errors when trying to do it, and I reached the conclusion (may not be true, but I did not investigate it more) that GDXMRW does not work well when the code is compiled (Not even using “coder.extrinsic”). Hence I decided (with very helpful advice from Rhonda Jordan at MIT) to pass data to GAMS using “.txt” files, and to read it back from GAMS using “.csv” files. To write the text files we use “fprintf” (already using the formatting needed by GAMS), we put them into the “...\GAMS_SubModel\TxtDataFilesGAMS” folder, and are read from GAMS using “include” statements. The outputs of GAMS are written into the “MASTER_DS_GAMSOOutCSV.csv” file using “put”, and the read from the Simulink block using “csvread”. To write the CSV file I also tried to use “gms2csv”, but I did not manage (also, was obtaining some strange errors). I concluded (I may be wrong, again) that it works well in GAMS standalone, or when you call GAMS from a Matlab script, but it does not work when code compilation is done. So I used “put” which is not as intuitive but it works.

Software you will need:

1. Windows. I have tried it both with Windows XP (32bit, my IIT computer) and Windows 7 (64bit, my laptop), and it was ok in both (only the path to the GAMS .exe has to be changed, in the Simulink blocks where GAMS is called). Linux and/or Mac: I have not tried

it. I think it should work ok in other operating systems because I am NOT using GDX files to exchange info (GDX files are, I think, not supported in Unix), but only “.txt” and “.csv”, which should be fine.

2. Matlab with Simulink: it has to be at least Matlab R2011b in order for the Discrete Delay block () in Simulink to be included, which is absolutely needed. I have tried the model both with the 32bit Matlab (at IIT) and 64bit one (in my laptop) and it worked fine. Simulink comes with Matlab by default (unless you chose not to). To open it, press an icon  on the top bar in Matlab’s main window ().
3. GAMS with a valid licence. To avoid problem (especially if GDXMRW is needed, see below), If the operating system and Matlab is 32 (64) bits, GAMS should be the same. It is also good to have the latest version of Matlab when you install/configure GDXMRW for the first time, as they recommend in their web page.
4. GDXMRW working well?? (even if I am not using it as said above), I think it may be required to be able to call GAMS from Matlab using the “gams” command, but finally I am not using it, because I am calling it with the “system” command? To check that you have it and it works ok, look for a pdf file in Google called “GDXMRW: Interfacing GAMS and MATLAB” (by Michael C. Ferris et al, February 7, 2011). Follow sections 1,2 and 3. If all the tests in section 3 work fine, it should be ok. If you have trouble with this, try in The GAMS Support Wiki a page called “GDXMRW Debugging and Support Instructions” (<http://support.gams-software.com/doku.php?id=interfaces:gdxmrwsupport>) or “Matlab and GAMS: Interfacing Optimization and Visualization Software via the GDXMRW Utilities” ([http://support.gams-software.com/doku.php?id=matlab and gams:interfacing optimization and visualization software via the gdxmrw utilities](http://support.gams-software.com/doku.php?id=matlab%20and%20gams:interfacing%20optimization%20and%20visualization%20software%20via%20the%20gdxmrw%20utilities)).
5. You need a C compiler, in order for Simulink to be able to compile the model into C before executing it. Some Matlab distributions already bring the “C Compiler”, or “Lcc”. My friend Renato with Matlab R2009b indeed had Lcc installed by default. He did not have to do anything else, it just worked fine (go to the next section, number 6). If your Matlab does not bring a compiler, in the Matlab documentation they recommend Microsoft Windows SDK. My advice: just read about the compilers in your Matlab (not in the web page because it may apply to a different Matlab distribution) and install what they recommend, taking into account if your Matlab and/or operating system is 32 or 64 bits. In my case, for my laptop I installed Microsoft Windows SDK 7.1. Once downloaded, they told me that before installing it I had to have Microsoft .NET Framework 4 correctly installed. I downloaded it and installed it from Microsoft official web page. Then I installed the SDK. When SDK is installed, you have to configure Matlab to correctly use the compiler you just installed. For this (always following the Matlab documentation): in the Matlab command prompt you type “mex -setup “, you ask him to show you the list of installed compilers, and then you choose “Lcc” or “SDK” (or whichever compiler you want to use). You also have to confirm in which folder it is. Finally, the default language has to be “C++”. This was already my case, but to check it you can type “cc = mex.getCompilerConfigurations” and verify the content in “cc”. In my case it was ok because in build options used by the selected compiler it said “Language: ‘C++’” (see below). To see these build options used by the selected compiler, type: “ccOptions = cc.Details”. But this is just for information, you do not need to change anything else here. If you want to know more, for more info on

how to modify options files for particular systems, see “Custom Building MEX-Files.” Here you will see what I see when I type “ccOptions = cc.Details”

Properties:

Name: 'Microsoft SDK'

Manufacturer: 'Microsoft'

Language: 'C++'

Version: '7.1'

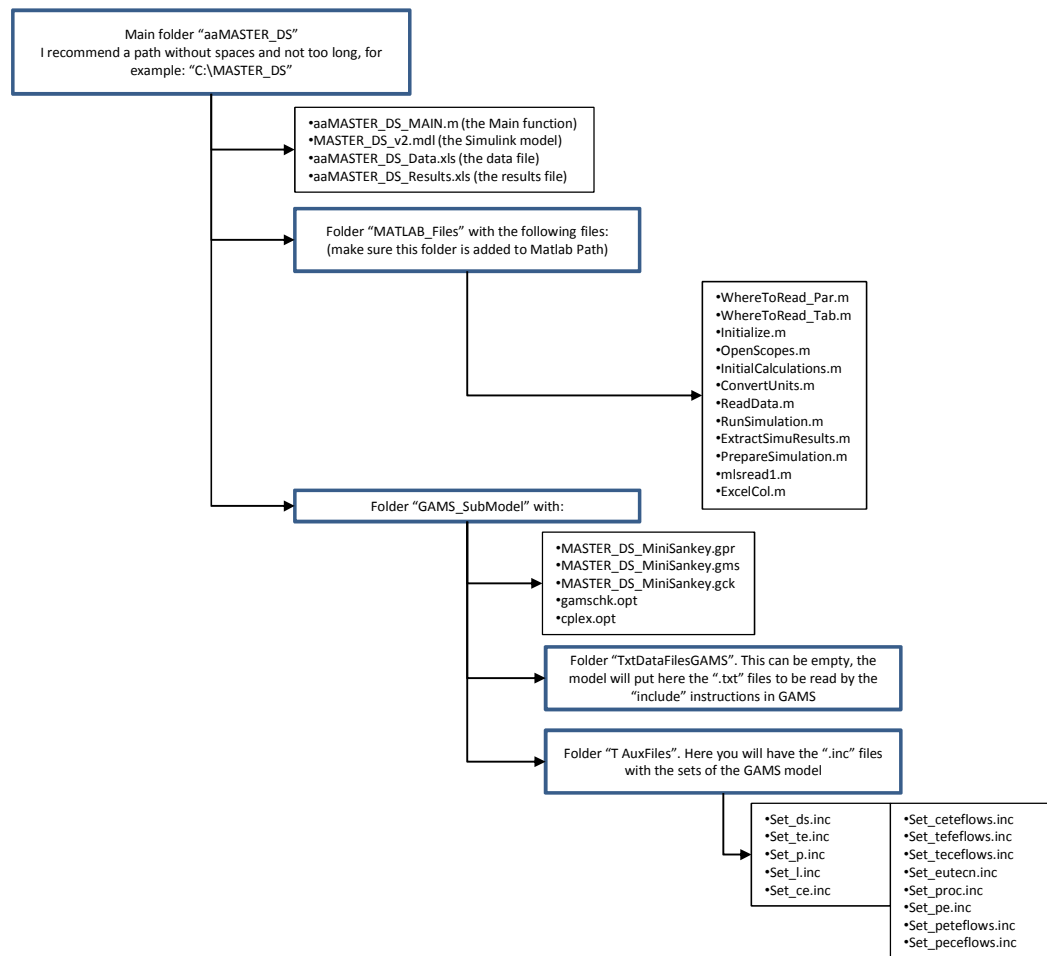
Location: 'C:\Program Files (x86)\Microsoft Visual Studio 10.0'

Details: [1x1 mex.CompilerConfigurationDetails]

6. Once this is done, your compiler should be working ok and you should be able to run the MASTER_DS model (because Simulink will already be able to compile the code). You just need to make sure you have all the needed files.

Files you will need:

The following figure (look at it, it will be useful) describes the minimum files that you need to run MASTER_DS, and the folder structure. Please, look at this figure and make sure you have all these files (not just the ones I have created but also some exogenous matlab functions I downloaded from the internet, such as “ExcelCol.m” and “xlsread1.m”). Make sure that you keep the names of the files and folders, and that you add it all under a folder which is in a simple path. I recommend a path without spaces and not too long, for example: “C:\MASTER_DS”. Make sure also that this path, and the one of the “MATLAB_Files” folder, are added to the Path variable in Matlab. I am not sure if it is needed but just in case do the same with the “Gams_SubModel” folder.



Changes you need to do in the code to make it work in YOUR computer:

In addition, you may have to change some of the paths in the code to fit it to your computer. I am NOT referring to the “Matlab Path” (as in the previous paragraph), but to some paths in the Matlab code within some of the blocks in the Simulink. For this, open the model (steps 1, 2 and 3 in the next section called “How to execute it”.) Specially:

1. The “MainModelFolder” variable within the “aaMASTER_DS_MAIN.m” file.
2. Within Simulink, in the blocks where the GAMS model is called (the “WholesaleMarket” and the “UtilitiesForecasting”), the line where the call is done should point at the correct GAMS .exe file, and this is a path such as “C:\GAMS\win32\23.9\gams.exe”. In my case, the GAMS call from my IIT computer and from my laptop are:
 - IIT: [system_status, system_text] = system('C:\GAMS\win32\23.9\gams.exe' GAMS_SubModel\MASTER_DS_MiniSankey.gms');
 - LAPTOP: [system_status, system_text] = system('C:\GAMS\win64\23.9\gams.exe' GAMS_SubModel\MASTER_DS_MiniSankey.gms');

How to execute it:

1. Open Matlab and the “aaMASTER_DS_MAIN.m” function (I normally just double click on this file)
2. Open Simulink, in the Simulink icon in Matlab
3. From Simulink, open the model (“MASTER_DS_v2.mdl” file). These two last steps are not always necessary, if it is not open, the command “open_system('MASTER_DS_v2')” in the Main function will do it.
4. Modify the data you want in the Data excel file
5. To run: just execute the “aaMASTER_DS_MAIN.m” function from Matlab. At that moment, you will get a message “Executing MASTER_DS, the dynamic simulation model for sustainable energy policy analysis... (wait, please)” and then asking you “ Do you want to maintain old workspace variables? (y/n, default is "n")”. Just press “enter”, to say “no”, which completely clears the workspace. Just use “yes” if you have created some variables in the workspace (in your own work) which you do not want to be deleted. In any case, the values of existing variables which have to be read from the Excel data book will be actualized.

QUICK INSTALLATION GUIDE (my thanks to Renato Rodrigues)

1. **Install Matlab, 2011b or superior version (it must have Simulink).**
2. **Install GAMS with a valid license.**
3. **Install GDXMRW.**
 - a. Follow the instructions described on this link: <http://support.gams-software.com/doku.php?id=interfaces:gdxmrwsupport>
4. **Check if you have a Matlab C compiler installed.**
 - a. Run in MATLAB the following command line:

```
>> mex -setup
```
 - b. Choose yes to locate installed compilers.
 - c. If you don't have a compiler installed go to the next step.
 - d. Choose the compiler to be used.
5. **Install a C compiler LCC, "C Compiler" or use the Microsoft Windows SDK to install a C compiler to your computer. It is possible that the Microsoft SDK require the Microsoft .NET Framework 4 installed. Go back to step 4.**
6. **Create a folder for the MASTER model:**
 - a. It is recommend to choose a path without spaces and not too long, for example: "C:\MASTER_DS"
7. **Copy the model files to the folder you created.**
8. **Add these paths to the MATLAB folders:**
 - a.

```
>> addpath 'C:\MASTER_DS'; savepath;
```
 - b.

```
>> addpath 'C:\MASTER_DS\MATLAB_Files'; savepath;
```
9. **Open the model file "aaMASTER_DS_MAIN.m" in MATLAB**
10. **Change the model path to your folder selection at the line:**
 - a.

```
MainModelFolder='C:\MASTER_DS \';
```
11. **Open Simulink, in the Simulink icon in Matlab.**
12. **From Simulink, open the model ("MASTER_DS_v2.mdl" file).**
13. **Double click on the wholesale MKt block.**
14. **Change the GAMS path at the line:**
 - a.

```
[system_status, system_text] = system('"C:\Archivos de programa\GAMS\gams.exe');
```
15. **Save the file and get back to Simulink blocks view and double click on the Utility Forecasting block.**
16. **Change the gams path at the line:**
 - a.

```
stem_status, system_text] = system('" C:\Archivos de programa\GAMS \gams.exe" GAMS_SubModel\MASTER_DS_MiniSankey.gms');
```
17. **Save the file.**
18. **Master model is completely installed you can execute thye model by simply following the bellow steps.**
19. **Modify the data you want in the Data excel file.**
20. **To run: just execute the "aaMASTER_DS_MAIN.m" function from Matlab.**