MASTER.SO: a Model for the Analysis of Sustainable Energy Roadmaps. Static Optimisation version.

Paper previously called "A Policy-Oriented Energy Optimization Model with Sustainability considerations"

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This working paper contains a description of the model used for carrying out the study "Renewables in the Spanish Energy Sector: a Cost-Efficiency Evaluation for CO_2 Emissions Reduction", presented in the Workshop "The Cost of Renewable Energy in the EU" that took place in the European University Institute, Florence, in May 2011.

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Abstract:

This paper describes in detail MASTER.SO, a sustainable energy policymaking model, developed in the BP Chair on Energy and Sustainability at the Universidad Pontificia Comillas, Madrid. It is a bottom-up partial equilibrium static model of energy systems that has been conceived for sustainable energy policy analysis. It strikes a balance between technical accuracy on one side and simplicity and compactness (being easily computable and simple to understand by the user) on the other. For this last purpose, the model's results are presented by means of Sankey diagrams, a very intuitive representation of energy systems. It is a linear programming model that satisfies demands for final energy and/or energy services (input parameters) while maximising the sustainability of the system. Sustainability is represented through the objective function, which is conceived as a comprehensive indicator of energy sustainability, and includes, for instance, total costs of energy supply (investment costs, operating costs, imports costs, subsidies, etc) as well as externalities. While supplying demand maximising sustainability, the model respects the main technical constraints of energy systems, such as energy balances, capacity limitations, and technical reliability conditions, among others. It is programmed in GAMS language, and solved using CPLEX optimizer.

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Outline

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1 Introduction

The implications of energy use for sustainable development are clear, and have been widely assessed in the literature. A sustainable energy system is basic for the virtuous development of societies. However, the current world energy system is clearly unsustainable, and the Spanish one is not an exception. For an assessment of the sustainability of the Spanish energy system, refer to the *Observatory on Energy and Sustainability,* published every year by the BP Chair on Energy and Sustainability (López-Peña, Danesin, et al., 2011).

In a context of energy markets' liberalisation, like in the Spanish case, it seems that free markets are indeed introducing greater efficiency in the allocation of scarce resources, which was one of the main arguments for liberalisation in the eighties and nineties. However, markets alone are not making energy systems evolve towards sustainability, because of market failures that are especially relevant in the energy industry. Important externalities, such as climate change or long-term resources depletion, are not necessarily accounted for in energy prices, and therefore completely free energy markets are flawed.

Regulation is needed in energy markets in order to make them work better, making energy systems evolve towards sustainability and hence maximising social welfare in the long term. The policies and regulations applied to energy systems with the aim of making them more sustainable are going to be called, from now on, *sustainable energy policies*.

Sustainable energy policies, like any other public policy, must be analysed prior to its implementation, in order to simulate its effects, associated costs and benefits, unexpected consequences, etc. This analysis, quantitative as well as qualitative if possible, helps policymakers in designing sound policies. When performing these analyses, modern policymaking relies heavily on representing the affected economic sectors in mathematical models that, thanks to the important developments that have taken place in computing science during the last decades, can be easily solved. Energy policymaking is not an exception, and mathematical models of energy systems, and its linkages with the economy and the environment, are nowadays widely used.

The purpose of this paper is to present MASTER.SO, a mathematical model designed for assessing sustainable energy policies. It has been developed within the PhD Thesis of Mr. Álvaro López-Peña Fernández, done at the BP Chair on Energy and Sustainability and the Instituto de Investigación Tecnológica, Universidad Pontificia Comillas, Madrid. The version of the model that is described here is the one used for the study "Renewables in the Spanish Energy Sector: a Cost-Efficiency Evaluation for CO2 Emissions Reduction" (López-Peña, Linares & Pérez-Arriaga, 2011).

The model has two main purposes:

1. To calculate an energy supply for a country in a year taking into account sustainability considerations (such as the social cost of carbon emissions or the externalities of energy imports), and allowing an easy identification of the main trade-offs involved in energy policy.

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2. To present the results in an easily understandable and transparent way, as required by policymakers. The aim is to overcome the usual problem of very complex energy models that are seen as black boxes and therefore, not trusted by decision makers.

For the first objective, the model has been conceived as an optimization model using linear programming (LP). The objective function to be optimised is a comprehensive measure of the energy supply's sustainability, that is, the optimization model aims at maximising sustainability. The precise formulation of the objective function is shown below in this document. This objective function means that the point of view chosen for the analysis is that one of a policymaker aiming at improving the sustainability of the complete energy system, what in other words implies maximising social welfare over the long run. It is therefore a centralised perspective, similar to the ones used for energy markets' analysis in the past under the regulated paradigms that were usual prior to the liberalisation processes. This centralised perspective is however useful in liberalised frameworks as well, when the point is to carry out long-term normative studies, as it is the case here.

The LP formulation has been chosen because it allows for enough technological detail for a long-term analysis, while at the same time keeping the model conceptually simple, compact and fast to compute, and providing important information with its constraints' shadow prices. Indeed, a correct interpretation of these shadow prices in combination with the observed values of the objective function (which represents sustainability) can provide interesting insights on the main tradeoffs affecting sustainable energy policymaking. In order to achieve a large modelling flexibility and a high technological detail, the process-based modelling paradigm of the MARKAL/TIMES models has been used (Fishbone & Abilock, 1981), (Loulou et al., 2005). Thus, the model can be classified within the *bottom-up* category of models. The demand of each type of energy in each sector is an input to the model, which therefore follows a partial equilibrium approach with inelastic demand. In conclusion, this technology-rich model satisfies the (externally-fixed) energy demand for a country in a year with the objective of maximizing the sustainability of the resulting energy system.

For the second objective (describing the results in an easily understandable and transparent way) the *Sankey diagram* representation has been adopted. It has been found to effectively combine with the process-based modelling paradigm. Once the model is solved, Sankey diagrams provide an intuitive and schematic way of representing the model's output. It shows all the energy flows in a country, starting from primary energy imports/exports, total primary energy consumption, energy conversions, final[1] energy imports/exports, final energy transportation and distribution and lastly, final energy consumption per sector. Losses in all these processes are represented as well. These diagrams' main advantage is that they depict in a graphical and easily understandable way all the energy flows and, what is even more important, the relative magnitudes of all flows and processes.

Sankey diagrams can have many different topologies and representations. However, in the BP Chair on Energy and Sustainability, we develop a yearly Sankey diagram of the Spanish energy

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[1]Final energy stands for ready-to-use energy carriers, which have normally been converted from a primary energy source. Examples are electricity or oil products such as gasoline.

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system within the *Observatory on Energy and Sustainability* (López-Peña et al., 2011). The diagram corresponding to 2009 can be seen in Figure 1:
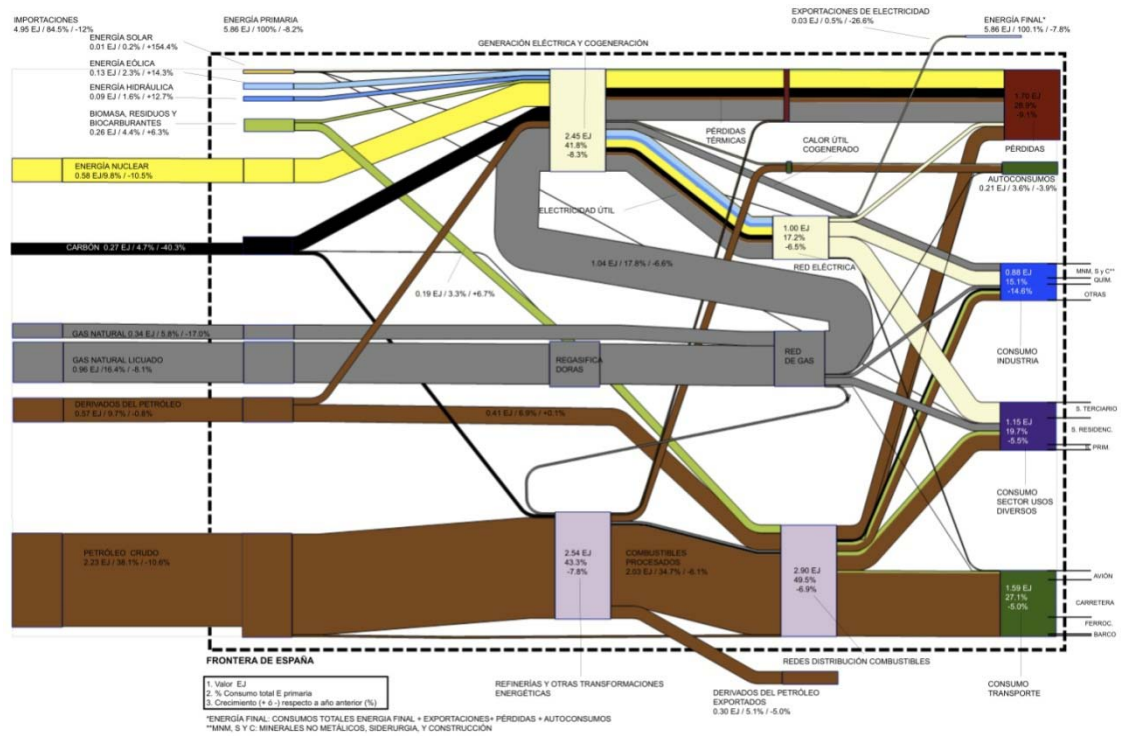

Figure 1: Sankey diagram of the Spanish energy sector in 2009. Source: (López-Peña, Danesin, et al., 2011)

The rest of this paper is devoted to describe, in great detail, the underlying philosophy of the model, including its hypothesis, mathematical formulation, parameters, and execution options, among other things.

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2 From the Sankey diagram to the process-based modelling approach

The above-shown Sankey diagram represents the actual Spanish energy system by using *boxes* and *energy flows* that go from *box* to *box*. But in order to develop a mathematical model based on it, an abstraction phase must be carried out first. It will allow us to convert each of those *boxes* in a *process*, which can be modelled as an element in a set of the optimization model. For example, the grey box in Figure 1 marked as "Regasificadoras" represents the liquefied natural gas regasification terminals. After this abstraction process, it will be an element of the set of *energy conversion* processes, because it can be said that it converts LNG into natural gas. Afterwards, the *energy flows* will be represented as variables of the mathematical model, as numbers that contain the information of how much energy is flowing from process to process. This abstraction procedure is going to be further explained now.

In the BP Chair's Sankey diagram shown in Figure 1, the dotted line represents the imaginary border of the country represented. Within it, four imaginary columns can be identified, as represented in Figure 2.
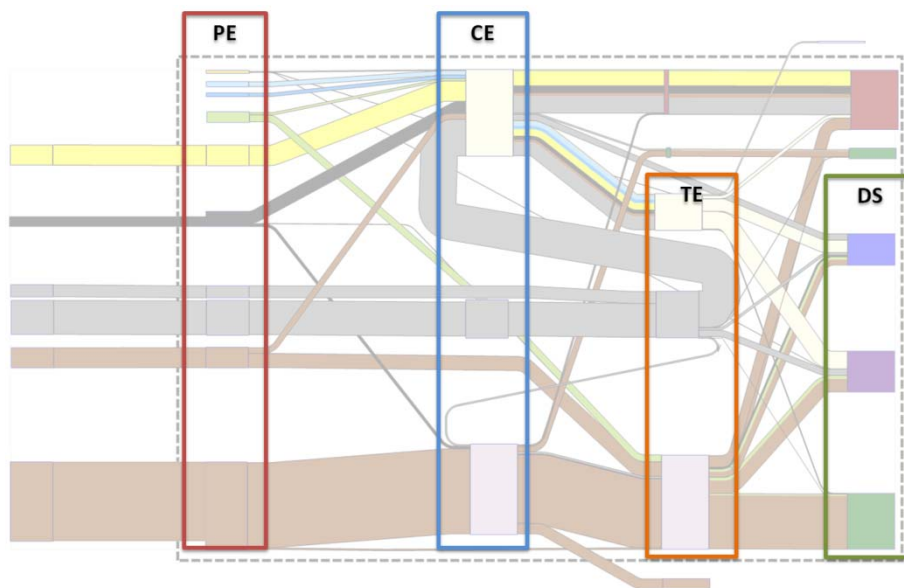

Figure 2: columns that can be identified within the Sankey diagram

The column PE (Primary Energy) represents the total amount of each type of primary energy (nuclear, natural gas, renewables,...) that is used by the country's energy system. The column CE (Conversion of Energy) represents the energy conversion processes, notably electricity generation (on top), oil refining (bottom) and liquefied natural gas (LNG) regasification (center). From these processes, some losses and self consumptions are produced, which are represented on the top right of the diagram. Below losses and self consumptions, the other two columns can be seen. TE stands for Transportation of Energy, and represents the energy transportation and distribution networks that deliver final energy to where it is demanded. Through these networks, final energy is delivered for final use. In the last column, DS stands for Demand Sectors, and represents the economic sectors that demand energy. In this case,

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three sectors are represented: industry on top, other uses (residential, services and agriculture) in the centre and transportation sector in the bottom. 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.

As said above, the Sankey diagram representation used in the optimization model is an abstraction of the scheme presented in the figures above, abstraction that has been done for being able to represent in the most general way different energy systems with different topologies (different processes and relations among them). This abstraction has been done with a similar philosophy as in MARKAL/TIMES models where the description of the energy system is carried out through processes, which can be seen as the *nodes* between which energy flows. These processes can be primary energy processes, energy conversion processes, energy transportation processes, demand sectors or regions with which energy is traded. In the representation done here, the energy flow between each pair of these processes is termed QPWR (standing for Quantity of Power, because it is measured in power units, normally GW), and the sub indexes mean the sense of this flow, as can be seen in Figure 3, where the primary and transformed energy imports and exports (from/to region *rg*) are as well represented. The flow of power going through each of these processes can be subject to a capacity restriction, and the model can decide to invest in new capacity in some of these processes. Therefore, the basic outcome of the LP model is the amount of power flowing between each two processes, as well as the investments in new capacities in some of them, if the model considers it as necessary. And this is calculated for meeting the externally-given energy demand while maximising sustainability.
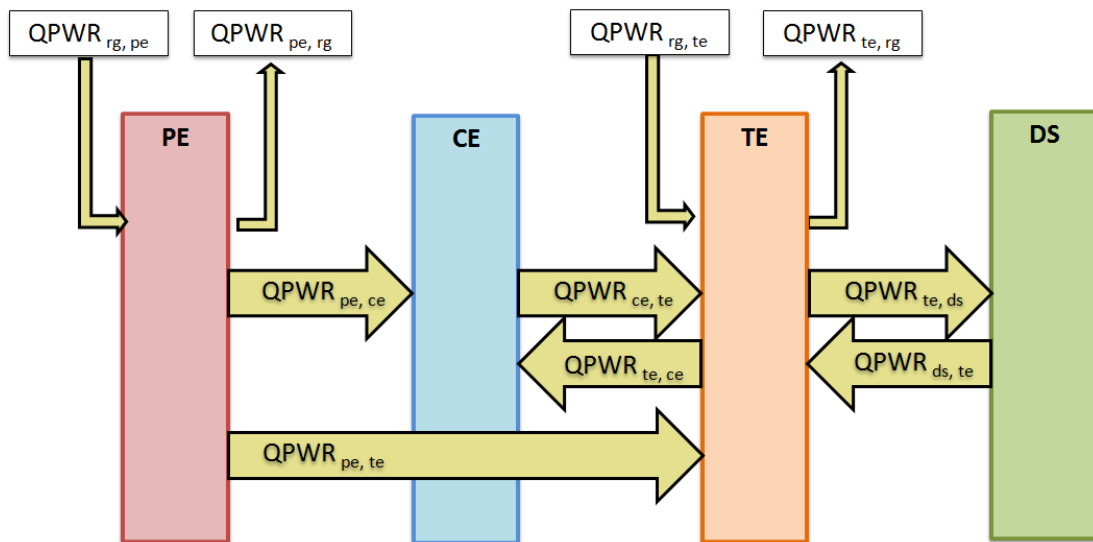

Figure 3: generalised Sankey diagram for modelling purposes.

In this linear programming model, the Sankey diagram is computed for each time slice (year, month, day, group of hours,...) in which the model is represented. It is calculated as an optimization problem programmed in GAMS language. This model will be described now in the usual optimization problems description way, which consists on describing its sets, its parameters, its variables, its constraints and finally, its objective function. For more details on

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GAMS, optimization problems and their related terminology (sets, parameters, variables, etc) refer to (Rosenthal, 2010).

3 Sets

3.1 Time definition

The first time-definition set is that of time horizon years, which, at the moment, is just one year given that this is a static model, i.e. it solves the problem only for one year. This set is characterized by the "y" symbol.

In this model, 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 needed, it is used here in order to be able to model the electricity part of the energy system with enough precision. 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 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).*

3.2 Processes

As stated in the introduction, the *processes* philosophy of the MARKAL/TIMES models is used here as well. In this model, the processes can be primary energy processes, energy conversion processes, energy transportation processes, demand sectors or regions with which energy is traded. They all belong to the *proc* set, which is composed of different subsets that are explained below:

- Demand sectors (DS, elements of the *ds* subset):

  They represent the sectors in the economy that are demanding energy. There can be as many as is desired.

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Example: *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. Refer to Figure 4:*

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_ROA	"DS Transportation Road"
DSTRA_RWY	"DS Transportation Railway"
DSTRA_AIR	"DS Transportation Air"
DSTRA_SEA	"DS Transportation Sea"

Figure 4: example of elements in the DS subset.

- Energy transportation processes (TE, elements of the *te* subset):

These represent the energy transportation and distribution networks that deliver final energy to demand sectors. These also include, in order to be strict with the conceptual structure of the model, energy that is transported through a very short distance. This is because it is converted and consumed in the same location. Examples could be heat and power in residential combined heat and power (CHP) stations, biomass in residential heating stations, or solar thermal for roofs. Each process transports one and only one final energy type. Some important hypotheses and conventions must be explained here. The first convention concerns the *Centralised* and *Distributed* TE types. The process "TE Electricity Centralised", for instance, represents the complete electricity grid, while "TE Electricity Distributed" represents the electricity networks that transport the electricity produced in distributed generation, such as in micro photovoltaic and micro CHP facilities. Therefore, the latter will have a lower losses factor. Something similar would be applicable for heat distribution networks, when used. The second hypothesis that must be explained is that the process "TE Coal" represents coal transportation, even if it is mainly done through trains and trucks, which could be seen as belonging to the Transportation DS (demand sectors). The costs are considered here, but not the emissions, which are accounted for in the Transportation sector. Something similar occurs with the various TE processes transporting oil products. Here the transportation is mainly done through oil pipelines and trucks, and perhaps through trains. This is also applicable to biomass (which is mainly local transport, done primarily with trucks) and biofuels. Contrarily, "TE Electricity Centralised" and "TE Natural Gas" can be considered as the actual electricity and natural gas networks, comprising of the physical infrastructure, the system operator and other associated elements.

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Example: in this version of the model, the TE processes were the ones represented in Figure 5:

TEELECE	"TE Electricity Centralised"
TEELEDI	"TE Electricity Distributed"
TEHEACE	"TE Heat Centralised"
TEHEADI	"TE Heat Distributed"
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"
TEBIOFUE	"TE Biofuel"
TEBIOMA	"TE Biomass"
TEOTREN	"TE Other Renewables"

Figure 5: example of elements in the TE subset.

- Energy Conversion Technologies (CE, elements of the *ce* subset):

These represent all the technologies used to transform primary energy sources into final energy that, through the TE processes, is transported and distributed for final uses. Among them, some special types should be described: the *centralised* power plants type represents the big power plants that transport their electricity through the grid whereas the *distributed* type accounts for the small plants installed at final uses and in distribution networks, such as *distributed electricity generation*. Not only electricity generation can be modelled with CE processes, but also oil refineries, biofuel production or LNG regasification.

Example: the energy conversion technologies considered at the moment are the following:

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CENUCLEAR	"CE Nuclear Power"
CENACOTRA	"CE National Coal Traditional"
CEIMCOTRA	"CE Imported Coal Traditional"
CENACOCCS	"CE National Coal with CCS"
CEIMCOCCS	"CE Imported 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"
CECHPWRCE	"CE Combined Heat and Power Centralised"
CECHPWRDI	"CE Combined Heat and Power Distributed"
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"
CESOPHVCE	"CE Solar Photovoltaic Centralised"
CESOPHVDI	"CE Solar Photovoltaic Distributed"
CESOTELCE	"CE Solar Thermoelectric Centralised"
CESOTHECE	"CE Solar Thermal Centralised"
CESOTHEDI	"CE Solar Thermal Distribited"
CEBIOMECCE	"CE Biomass Energy Crops Centralised"
CEBIOMAWCE	"CE Biomass Agriculture Waste Centralised"
CEBIOMFWCE	"CE Biomass Forestry Waste Centralised"
CEBIOMADI	"CEBiomass Distributed"
CESLDWAST	"CE Solid Waste "
CEMINIHYDR	"CE Mini Hydro"
CEREFINLOWC	"CE Refinery Low Complexity"
CEREFINHIGC	"CE Refinery High Complexity"
CEREFINVHIC	"CE Refinery Very High Complexity"
CEREGASIF	"CE Regasification Terminal"
CEBIOFUEPP	"CE Biofuel Production Plant"

Figure 6: example of elements in the CE subset.

Within the *ce* subset, there are some other subsets:

1. *celoadf*: stands for "CE processes modelled with load factors". It is the set of intermittent 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 was to be better represented, but due to data availability, the yearly load factor is the one used. ***Example:*** *only some renewable electricity generation technologies are represented for the moment. Currently, the technologies in this subset are the ones shown in Figure 7. Of these, MiniHydro's yearly load factor is later modified (in the InitialCalculations module) to obtain a monthly load factor depending of each month's hydraulicity but maintaining this yearly load factor as the average.*

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CEWINDONS1	"CE Wind Onshore 1st class best sites h
CEWINDONS2	"CE Wind Onshore 2nd class medium si
CEWINDONS3	"CE Wind Onshore 3rd class worst sites
CEWINDOFF	"CE Wind Offshore"
CESOPHVCE	"CE Solar Photovoltaic Centralised"
CESOTELCE	"CE Solar Thermoelectric Centralised"
CEMINIHYDR	"CE Mini Hydro"

Figure 7: example of elements in the CELOADF subset.

2. *ceelerelconstr*: stands for "CE processes affected by the electricity reliability constraints". Real large electricity systems must comply with some reliability conditions for their smooth and secure functioning. For a good explanation on the subject see (Batlle et al., 2007). In this model, 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 constraints are used to represent the technical conditions that must be preserved in the model's power system for it to be operated with enough reliability. The *adequacy* one, which affects the generation capacity investment decisions, is used for ensuring that enough firm capacity is installed on the system with a fair reserve margin over the yearly peak demand. The *reserves* constraint, which affects the electricity generation operation decisions, represents the need for enough idle flexible generation to cover the need for reserves. For more information refer to the description of these constraints further on in this document. In this model, the following hypothesis is considered: these constraints only apply to the electricity generation processes connected to the central power grid (i.e. the centralised ones, mainly). This subset is therefore used to identify, among all the CE elements, which are affected by these two reliability constraints. ***Example:*** *the elements of the "ce" subset that belong to the "ceelerelconstr" subset are shown in Figure 8:*

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CENUCLEAR	"CE Nuclear Power"
CENACOTRA	"CE National Coal Traditional"
CEIMCOTRA	"CE Imported Coal Traditional"
CENACOCCS	"CE National Coal with CCS"
CEIMCOCCS	"CE Imported 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"
CECHPWRCE	"CE Combined Heat and Power Centralised"
CEWINDONS1	"CE Wind Onshore 1st class best sites high load factor"
CEWINDONS2	"CE Wind Onshore 2nd class medium sites medium load facto
CEWINDONS3	"CE Wind Onshore 3rd class worst sites low load factor"
CEWINDOFF	"CE Wind Offshore"
CESOPHVCE	"CE Solar Photovoltaic Centralised"
CESOTELCE	"CE Solar Thermoelectric Centralised"
CEBIOMECCE	"CE Biomass Energy Crops Centralised"
CEBIOMAWCE	"CE Biomass Agriculture Waste Centralised"
CEBIOMFWCE	"CE Biomass Forestry Waste Centralised"
CESLDWAST	"CE Solid Waste "
CEMINIHYDR	"CE Mini Hydro"

Figure 8: example of elements in the CEELERELCONSTR subset.

- Primary energy sources (PE, elements of the *pe* subset):

  These account for the total primary energy used in each moment, be it domestic or imported, renewable or non renewable.

  Example: *these primary energy sources are shown in Figure 9.*

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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"
PEWINON	"PE Wind Onshore"
PEWINOF	"PE Wind Offshore"
PESOLPV	"PE Solar Photovoltaic "
PESOLTE	"PE Solar Thermoelectric"
PESOLTH	"PE Solar Thermal"
PEBIOMEC	"PE Biomass Energy Crops"
PEBIOMAW	"PE Biomass Agriculture Waste"
PEBIOMFW	"PE Biomass Forestry Waste"
PESWAST	"PE Solid Waste"
PEMNHY	"PE Mihi Hydro"
PEBIOFPI	"PE Biofuel Production Inputs"

Figure 9: example of elements in the PE subset.

Within the *pe* subset, there are some other subsets:

1. *pelimey*: 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. **_Example:_** *the elements belonging to this subset are listed in Figure 10.*

PEBIOMEC	"PE Biomass Energy Crops"
PEBIOMAW	"PE Biomass Agriculture Waste"
PEBIOMFW	"PE Biomass Forestry Waste"
PESWAST	"PE Solid Waste"

Figure 10: example of elements in the PELIMEY subset.

- Energy trade regions (elements of the *rg* and *dr* subsets):

Representing the regions in the model, with which the modelled energy system can exchange both primary and final energy, where each region has different prices and different exchange capacities.

Example: *as a first approach, a mainly geographical division has been done. Economic or trading division could be done as well (OPEC, OECD, etc.). Refer to Figure 11.*

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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"

Figure 11: example of elements in the RG subset.

For modelling needs, the domestic region, which represents autochthonous energy supply, has also been created. It is the only element in the "dr" subset.

| DOMEST | "Domestic Region" |

Figure 12: element in the DR subset.

3.3 Demand Management Measures

Demand Management Measures (DMM, elements of the *dmm* set): represent the possible policies and measures that the central authority in the country (government, regulator,...) could implement to affect energy demand (for instance aiming at improving efficiency, promoting fuel switching, etc). Each of these DMMs will have an associated investment cost (to be paid by the government, and therefore by the entire society) and some effects on DS energy demands, as will be seen later on. ***Example: the current considered DMMs are the ones shown in Figure 13. It must be taken into account that in this model's version (Florence) the system was studied until 2008 so no future DMMs (like electric cars promotion) were introduced.***

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ECODRIVING	"Eco Driving principles for car drivers"
TELECONFERENCE	"Teleconference incentives for businesses"
TYREINFLATION	"Promote correct tyre inflation in Cars"
BIOFUELS7PC2008	"7% share of biofuels in 2008"
FUELSAVDEVCARS	"Promote fuel saving devices in cars"
URBANBIKINGCITY2	"Promote urban biking in all cities bigger than 200k inhabitants"
CARSCRAPPING	"Promote car scrapping"
REGBRAKEMETRO	"Install regenerative brakes in Metro"
RISEFUELTAXES	"Rise fuel taxes for particular cars"
ACCESSTOLLCITY20(	"Install access tolls in cities bigger than 200k inhabitants"
IMPROVEDAIRTRAF	"Improved air traffic opetarions"
RAILWAYFREIGHT	"Increase freight by railway, decreasing truck"
FREIGHTINSHIPATH	"Promote freight in ship in Athlantic coast"
RATIONALLIGHTING	"Rational lighting systems residential sector"
RATIONALCOOLING	"Rational cooling systems residential sector"
RATIONALHEATING	"Rational heating systems residential sector"
EFFICIENTAPPLRESI	"Efficient appliances residential sector"
EFFICIENTELECTRRE	"Efficient electronics residential sector"
EFFICIENTTYRES	"Efficient tyres for cars"
EFFICIENTBOILERS	"Efficient boilers for residential sector"
IMPROVEDTHERMA	"Improved thermal insulation for residential sector"
DOUBLEWINDOWS	"Double windows for better insulation in residential sector"
IN-FLOORRADIANT|	"In-floor radiating heating devices in residential sector"
SOLARWATERHEAT|	"Solar thermal water heating in residential sector"

Figure 13: example of elements in the DMM subset.

3.4 Possible energy flows

The energy system's definition, once the processes (DS, TE, CE, PE and RG) have been defined, is completed allowing energy to flow among them. This is done through the definition of energy flows, which are the possible flows that energy can follow, with a determined sense (i.e. from A to B, but not from B to A). For example, "PE nuclear" (nuclear fuel) can only be used in CE nuclear power plants, whereas PE biomass can be used in CE biomass power plants, in CE biofuel production plants, or distributed for final consumption through the TE biomass process. These flows determine the topology of the energy system in the studied year, and given that this topology is something that may want to be changed (for modelling a new solar technology, for instance), 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 a DS (formerly considered FE, standing for *final energy*, but it's an equivalent notation)), *teceflows* (flows from a TE to a CE), and finally *fefeflows* (flows from a DS to a TE). ***Example:*** *these double sets, defining possible energy flows, are currently the ones in the "_Flows" sheet in the Florence Data Excel book. The main underlying hypotheses in this current implementation follow:*

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1. *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.*

2. *Liquefied natural gas passes through the regasification process before entering the natural gas network.*

3. *Given than in this model's implementation (Florence version) we are looking at years 1996-2008, distributed electricity generation is not considered, because in these years it could be considered to be small.*

4. *As cogeneration in these years was quite small, cogeneration is accounted for in the sectors demanding final energy (be it biomass, natural gas or others).*

4 Parameters

In this *Parameters* section, all the numerical data exogenous to the model is 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, this differentiation has not been carried out, for the sake of simplicity.

4.1 General parameters

- CO2PRICE: carbon price in €/tCO$_2$ used for valuating the social cost of carbon emissions (the value of the externality) in the objective function.

- 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.

- GENAMORTRATE: (GENeral AMORTization RATE): general interest rate used for investments amortization.

- CEHYPSTORCYEF: (CE HYdro Pumping STORage Cycle EFficiency): efficiency of the pumping storage cycle in CEHYPSTOR.

- CERESMRG4ADEQ: (CE REServe Margin For ADEQuacy): required <u>firm capacity</u> reserve margin over yearly peak electricity demand, for the adequacy constraint applied to the elements of the *ceelerelconstr* set.

- CEDEMAVGPRERR4RSRV: (CE DEMand Average Prediction ERRor For Reserves): average prediction error in demand, for the reserves constraint applied to the elements of the *ceelerelconstr* set.

- CELOADFAVGPRERR4RSRV: (CE LOAD Factor Average PREdiction ERRor For Reserve): average forecast error in electricity produced by intermittent power plants (the ones in the set *celoadf*), for reserves constraint. Applied over their mean yearly production, for the reserves constraint.

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- CELARGCEFPROB4RSRV: (CE LARGe CE Failure PROBability For Reserve): largest electricity generation plant failure probability (for reserves constraint).

- CELARGCECAP4RSRV: (CE LARGe CE CAPacity For Reserve): largest electricity generation plant failure size (for reserves constraint).

- $D_{p,s,l}$: duration in hours of each load level The values are 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.

4.2 DS Parameters

- DMMCOSTYEAR $_{dmm}$: yearly promotion cost for the government of implementing each DMM. It is the incremental cost that the society faces when adopting this DMM, i.e. if ultra efficient car purchase is promoted, the cost of the measure is not the complete cost of the car (because people would have bought a normal car instead of the ultra efficient car), but the cost difference between the ultra efficient and the normal car. Taxation is considered to be neutral because it represents pure wealth redistribution amongst society and it is supposed to cause no distortions in the economy. Amortization of investments is done at *government perspective* for computing yearly cost: 10 years and 5% interest rate.

- QFDEMD$_{te,ds,p,s,l}$: stands for Quantity Final Demand Data, and represents the energy demand data for final energy type *te* (the type of final energy transported through process *te*) in demand sector *ds* during the time slice defined by "*p,s,l*". It should not be interpreted as the *energy services* demand, because final use technologies are not represented and therefore energy losses in final use are included here as well. In other words, this final energy demand represents the final energy services (expressed in energy units) plus the losses in final energy use. It is expressed in power units (GW) for each time slice.

- NSFECOST $_{te,ds}$: stands for Non-Supplied Final Energy Cost and it does <u>not</u> measure the utility of unserved energy demand. For electricity, for instance, this utility of unserved demand is considered to be somewhere between 200 and 5,000 €/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 *te* in all demand sectors *ds*. 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.

- FEUEMISSF$_{te,ds}$: stands for Final Energy Use Emissions Factor and represents the unitary CO_2 emissions produced when each type of final energy *te* is used in each demand

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sector *ds*. The values are applied to the actual energy consumed by the demand sector, not to the associated *energy service*. In other words, the energy lost in these final uses also produces emissions because it is indeed consumed. The values have been estimated using the annual National Emissions Inventory prepared by the Spanish Environment Ministry.

- FESWITCHMAX $_{ds,te,te'}$: stands for Maximum possible Final Energy Switch and it is a preliminary attempt to model energy switching in final demand sectors. It is the maximum percentage of demand of energy *te* in sector *ds* (the demand given through the QFDEMD parameter) that could be supplied by energy *te'*. If final energy switching is allowed, the model can choose to supply up to that percentage of *te* demand in *ds* with *te'*, and it will do so if it is better from the global optimization perspective. This switching, however, does not have any elasticity or cost associated, so the costs, needed for the investments in energy-use equipment that would in reality allow for these switches, are not considered in the model. This will be improved when the actual DS processes are modeled, the ones that convert from final energy to energy services: in these, possible technologies will be modeled and their associated costs will be considered. For the Florence case in May 2011, switching was not allowed.

- DMMPOT $_{dmm,ds,te}$: stands for Demand Management Measure Potential, and represents the effect that the measure with the *dmm* index produces in the demand in sector *ds* of the energy type *te*, expressed in % as the original demand of that *te* in the *ds*. For instance, imposing a biodiesel penetration target for road transportation can make diesel demand (demand of "TEOPDIE") decrease 1% in the *ds* element "DSTRA_ROA", but at the same time it can make biofuel ("TEBIOFUE") demand increase by 70% in the same *ds*. This would be represented the following way: DMMPOT $_{BIODIETARGET, DSTRA\_ROA, TEOPDIE}$ = -0.01 and DMMPOT $_{BIODIETARGET, DSTRA\_ROA, TEBIOFUE}$= +0.70.

4.3 TE Parameters

- TECAP$_{te}$: 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 <u>input</u>. 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 a very high level so that they do not become active limitations.

- TELF$_{te}$: represents the total energy losses in each transportation process, measured as a percentage of the <u>incoming</u> energy. For instance, if the electricity grid has a losses factor of 9%, for delivering 100 MW, the amount of electricity generated (input to the electricity grid) must be 109.9MW, so that (100%-9%)*109.9MW=100MW.

- ECOVCTE$_{te}$: stands for the 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 in the process, and it is measured in €/MWh. It is 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

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for both the physical infrastructure levelised costs and its operation costs (system operator allowances, etc). It can also be a relevant cost for biomass delivery, given its low energy content per volume unit.

- $CO2EFTE_{te}$: stands for the CO_2 Emission Factor of each TE, that is, the unitary CO_2 emissions produced per unit of transported energy, measured in tCO_2/MWh. It is applied to the <u>incoming</u> energy of the process. At the moment, the emissions produced in the gas network are not considered because they are methane emissions, not CO_2 ones, and methane is not considered in this model. The emissions produced by the trains and trucks used to transport biomass, oil products, coal and biofuels are accounted for in the transportation DS. Electricity grids do not produce any emissions. Therefore, for the moment, these factors are null for all TEs.

4.4 CE Parameters

- $CEPREVCAP_{ce}$: represents the CE process's previous capacity, that is, the capacity installed prior to the model's execution, expressed in GW. This capacity is considered to be already fully paid, so the annuity of its investment costs is not considered in the objective function. This may underestimate the energy system's costs. However, this is not a problem if the study aims at comparing system costs, because in this case, it is just a constant that would disappear when comparing costs. On the other hand, if the absolute system cost is needed, the residual economic value of the previous capacity must be added, and its annuity added to the objective function. These capacities are measured in the process's total <u>output</u>, 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).

- $CECAPTOTINVSTCOST_{ce}$: stands for CE Capacity Total Investment Cost, and measures the total investment cost per unit of capacity of a CE process (measured over the process's useful output as explained above). The word *total* implies that it is the complete cost that must be paid over the investment's amortization period. It is measured in €/kW.

- $CECAPAMORTYEARS_{ce}$: stands for CE Capacity Amortization years, and represents the amortization years of a new investment in CE capacity, that is, the number of years of annuity. This should normally be the *technical life* of the process or, if for taxing purposes the private companies amortize the investment in fewer years, the desired amount of years (which is sometimes called *economic life*). Given that the model is a static one (represents only one year), the different technical lives of different technologies (and thus, different amortization periods) can influence the calculation of each technology's annuity and therefore, the investment decisions made in that one year. This problem is not present in a dynamic problem (representing several years), where the complete cash flow associated to an investment over its complete life is considered. In a static problem, if a constant amortization formula (interests + capital giving a constant annuity throughout all the period) is chosen, the amount of years does not have too large of an influence on the relative values of the annuity. In this model, this amortization formula is used. Moreover, in order to completely eliminate this parameter's influence on the model's results, the following hypothesis is made: a constant value of 20 years is used for all processes, irrespective of their real physical life.

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- CECAPRISKPREM$_{ce}$: stands for CE Capacity Risk Premium, and represents the risk premium (over the general market amortization rate) that an investment in a certain CE process implies for the investor, measured in %. It is added to the GENAMORTRATE value for calculating the interest rate with which a particular investment in a CE process is amortized. This parameter can be used for representing the additional risk that investments in some technologies (e.g. nuclear) can imply for the investor.

- ACECAPFIXDCOSTYEAR$_{ce}$: stands for Active CE Capacity Fixed Costs per Year, and represents the yearly fixed costs of keeping *active* a unit of CE capacity. 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 a year, saving its fixed 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, which in this model's terminology, means to not activate that power plant.

- CELF$_{ce}$: represents the total energy losses in each conversion process CE, measured as a percentage of the <u>incoming</u> energy. It accounts for both energy losses and self consumptions. For a modern combined cycle gas turbine with 60% efficiency, this parameter is 40%.

- CEMAXACTIVECAP$_{ce}$: represents the maximum active capacity possible in a CE, measured in GW. This is especially useful for limiting the amount of capacity installed by the model in certain technologies with physical limitations like renewables such as hydro, which has a limited potential. This is also used for representing wind power, where three types of wind power plants with decreasing load factor and limited active capacity are used for representing resource potential.

- CELOADFACTOR$_{celoadf}$: for the conversion processes modeled with load factor (elements of the *celoadf* set), this value is its yearly average load factor. That is the % of equivalent hours in the year functioning at full power that would produce the same energy as the one produced in an actual average year. This load factor is modified for the minihydro technology with the monthly hydraulicity HYDRONRGMONTH$_p$. Therefore, in months with more hydraulicity the load factor is bigger, but always keeping the given yearly one (the data in CELOADFACTOR) as the average throughout all the periods in a year. For wind power (best resource quality), for instance, this value is 24%.

- CEFIRMNESS4ADEQ$_{ceelerelconstr}$: stands for CE Firmness For Adequacy, and represents the amount of *firm* capacity that each unit of this CE's capacity adds to the system, with regards to calculating the *adequacy* constraint of the system. As previously mentioned, this constraint establishes that the 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. For instance, in this model, wind power is supposed to have a firmness factor of 7.5%: each GW of installed capacity provides the system with 75MW of *firm* capacity.

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- CEFLEXIBILITY4RSRV$_{ce,elerelconstr}$: stands for CE Flexibility For Reserves, that is, the measurement of how flexible this technology is for the *reserves* constraint. 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 output. In this 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$_{ce,te}$: stands for 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 transformed 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, 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 *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 document. For each CE, the values of CEINSHARETE$_{ce,te}$ and CEINSHAREPE$_{ce,pe}$ for all TEs and PEs must add 100%.

- CEINSHAREPE$_{ce,pe}$: stands for 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%.

- CEMAXTEOUTSHARE$_{ce,te}$ and CEMINTEOUTSHARE$_{ce,te}$: 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 is restricted through these parameters, which are measured in %. This is particularly useful for modeling oil refineries, where a more modern and flexible refinery will have wider limits on the shares, or where a refinery with a coker would reduce the shares of heavy products and increase the shares of light ones. All this is done with these two parameters.

- ECOVCCE$_{,ce,te}$: 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.

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- CO2EFCE$_{ce,te}$: CO_2 Emissions factor of producing each unit of output TE in each conversion process CE. They are measured in tCO_2/MWh.

- CEFIXEDPROD$_{ce,te,p,s,l}$ and CEFIXEDTECONS$_{ce,te,p,s,l}$: 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. This may be useful, for example, for pumping storage modeling if electricity prices are not sufficiently different between peak and offpeak periods and therefore pumping storage units do not function. However, these parameters must be used with great care because if not correctly coordinated with other model's parameters (such as possible energy flows, capacity constraints or CE input and output share limitations) they may make the optimization problem infeasible.

4.5 PE Parameters

- PEDOMCONSCAP$_{pe}$: domestic primary energy consumption capacity. Used for modeling 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 wants 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 must be used.

- PEMAXECONSYEAR$_{pelimey}$: stands for 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 production in the country in a year.

- ECOVCPEDOM$_{pe}$: stands for Economic Variable Cost of Domestic PE (primary energy) production, and 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.

- CO2PEDOMEF$_{pe}$: CO_2 Emissions factor of domestic primary energy production, measured in tCO_2/MWh. This parameter is especially useful for modeling emissions from activities such as coal mining.

- PEID$_{pe}$: stands for PE Import Dependence and 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.

- HYDRONRGMONTH$_{p}$: stands for Hydro Energy per Month, and represents the hydraulicity or 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": partly for the run-off-the-river hydro power plants and the rest for the reservoir capacity hydro power plants. The amount of hydro energy used by minihydro power plants ("Régimen Especial") is not included in this parameter.

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Normally this parameter is set to the hydraulicity 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$_p$: stands for Run-off-the-River Energy Share. As mentioned in the previous paragraph, available hydraulic energy is used by the model for the run-off-the-river and for the reservoir capacity power plants. This parameter establishes the share of energy that, each month, is used in run-off-the-river plants. The actually-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.

4.6 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$_{rg,te}$: the import capacity of final energy TE (maximum imported energy) measured in GW from region *rg*.

- TEIMPCOST$_{rg,te}$: the importation cost of each unit of final energy TE from region *rg*, measured in €/MWh.

- TEEXPCAP$_{te,rg}$: the export capacity of final energy TE (maximum exported energy) measured in GW to region *rg*.

- TEEXPREVE$_{te,rg}$: the export revenue of each unit of final energy TE to region *rg*, measured in €/MWh.

- PEIMPCAP$_{rg,pe}$: the import capacity of PE (maximum imported energy) measured in GW from region *rg*. Modeling hypothesis: 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$_{rg,pe}$: the importation cost of each unit of PE from region *rg*, measured in €/MWh.

- PEEXPCAP$_{pe,rg}$: the export capacity of PE (maximum exported energy) measured in GW to region *rg*.

- PEEXPREVE$_{pe,rg}$: the export revenue of each unit of PE to region *rg*, measured in €/MWh.

5 Variables

The main decision variables in this model belong to four groups:

- The useful energy flows (QPWR) from one process to another in the energy supply chain, as well as the level of unsupplied final energy.

- The level of application of Demand Management Measures.

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- The level of application of final energy switching (this can be disabled in this version of the model).

- The capacities in the conversion processes, both the new capacity additions decided by the model and the active capacity that it decides to use (it can choose to not have some of the previously installed capacity active, therefore saving the fixed O&M costs of that capacity).

- The amount of reserves that each of the electricity generation technologies affected by the reliability constraints are providing.

The graphical representation of the energy flows, already introduced in this document's introduction, can be graphically seen in Figure 14:
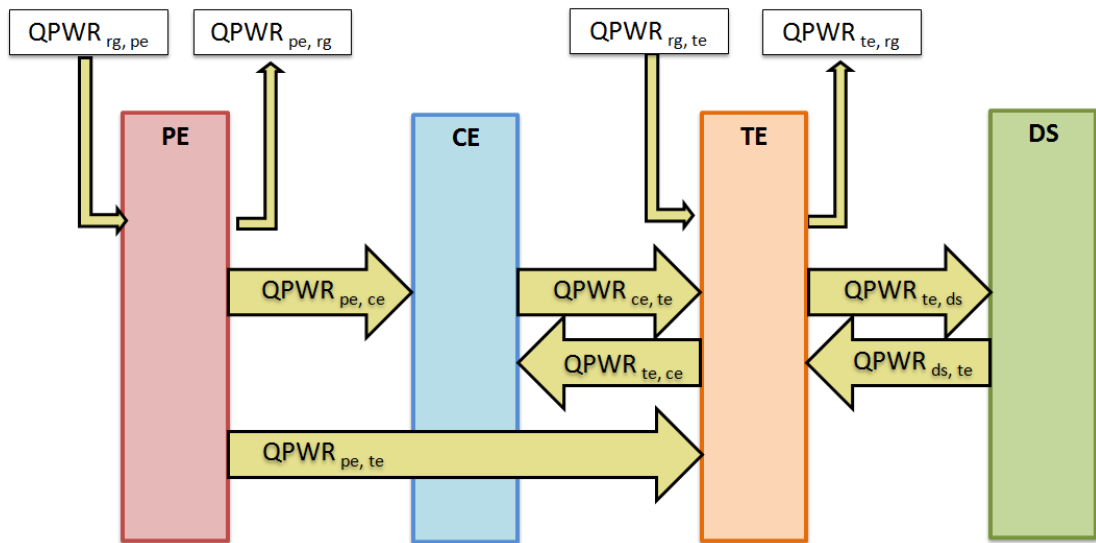
Figure 14: possible energy flows represented in the model. Note: in this figure, for greater simplicity, the time indexes (p,s,l) have been omitted because the figure represents the energy flows in a time instant, a snapshot of the energy system. In the real mathematical formulation all variables have the time sub indexes p,s,l, in addition to the ones represented in the figure.

In general, the flow variables of the system are expressed as $QPWR_{proc, proc, p, s, l}$: quantity of power (expressed in GW) that in each instant flows from *proc* to *proc* in period *p*, sub-period *s*, and level *l*. Given that the set *proc* has different subsets, as explained above, the real flows that have been defined are the ones shown in the figure and are described in greater detail below. Notice the importance of the sub-indexes' order: it gives the sense of the flow. In these QWPR variables below, the subsets *p*, *s* and *l* have been omitted for greater simplicity, but these variables are calculated for each time slice. Given that the order of the sub-indexes represents the flow sense, all these QPWR variables are positive variables.

- $QPWR_{rg, pe}$: positive variable, quantity of imported primary energy *pe* from region *rg*.

- $QPWR_{pe, rg}$: positive variable, quantity of exported primary energy *pe* to region *rg*.

- $QPWR_{pe, ce}$: positive variable, quantity of primary energy *pe* used in conversion process *ce*.

- $QPWR_{pe, te}$: positive variable, quantity of primary energy *pe* directly transported to final uses in *te*.

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- QPWR $_{ce, te}$: positive variable, quantity of final energy flowing from *ce* to *te*.

- QPWR $_{te, ce}$: positive variable, quantity of final energy of type *te* used in conversion *ce*.

- QPWR $_{rg, te}$: positive variable, quantity of imported transformed energy *te* from region *rg*.

- QPWR $_{te, rg}$: positive variable, quantity of exported transformed energy *te* to region *rg*.

- QPWR $_{te, ds}$: positive variable, quantity of transformed energy *te* used in demand sector *ds*.

- QPWR $_{ds, te}$: positive variable, quantity of transformed energy *te* given back from demand sector *ds*.

In addition to the flow variables, the non supplied energy is represented through the following variable:

- QNSFE $_{te, ds, p, s, l}$: positive variable, quantity of non supplied final energy of type *te* in demand sector *ds*, in period p, subperiod *s* and level *l*, expressed per unit of time, therefore in power units (GW).

For the level of application of Demand Management Measures, the following variable is used:

- DMMLVL$_{dmm}$: positive variable, limited to a maximum value of 1. Represents the level of application of the Demand Management Measure *dmm* in the year, expressed in per-unit terms: if the value is 0, this DMM is not applied at all, if the value is 0.6, this DMM is applied at 60%, and therefore 60% of its effects are born by the energy system, and 60% of its cost is computed in the system's total cost in the year.

For the level of application of final energy switching, the following variable is used:

- FESWITCH $_{ds,te,te',p,s,l}$: positive variable that represents the amount of demand of energy type *te* in sector *ds* that is covered with energy type *te'*, in the time slice defined by *p,s* and *l*. Measured in GW. As already mentioned, final energy switching can be deactivated in this version of the model, in which case this variable takes null value.

In order to represent the model's decisions in active capacity and new investments, the following variables are used:

- PREVACTIVECAP$_{proc}$: Previously installed capacity (CEPREVCAP$_{ce}$ or its equivalent in other processes) of process *proc* that the model decides to use and therefore activates (having to pay its fixed O&M costs) in the year (GW).

- NEWINSTALLCAP$_{proc}$: Newly installed capacity of process *proc* available in the year, measured in GW. If the model decides to install more capacity, it is because it needs it and therefore it will always activate it. Hence, the model must pay, for this new active capacity, both the investment's annuity and the fixed O&M costs in the year.

Concerning the reliability constraints, the processes affected by them (elements of the *ceelerelconstr* set) have to comply with two conditions, as stated above: one of *adequacy* and one of *reserves*. The *adequacy* constraint has to do with the system's installed capacity, and therefore it is sufficiently characterised through the investment variables described in the previous paragraph. The *reserves* constraint does need a new variable for its characterization:

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- CEELERSRVPWR$_{ce,p,s,l}$: positive variable that represents the reserve power (in GW) that each electricity generation process is providing to the system, through idle capacity, in each time slice.

6 Constraints

6.1 Constraints in DS

6.1.1 Power balance in each demand sector

Power balances must be correctly met in every demand sector in all time slices. The power balance restriction (expressed in GW) is expressed here, followed by its definition. Although it is not activated in this version of the model, there is the possibility of power flowing back from the DS to the TE process, in order to be able to model some specific technologies such as electric cars giving power back to the electricity grid.

The shadow price of this restriction has been represented with the Greek letter ρ, and in the current version of the model (minimisation of total private cost of energy supply, see objective function description) represents the price of each type of energy in each demand sector and in each time slice. This is because it is the marginal cost for the system of providing an extra unit of demand.

$$\forall\, te, ds, p, s, l \;\; :$$ $$QPWR_{te,ds,p,s,l} - \sum_{feteflows(ds,te)} QPWR_{ds,te,p,s,l} + QNSFE_{te,ds,p,s,l}$$ $$= QFDEMD_{te,ds,p,s,l} + \sum_{dmm}\left(DMMLVL_{dmm} \cdot DMMPOT_{dmm,ds,te} \cdot QFDEMD_{te,ds,p,s,l}\right)$$ $$+ \sum_{te'} FESWITCH_{\,ds,te',te,p,s,l} - \sum_{te'} FESWITCH_{\,ds,te,te',p,s,l} \qquad [GW]$$ $$\perp\;\; \rho_{te,ds,p,s,l}$$ *For all final energy types reaching each demand sector, and in all periods of time:* *power served from the transportation process TE* *- power delivered back to transportation processes* *+ non supplied energy (in power units) =* *final energy demand (data)* *+increments in this energy type's demand due to the effect of DMMs* *+demand of other types of energy (te') covered with this TE through switching* *- demand of this type of energy covered with other types of TE (te') through switching*	Equation 1

6.1.2 Fuel switching limitation

The amount of fuel switching (in GW) is limited by the FESWITCHMAX $_{ds,te,te'}$ parameter, using this constraint.

$$\forall\, ds, te, te', p, s, l \,/\, te \neq te' \;\; :$$ $$FESWITCH_{\,ds,te,te',p,s,l} < FESWITCHMAX_{\,ds,te,te'} \cdot QFDEMD_{te,ds,p,s,l} \qquad [GW]$$ *In each sector, for all combinations of TEs except the same repeated one, in all time slices:* *quantity of this type of energy covered with other types of TE (te') through switching (in GW)* *< maximum allowed switching allowed for this TE in this DS with other types of TEs (te')* *expressed in GW, which is calculated by multiplying the unitary amount with demand*	Equation 2

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6.2 Constraints in TE

6.2.1 Power balance in each transport process

Power balances must be correctly met in every transport process in all time slices. 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 supposed that this amount of energy travels through the whole grid and thus, produces lost energy. Concerning gas network's technical constraints, this simple energy balance suffers for its correct representation, considering as true these two (very plausible) hypotheses: constant pressure, and that only operative gas is being used (usage of gas bed supposed to be null).

$$\forall \, te, p, s, l \quad :$$ $$TOTQTEIN_{te,p,s,l} - QLTE_{te,p,s,l} = TOTQTEOUT_{te,p,s,l} \qquad [GW] \qquad where:$$ $$TOTQTEIN_{te,p,s,l} = \sum_{peteflows(pe,te)} QPWR_{pe,te,p,s,l} + \sum_{ceteflows(ce,te)} QPWR_{ce,te,p,s,l}$$ $$+ \sum_{feteflows(ds,te)} QPWR_{ds,te,p,s,l} + \sum_{rg} QPWR_{rg,te,p,s,l}$$ $$QLTE_{te,p,s,l} = TELF_{te} \cdot TOTQTEIN_{te,p,s,l}$$ $$TOTQTEOUT_{te,p,s,l}$$ $$= \sum_{teceflows(te,ce)} QPWR_{te,ce,p,s,l}$$ $$+ \sum_{tefeflows(te,ds)} QPWR_{te,ds,p,s,l} + \sum_{rg} QPWR_{te,rg,p,s,l}$$ *For all transportation processes in all periods of time:* *Total incoming power – losses = total outgoing power, where:* *Total incoming power is the sum of power from all PE, CE and DS 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 and DS processes, plus exports*	Equation 3

6.2.2 Capacity constraint in each transport process

The total incoming power to a transportation process cannot be greater than its capacity.

$$\forall \, te, p, s, l \quad :$$ $$TOTQTEIN_{te,p,s,l} < TECAP_{te} \qquad [GW]$$ *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)*	Equation 4

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6.3 Constraints in CE

6.3.1 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 below.

$\forall ce, p, s, l \quad / ce \neq \text{"CE Pumping Storage"}$: $TOTQCEIN_{ce,p,s,l} - QLCE_{ce,p,s,l} = TOTQCEOUT_{ce,p,s,l} \qquad [GW] \qquad where:$ $TOTQCEIN_{ce,p,s,l} = \sum_{\text{peceflows}(pe,ce)} QPWR_{pe,ce,p,s,l} + \sum_{\text{teceflows}(te,ce)} QPWR_{te,ce,p,s,l}$ $QLCE_{ce,p,s,l} = CELF_{ce} \cdot TOTQCEIN_{ce,p,s,l}$ $TOTQCEOUT_{ce,p,s,l} = \sum_{\text{ceteflows}(ce,te)} QPWR_{ce,te,p,s,l}$ *For all conversion processes except pumping storage, in all periods of time:* *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*	Equation 5

6.3.2 Share limitations in power flows outgoing from CE processes

As previously mentioned, one CE process can produce more than one flow of transformed 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. It may be useful to limit the maximum and minimum shares that each outgoing flow can represent in the total output. This is done through the above-mentioned CEMAXTEOUTSHARE$_{ce,te}$ and CEMINTEOUTSHARE$_{ce,te}$ parameters, that are used in these share-limitation constraints. These are mainly used for modeling oil refining processes.

As defined above: $TOTQCEOUT_{ce,p,s,l} = \sum_{\text{ceteflows}(ce,te)} QPWR_{ce,te,p,s,l}$ $\forall ceteflows(ce,te), p, s, l$: *Maximum share limitation:* $QPWR_{ce,te,p,s,l} < TOTQCEOUT_{ce,p,s,l} \cdot CEMAXTEOUTSHARE_{ce,te} \qquad [GW]$ *Minimum share limitation:* $QPWR_{ce,te,p,s,l} > TOTQCEOUT_{ce,p,s,l} \cdot CEMINTEOUTSHARE_{ce,te} \qquad [GW]$ *For all CEs and TEs linked by an allowed energy flow, in all periods of time:* *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.*	Equation 6

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6.3.3 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). This can be used for improving model's accuracy. The shares of each PE or TE that a process must use in order to produce each unit of output are specified in the above-mentioned CEINSHAREPE$_{ce,pe}$ and CEINSHARETE$_{ce,te}$ parameters, that are used in these constraints.

As defined above: $$TOTQCEIN_{ce,p,s,l} = \sum_{peceflows(pe,ce)} QPWR_{pe,ce,p,s,l} + \sum_{teceflows(te,ce)} QPWR_{te,ce,p,s,l}$$ *PE share definition*: $$\forall\, peceflows(pe,ce), p, s, l:$$ $$QPWR_{pe,ce,p,s,l} = TOTQCEIN_{ce,p,s,l} \cdot CEINSHAREPE_{ce,pe} \quad [GW]$$ *TE share definition*: $$\forall\, teceflows(te,ce), p, s, l:$$ $$QPWR_{te,ce,p,s,l} = TOTQCEIN_{ce,p,s,l} \cdot CEINSHARETE_{ce,te} \quad [GW]$$ *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.*	Equation 7

6.3.4 Energy conservation in pumping storage power generation process

The pumping storage electricity generation is supposed to be all pure pumping storage, i.e. no natural hydro inflows. Therefore, in the pumping storage process, 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. Daily pumping storage regime has been supposed, which is a reasonable hypothesis for the Spanish case. Additionally, it has been assumed that these power plants are connected to the centralised electricity grid, that is, to "TE Electricity Centralised".

$$\forall\, p, s :$$ $$\sum_{l} \left(QPWR_{\text{"CE Pumping Storage","TE Elec Centr"},p,s,l} \cdot D_{p,s,l} \right) =$$ $$\sum_{l} \left(QPWR_{TE\,Elec\,Centr,"CE\,Pumping\,Storage",p,s,l} \cdot D_{p,s,l} \cdot CEHYPSTORCYEF \right) \quad [GWh]$$ *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%)*	Equation 8

6.3.5 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. This implies the hypothesis that no water is kept from one month to another. 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. The

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amount of hydro energy available each month is determined by the hidraulicity parameter HYDRONRGMONTH, after subtracting from it the amount of hydro energy used by Run-off-the-river power plants, as done below with the RURIVNRGSHARE parameter. As with pumping storage, it is supposed that these power plants are connected to the centralised power grid.

$\forall p:$ $$\sum_{s,l}\left(QPWR_{\text{"CE Hydro Reservoir Capacity","TE Elec Centr"},p,s,l} \cdot D_{p,s,l}\right) =$$ $$HYDRONRGMONTH_p \cdot \left(1 - RURIVNRGSHARE_p\right) \qquad [GWh]$$ *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)*	Equation 9

6.3.6 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 hydraulicity parameter. Of all this available hydro energy in each month, the share of run-off-the-river energy is expressed by RURIVNRGSHARE. And then 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 supposed that these power plants are connected to the centralised power grid.

$\forall p, s, l:$ $$QPWR_{\text{"CE Hydro Run-off-the-river","TE Elec Centr"},p,s,l} =$$ $$\frac{HYDRONRGMONTH_p \cdot RURIVNRGSHARE_p}{\sum_{s,l} D_{p,s,l}} \qquad [GW]$$ *For all months of the year (for all periods), in each time slice (subperiod and level):* *Power generated in run-off-the-river plants (in GW) =* *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 divided by the duration of the month, in hours.*	Equation 10

6.3.7 CE processes' capacity limitations

Each CE process must comply with a main capacity limitation: its total <u>outgoing</u> power flow cannot be bigger than its *total* active capacity. The term *total* means that it can be either previous capacity or new one decided by the model (in this case, the annuity of the investment costs is considered in the total costs of the system). 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, this capacity cannot produce any output. On the other hand, the electricity generation processes affected by the reliability constraints (reserves and adequacy) may have to have some idle capacity (active but not producing

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electricity) providing reserves to the system (for more detail on these reliability constraints see below). Therefore, as shown next, the addition of total outgoing power plus idle capacity providing reserves cannot be greater than the total active capacity of the process.

$As\ defined\ above$: $$TOTQCEOUT_{ce,p,s,l} = \sum_{ceteflows(ce,te)} QPWR_{ce,te,p,s,l}$$ $$\forall\ ce, p, s, l :$$ $$TOTQCEOUT_{ce,p,s,l} + CEELERSRVPWR_{ce,p,s,l} < TOTACTIVECAP_{ce} \qquad [GW]$$ $$TOTACTIVECAP_{ce} = PREVACTIVECAP_{ce} + NEWINSTALLCAP_{ce} \qquad [GW]$$ $$PREVACTIVECAP_{ce} < CEPREVCAP_{ce} \qquad [GW]$$ $$TOTACTIVECAP_{ce} < CEMAXACTIVECAP_{ce} \qquad [GW]$$ *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)*	Equation 11

6.3.8   Reserves constraint for electricity generation CEs

In large power systems, there is always a degree of uncertainty in the load that power plants have to provide. This is due to the imprecision 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 large power systems imply that load and generation must be in balance all the time, so if there is a sudden increase in load (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. In conclusion, the restriction 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 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, 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 *ceelerelconstr* set. As previously mentioned, these elements are the electricity generation processes connected to the main centralised electricity network (the centralised TE

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electricity process). From another perspective, another modelling hypothesis will be commented next. In reality, three 100MW groups are able to provide more reserves to the system than one 300MW group, because their technical flexibility is greater than that of a 300MW group. In this model it is supposed that the reserve given by three 100 MW groups equals the one given by one 300MW group.

$$
\forall\, p, s, l \quad :
$$

$$
\sum_{ceelerelconstr} \left(CEELERSRVPWR_{ce,p,s,l} \cdot CEFLEXIBILITY4RSRV_{ce} \right) >
$$

$$
CELARGCECAP4RSRV
$$
$$
+
$$
$$
\left(\sum_{ds} QFDEMD_{"TE\ Elec\ Centr",ds,p,s,l} \right) \cdot CEDEMAVGPRERR4RSRV
$$
$$
+
$$
$$
\left(\sum_{celoadf} \left(TOTACTIVECAP_{ce} \cdot CELOADFACTORP_{ce,p} \right) \right) \cdot CELOADFAVGPRERR4RSRV
$$
$$
[GW]
$$

For all periods of time:
Total reserve of the system (capacity of ceelerelconstr processes giving reserves and multiplied by the flexibility factor) >
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, it is modified with the monthly hydraulicity, but keeping as average the yearly value given through data.

Equation 12

6.3.9   Adequacy constraint for electricity generation CEs

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. However, it is not only about *how much* capacity but as well about *which* capacity. It must be capable to produce in the peak moments, where the system is under stress. The ability of a technology to produce electricity, with a high probability, in these stress moments, is what in this model is called *firmness factor* (refer to Batlle et al., 2007). By multiplying this factor and the installed capacity of a technology, the *firm capacity* is obtained. For instance, in this model, wind power is supposed to have a firmness factor 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) on 75MW of production at peak times. This constraint is used to impose that the firm capacity in the system must be greater than the maximum yearly demand (peak demand) multiplied by the required reserve margin (normally 10% excess capacity ever peak demand).

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$$\sum_{ceelerelconstr} (TOTACTIVECAP_{ce} \cdot CEFIRMNESS4ADEQ_{ce}) >$$ $$(1 + CERESMRG4ADEQ) \cdot MAXDEMYR_{"TE\ Elec\ Centr"} \quad [GW]$$ $Where:$ $$MAXDEMYR_{"TE\ Elec\ Centr"} = \max_{p,s,l}\left(\sum_{ds} QFEDEMD_{"TE\ Elec\ Centr",ds,p,s,l}\right)$$ *The total firm capacity (total active capacity*firmness factor) of technologies affected (elements of the ceelerelconstr set) >* *Peak demand of central electricity increased by the reserve margin (CERESMRG4ADEQ).* *The peak demand is the maximum yearly value of the total demand of centralised electricity in all demand sectors.*	Equation 13

6.3.10 Production in CE processes modelled with load factors

Some elements of the *ce* set are modelled with load factors, as stated above. These elements belong to the *celoadf* subset. These constraints, using the CELOADFACTOR$_{celoadf}$ parameter, establish the production of each of these processes.

$$\forall\ celoadf, p, s, l \quad :$$ $$TOTQCEOUT_{ce,p,s,l} =\ TOTACTIVECAP_{ce} \cdot CELOADFACTORP_{ce,p} \quad [GW]$$ *For all CE processes modelled with load factors, in all periods of time:* *Total outgoing power = CE process's total active capacity * monthly load factor* *Note: CELOADFACTORP is the load factor in each period (month). For all technologies except for minihydro it equals the yearly data CELOADFACTOR. For minihydro, it is modified with the monthly hydraulicity, but keeping as average the yearly value given through data.*	Equation 14

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6.4 Constraints in PE

6.4.1 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 the primary energy used in the energy system (be it for conversion in CE processes, for delivery to final uses in TE 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). Primary energy exports will normally not take place in countries such as Spain, but the modelling allows it in any case.

$$\forall \, dr, pe, p, s, l \quad :$$

$$TOTQPEOUT_{pe,p,s,l} \;=\; QPWR_{dr,pe,p,s,l} + \sum_{rg} QPWR_{rg,pe,p,s,l} \qquad [GW] \qquad where:$$

$$TOTQPEOUT_{pe,p,s,l} =$$

$$\sum_{\text{peceflows(pe,ce)}} QPWR_{pe,ce,p,s,l} \;+\; \sum_{\text{peteflows(pe,te)}} QPWR_{pe,te,p,s,l} \;+\; \sum_{rg} QPWR_{pe,rg,p,s,l}$$

$$QPWR_{dr,pe,p,s,l} \;=\; \left(1 - PEID_{pe}\right) \cdot TOTQPEOUT_{pe,p,s,l}$$

Equation 15

For all primary energy processes in all periods of time (and in the domestic region dr):
Total outgoing 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.
The total outgoing power is the addition of the power used in CE processes, the one delivered for final use in TE processes, 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.

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.

6.4.2 Domestic PE production capacity limitation

The amount of primary energy production in the country can be limited, in power terms, through this constraint.

$$\forall \, dr, pe, p, s, l \quad :$$

$$QPWR_{dr,pe,p,s,l} \;<\; PEDOMCONSCAP_{pe} \qquad [GW]$$

Equation 16

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

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.

6.4.3 PE consumption energy limitation

The total amount of primary energy consumption in the country can be limited through this constraint, is only applied to the elements of the *pelimey* set. It is important to understand the difference between this restriction and the previous one: the previous one limits domestic energy, whereas this one limits all primary energy consumption, be it imported or domestic.

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$\forall\ pelimey\ :$ $$\sum_{p,s,l}\bigl(TOTQPEOUT_{pe,p,s,l}\cdot D_{p,s,l}\bigr)<\ PEMAXECONSYEAR_{pelimey}\qquad[GWh]$$ *For all primary energy processes with limited energy in the year:* *The total consumed energy off this type throughout the complete year (power*duration) <* *yearly energy limitation* *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.*	Equation 17

6.5   Constraints in EI

6.5.1   PE import capacity limitation

The imported PE power cannot be bigger than the import capacity.

$\forall\ pe,rg,p,s,l\ :$ $$QPWR_{rg,pe,p,s,l}<\ PEIMPCAP_{pe,rg}\qquad[GW]$$ *For all regions, primary energy processes, and time slices in the year:* *Imported power < import capacity*	Equation 18

6.5.2   PE export capacity limitation

The exported PE power cannot be bigger than the export capacity.

$\forall\ pe,rg,p,s,l\ :$ $$QPWR_{pe,rg,p,s,l}<\ PEEXPCAP_{pe,rg}\qquad[GW]$$ *For all regions, primary energy processes, and time slices in the year:* *Exported power < export capacity*	Equation 19

6.5.3   TE import capacity limitation

The imported TE power cannot be bigger than the import capacity.

$\forall\ te,rg,p,s,l\ :$ $$QPWR_{rg,te,p,s,l}<\ TEIMPCAP_{te,rg}\qquad[GW]$$ *For all regions, energy transportation processes, and time slices in the year:* *Imported power < import capacity*	Equation 20

6.5.4   TE export capacity limitation

The exported TE power cannot be bigger than the export capacity.

$\forall\ te,rg,p,s,l\ :$ $$QPWR_{te,rg,p,s,l}<\ TEEXPCAP_{te,rg}\qquad[GW]$$ *For all regions, energy transportation processes, and time slices in the year:* *Exported power < export capacity*	Equation 21

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7   Objective function:

As stated in this document's introduction, the linear programming model in question satisfies the given energy demand for a year while maximising sustainability of the resulting energy system. In other words, the objective function of the optimization problem is a measure of the energy system's sustainability, and the model tries to maximise it while satisfying the model's restrictions, its main one being demand satisfaction as expressed in section 6.1.1.

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, *sustainable* is considered to be an *energy system of minimum cost for society*. In this cost, both private costs and externalities are accounted for. The considered private costs are purely economic costs of energy supply, that is to say, domestic energy production costs, primary and final energy importation costs minus exportation revenues, energy conversion and transportation fixed and variable costs, new capacity investments' costs, and so on.

Along with these private costs, the cost of unsupplied energy is computed too. As was explained in section 4.2, in this version of the model unserved demand is highly penalised in the objective function, so that the model never chooses to leave unserved demand, that is, always satisfying demand completely. This has been done because in the literature on the subject there is a lack of accurate estimates of the final users' utility of energy consumption. For electricity, for instance, this utility is considered to be somewhere between 200 and 5,000 €/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. Hence, in this model it has been decided to set this parameter at a very high price (10,000€/MWh) for all types of final energy in all demand sectors, so that the model never leaves any unserved demand. The implications of this are that this term of the objective function cannot be considered as the lost utility of unserved demand. Rather, it is a penalisation for unsupplied energy. The underlying reason for this modelling is to have some flexibility in the LP model in order for it to decide to leave some unserved demand (although highly penalised) if the model's constraints impose it, therefore avoiding infeasibilities in the optimization problem.

Up to here, the model minimises private costs of energy supply for a country, which is equivalent to maximising the utility of society if the hypothesis of perfect energy markets is made.

However, in order to improve this characterization and make it evolve into a comprehensive evaluation of sustainability, the externalities of the energy supply born by society must also be considered in the objective function. The considered externalities should represent, in a broad way, the sustainability of the energy system in all its aspects (environmental, economic and social). These externalities could be quantified in money terms, and therefore added to the objective function directly, or, if this is not possible, some kind of multi-objective optimization

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should be used. For instance, results from the ExternE project could be used, where the value of several energy externalities was assessed.

In this first version of the model, only one externality is considered: the social cost of carbon emissions. A good study on the social cost of carbon emissions is (Pearce, 2003). This cost is included by multiplying an externally-given CO_2 price (CO2PRICE) by the total CO_2 emissions (not just those covered by the emissions trading scheme). For example, the total energetic CO_2 emissions in Spain in 2008 were 320 Mt, if they have a social cost of 30€/tCO_2, this would imply a total social cost of CO_2 emissions of 9.6 billion €, nearly 0.6% of Spanish GDP in that year.

The full objective function, which the optimization model minimises, is the following.

$min \{DOPECONSCOST + DOPECOEMCOST + PEIMPORTCOST -$ $PEEXPORTREVE + CECONVERCOST + CECONVEMCOST + CELERSRVCOST +$ $ACAPFIXDCOST + NCAPINVSCOST + TETRANSPCOST + TETRANEMCOST +$ $TEIMPORTCOST - TEEXPORTREVE + FEUEMISSCOST + DMMPROMOCOST +$ $NONSUPFECOST \qquad [M€]$ $min \begin{cases} Domestic\ primary\ energy\ cost \\ +Domestic\ primary\ energy\ production\ emissions\ social\ cost \\ +Primary\ energy\ imports\ cost \\ -Primary\ energy\ exports\ revenue \\ +Energy\ conversion\ variable\ cost \\ +Energy\ conversion\ emissions\ social\ cost \\ +Cost\ of\ the\ provision\ of\ electricity\ reserves\ by\ generators \\ +Active\ capacity\ fixed\ cost \\ +New\ capacity\ investment\ cost\ (annuity) \\ +Energy\ transportation\ cost \\ +Energy\ transportation\ emissions\ social\ cost \\ +Final\ energy\ imports\ cost \\ -Final\ energy\ exports\ revenue \\ +Final\ energy\ use\ emissions\ social\ cost \\ +Demand\ management\ measures\ promotion\ costs \\ +Non\ supplied\ energy\ cost\ (penalisation) \end{cases}$	Equation 22

All the listed terms will now be explained, and important hypothesis will be mentioned.

Domestic primary energy cost (e.g. coal mining or biomass production):

$$DOPECONSCOST = \sum_{dr,pe,p,s,l} \left(QPWR_{dr,pe,p,s,l} \cdot D_{p,s,l} \cdot ECOVCPEDOM_{pe}\right) \qquad [M€]$$ *Domestic primary energy cost* *=energy (power* duration) produced in the country in the year* *(flowing from the domestic region dr) multiplied by the unitary energy production cost*	Equation 23

Domestic primary energy production emissions social cost:

$$DOPECOEMCOST = CO2PRICE \cdot \sum_{pe,p,s,l} \left(EMPE_{pe,p,s,l} \cdot D_{p,s,l}\right) \qquad [M€]$$ Where: $$EMPE_{pe,p,s,l} = QPWR_{dr,pe,p,s,l} \cdot CO2PEDOMEF_{pe} \qquad [tCO_2/h]$$ *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*	Equation 24

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Primary energy imports cost:

$$PEIMPORTCOST = \sum_{rg,pe,p,s,l} \left(QPWR_{rg,pe,p,s,l} \cdot D_{p,s,l} \cdot PEIMPCOST_{pe,rg} \right) \quad [M€]$$ *Primary energy imports cost =* *imports from each region (power*duration)*import cost from that region*	Equation 25

Primary energy exports revenue:

$$PEEXPORTREVE = \sum_{pe,rg,p,s,l} \left(QPWR_{pe,rg,p,s,l} \cdot D_{p,s,l} \cdot PEEXPREVE_{pe,rg} \right) \quad [M€]$$ *Primary energy exports revenue =* *exports to each region (power*duration)*export revenue from that region*	Equation 26

Energy conversion variable cost (considers only O&M costs, because the costs of fuel are accounted for as imports costs):

$$CECONVERCOST = \sum_{ceteflows(ce,te),p,s,l} \left(QPWR_{ce,te,p,s,l} \cdot D_{p,s,l} \cdot ECOVCCE_{ce,te} \right) \quad [M€]$$ *Energy conversion variable cost (only O&M costs) =* *Total amount of energy (power*duration) of each type of TE produced by the process*unitary variable O&M cost of the conversion process*	Equation 27

Energy conversion emissions social cost:

$$CECONVEMCOST = CO2PRICE \cdot \sum_{ceteflows(ce,te),p,s,l} \left(EMCE_{ce,te,p,s,l} \cdot D_{p,s,l} \right) \quad [M€]$$ 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)*	Equation 28

Cost of the provision of electricity reserves by affected generators: this cost element accounts for the cost of having enough reserves in the system to comply with the reserves constraint as explained in section 6.3.8. The unitary cost of providing reserves by each generator is supposed to be equal to its variable O&M cost which, as stated above, does not consider fuel costs. In other words, it is supposed that generators providing reserves to the system are functioning (and therefore, must pay variable O&M costs) but do not burn any fuel. This cost element is defined as follows:

$$CELERSRVCOST = \sum_{ceelerelconstr,p,s,l} \left(CEELERSRVPWR_{ceelerelconstr,p,s,l} \cdot D_{p,s,l} \cdot CEELERSRVCOST_{ceelerelconstr} \right)$$ $$[M€]$$ *Cost of the provision of electricity reserves by affected generators (elements of ceelerelconstr)* *= Reserves provided by affected generators*duration of those reserves*reserves unitary cost*	Equation 29

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The term of active capacity fixed cost includes the fixed O&M costs of all processes (CE, TE processes, interconnections, etc). In this version of the model, only the fixed costs of CE processes are considered:

$$ACAPFIXDCOST = \sum_{ce}(TOTACTIVECAP_{ce} \cdot ACECAPFIXDCOSTYEAR_{ce}) \qquad [M€]$$ *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*	Equation 30

The term of new capacity investment cost includes the annuity of the investment costs of all processes (CE, TE processes, interconnections, etc). Although, in this version of the model, only the investment costs of CE processes are considered (they are the only processes where the model can increment the capacity). This annuity is computed using the linear amortization method, where the annual payments of investment depreciation are constant all over the asset's life.

$$NCAPINVSCOST = \sum_{ce}(NEWINSTALLCAP_{ce} \cdot NEWICAPINVCOSTYEAR_{ce}) \qquad [M€]$$ *Where:* $$NEWICAPINVCOSTYEAR_{ce} =$$ $$CECAPTOTINVSTCOST_{ce} \cdot \frac{AMORTRATE_{ce}}{\left(1 - \left(\frac{1}{1+AMORTRATE_{ce}}\right)^{CECAPAMORTYEARS_{ce}}\right)} \quad \left[\frac{€}{kW \cdot year}\right]$$ *Being:* $$AMORTRATE_{ce} = GENAMORTRATE + CECAPRISKPREM_{ce} \qquad [\%]$$ *New capacity investment cost = new installed capacity in all affected processes (for the moment just CE) * 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 (CECAPTOTINVSTCOST), 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).*	Equation 31

Energy transportation costs:

$$TETRANSPCOST = \sum_{te,p,s,l}(TOTQTEIN_{te,p,s,l} \cdot D_{p,s,l} \cdot ECOVCTE_{te}) \qquad [M€]$$ *Energy transportation costs =* *Total energy transported in all each processes (total incoming power*duration), multiplied by the unitary transport costs*	Equation 32

Energy transportation emissions social cost:

$$TETRANEMCOST = CO2PRICE \cdot \sum_{te,p,s,l}(EMTE_{te,p,s,l} \cdot D_{p,s,l}) \qquad [M€]$$ *Where:* $$EMTE_{te,p,s,l} = TOTQEIN_{te,p,s,l} \cdot CO2EFTE_{te} \qquad [tCO_2/h]$$ *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)*	Equation 33

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Final energy imports cost:

$$TEIMPORTCOST = \sum_{rg,te,p,s,l} \left(QPWR_{rg,te,p,s,l} \cdot D_{p,s,l} \cdot TEIMPCOST_{te,rg} \right) \quad [M€]$$ *Final energy imports cost =* *imports from each region (power*duration)*import cost from that region*	Equation 34

Final energy exports revenue:

$$TEEXPORTREVE = \sum_{te,rg,p,s,l} \left(QPWR_{te,rg,p,s,l} \cdot D_{p,s,l} \cdot TEEXPREVE_{te,rg} \right) \quad [M€]$$ *Final energy exports revenue =* *exports to each region (power*duration)*export revenue from that region*	Equation 35

Final energy use emissions social cost (accounts for the emissions produced in energy use by final demand sectors):

$$FEUEMISSCOST = CO2PRICE \cdot \sum_{tefeflows(te,ds),p,s,l} \left(EMFE_{te,ds,p,s,l} \cdot D_{p,s,l} \right) \quad [M€]$$ *Where:* $$EMFE_{te,ds,p,s,l} = QPWR_{te,ds,p,s,l} \cdot CO2EFTE_{te} \quad [tCO_2/h]$$ *Final energy use emissions social cost=* *Social cost of carbon, as represented by CO2PRICE multiplied by the total emissions produced in energy consumption (all TE types in all DS processes)*	Equation 36

Demand management measures promotion costs:

$$DMMPROMOCOST = \sum_{dmm} (DMMLVL_{dmm} \cdot DMMCOSTYEAR_{dmm}) \quad [M€]$$ *Demand management measures promotion costs= Level of application of each DMM*each DMM promotion cost (if applied completely)*	Equation 37

Non-supplied energy cost (as stated above, it is a penalisation, it does not represent the utility un unserved demand):

$$NONSUPFECOST = \sum_{tefeflows(te,ds),p,s,l} \left(QNSFE_{te,ds,p,s,l} \cdot D_{p,s,l} \cdot NSFECOST_{te,ds} \right) \quad [M€]$$ *Non-supplied energy cost = Total unsupplied energy of each type of final energy in each demand sector, multiplied by the unsupplied energy cost (penalisation)*	Equation 38

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8   Execution modes and options

8.1   Execution modes

The model can be executed in three modes:

- **Mode 1. Only operation:** the model cannot invest in any new capacity, or in demand management measures. The objective function therefore does not include these two terms. The variables $NEWINSTALLCAP_{proc}$ and $DMMLVL_{dmm}$ are obliged to be null. Final energy switching is not allowed either, i.e. $FESWITCH_{ds,te,te',p,s,l}$ variables are also obliged to be null.

- **Mode 2. Investment with previous capacity:** the model can invest in any new capacity (over the previously installed one), or in demand management measures. The previously installed capacity is given through external data. The objective function includes all terms.

- **Mode 3. Investment without previous capacity (*greenfield*):** the model can invest in any new capacity, or in demand management measures. The previously installed capacity is null. The objective function includes all terms. For the same demand and equal parameters, the objective function in this execution mode will normally take higher values than in mode two, because the model has to invest in all the capacity that, in mode two, is considered as previously installed (and free of investment costs for the model).

8.2   Execution options

- **Consider social cost of CO_2 emissions:** the social cost of CO2 emissions is only accounted for in the objective function if this execution option is activated.

- **Include adequacy constraint:** the adequacy constraint over electricity generation capacity is only applied if this execution option is activated.

- **Include reserves constraint:** the reserves constraint over electricity generators is only applied if this execution option is activated.

- **Demand Management Measures allowed:** DMMs application level is obliged to be null for all *dmms* unless this option is activated.

- **Final Energy Switching allowed:** final energy switching ($FESWITCH_{ds,te,te',p,s,l}$) is obliged to be null unless this option is activated.

9   Computer implementation

This model is programmed in GAMS, and solved with the CPLEX optimizator. With the level of data detail used in the Florence case study, it is a LP model with around 140,000 single equations and 140,000 variables. On a computer with an Intel Core2 Quad processing unit (four processors at 3GHz each) and 3.2 GB of RAM memory, data reading from Excel and model generation takes around 4 seconds, and then it is solved by CPLEX in 0.2 seconds.

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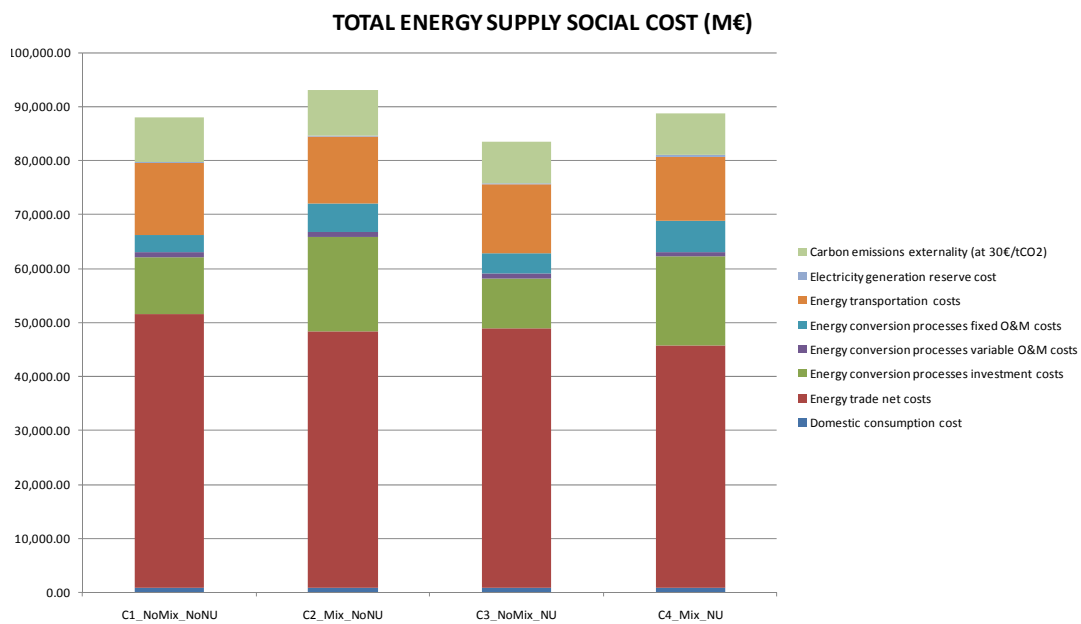*First version: September 2011. This version: February 2013*

10 Outputs of the model

10.1 Total CO₂ emissions produced within the energy system

The total carbon emissions of the system are easily calculated from previous variables applying the following expression:

$$TOTEM = \sum_{pe,p,s,l} \left(EMPE_{pe,p,s,l} \cdot D_{p,s,l}\right) + \sum_{ceteflows(ce,te),p,s,l} \left(EMCE_{ce,te,p,s,l} \cdot D_{p,s,l}\right)$$ $$+ \sum_{te,p,s,l} \left(EMTE_{te,p,s,l} \cdot D_{p,s,l}\right) + \sum_{tefeflows(te,ds),p,s,l} \left(EMFE_{te,ds,p,s,l} \cdot D_{p,s,l}\right)$$ $$[MtCO_2]$$ *Total energetic emissions= Emissions in primary energy production + Emissions in energy conversion + Emissions in energy transportation + Emissions in final energy use*	Equation 39

10.2 Example of some other model's outputs

First of all, the different elements of the objective function can be obtained separately and represented in a graph where the total social cost of energy supply under different scenarios is shown (Figure 15):

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Energy supply social cost (M€2010)	C1_NoMix_NoNU	C2_Mix_NoNU	C3_NoMix_NU	C4_Mix_NU
Domestic consumption cost	802.10	897.92	824.78	904.08
Energy imports costs	64,111.41	60,905.00	61,476.58	58,137.68
Energy conversion processes investment costs	10,437.47	17,412.15	9,240.98	16,590.60
Energy conversion processes variable O&M costs	1,076.91	936.25	970.33	826.09
Energy conversion processes fixed O&M costs	3,157.78	5,162.26	3,659.26	5,709.37
Energy transportation costs	13,212.47	12,407.04	12,822.91	11,868.20
Exports revenue	-13,334.64	-13,336.52	-13,337.65	-13,336.52
Electricity generation reserve cost	222.12	301.24	222.12	287.28
TOTAL ENERGY SUPPLY PRIVATE COST (M€)	79,685.62	84,685.34	75,879.30	80,986.80
as a % of the 2030 GDP in €2010	4.9%	5.2%	4.7%	5.0%
Carbon emissions externality (at 30€/tCO2)	8,334.90	8,334.90	7,651.14	7,856.99
TOTAL ENERGY SUPPLY SOCIAL COST (M€)	88,020.52	93,020.24	83,530.44	88,843.78
as a % of the 2030 GDP in €2010	5.4%	5.7%	5.2%	5.5%

Figure 15: example of energy supply social costs under four scenarios.

The electricity generation throughout all of the demand levels in a year can also be easily represented, as can be seen in Figure 16.
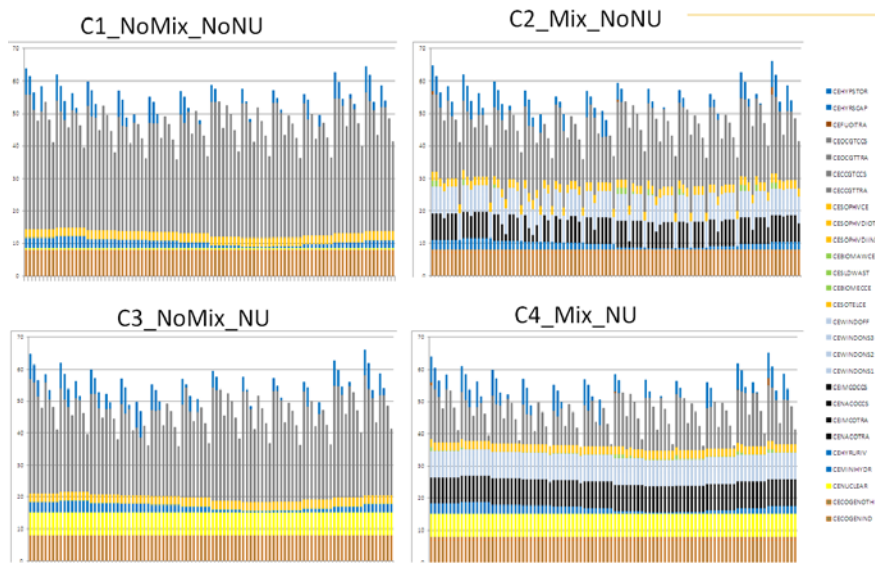
Figure 16: example of the yearly electricity generation (96 load levels) under four scenarios.

The capacities (previous, new, and active) in CE processes can be represented, as shown in Figure 17, where the previous capacities are in blue, the newly installed ones in red, and the active capacity are marked with a black line. The model is investing mainly in CCGT generators, and in regasification capacity. Concerning oil refining, the model has, as previously installed, some low complexity refineries (CEREFINLOWC) which are not being used at all, and some high complexity ones (CEREFINHIGC) which are completely used.

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Figure 17: example of the representation of CE capacities.

As stated in this document's introduction, the model has been conceived over the Sankey diagram philosophy, so all energy flows can be easily represented in a Sankey diagram. An example is shown in Figure 18: example of the representation in a Sankey diagram of the energy flows obtained with the model.Figure 18.

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Figure 18: example of the representation in a Sankey diagram of the energy flows obtained with the model.

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11 References

Batlle, C., Vázquez, C., Rivier, M., & Pérez-Arriaga, I. (2007). Enhancing Power Supply Adequacy in Spain: Migrating from Capacity Payments to Reliability Options. *Energy Policy*, *35*(9), 4545-4554. doi:10.1016/j.enpol.2007.04.002

Fishbone, L. G., & Abilock, H. (1981). MARKAL, A Linear-Programming Model for Energy Systems Analysis: Technical Description of the BNL Version. *International Journal of Energy Research*, *5*(4), 353-375.

López-Peña, Á., Danesin, A., Linares, P., Pérez-Arriaga, I., Fernández, A., & Dias Bleasby, R. (2011). *Observatorio de Energía y Sostenibilidad en España 2010*. Madrid: BP Chair On Energy and Sustainability. Retrieved from http://www.upcomillas.es/catedras/bp/Documentos/Actividades/Observatorio/Febrero2011/InformeObservatorio_2010_Act.pdf

López-Peña, Á., Linares, P., & Pérez-Arriaga, I. (2011). Renewables in the Spanish Energy Sector: a Cost-Efficiency Evaluation for CO2 Emissions Reduction. Presented at the Workshop "The Cost of Renewable Energy in the EU," European University Institute, Florence, Italy.

Loulou, R., Remne, U., Kanudia, A., Lehtila, A., & Goldstein, G. (2005). Documentation for the TIMES Model, Part I: General Description of the TIMES Paradigm.

Pearce, D. (2003). The Social Cost of Carbon and its Policy Implications. *Oxford Review of Economic Policy*, *19*(3), 362 -384. doi:10.1093/oxrep/19.3.362
Rosenthal, R. E. (2010). GAMS - A User's Guide.