Measuring energy sustainability

A new operational framework based on weak and strong indicators

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This dissertation is submitted for the degree of
Doctor of Philosophy

November 2018

I would like to dedicate this thesis to my beloved children Rosalía and Miguel Ángel. They are the origin and destiny of all my energy…

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements.

José Carlos Romero Mora
November 2018

Acknowledgements

And I would like to acknowledge so many people who have made it possible for this document to become real.

First of all, I would like to thank my thesis tutor, Pedro Linares, for his unwavering confidence in this doctoral candidate and for his infinite patience. Without his wise accompaniment, this work would have never seen the light of day.

To my family: my parents, my grandparents and my brother Antonio to whom I owe absolutely everything.

To my partner Ana, who has accompanied this whole process from the background with infinite patience and affection.

To the cave: Alessandro, Renato, Álvaro, Adela, Pablo, Zarrar,..., and all those who once inhabited it. From mere research colleagues we became friends able to share fatigue, illusions, successes and failures.

To the Society of Jesus. She was the one who put me on the track of this road, and she was the one who decided to support it, regardless of the cost and the circumstances.

To my AVELE friends, Quijotes in a world of windmills. The strength of their principles inspired me deeply.

And to all those who I do not mention here but who know very well that are part of this. Thank YOU.

Abstract

This thesis is aimed at offering an operational framework for energy sustainability studies capable of describing the reciprocal relations between the energy subsystem, the society and the environment that supports it. This new framework is based on a set of indicators that encompass in a complementary way the classical approaches to sustainability, i.e. weak and strong, from which this problem has traditionally been addressed. In summary, this thesis wants to offer a consistent framework aimed at helping the structuring of the goal, i.e. moving towards a sustainable model, and the decision-making process in the energy sector.

More specifically, this is an integrated proposal for a weak-strong sustainability analysis based on indicators that addresses, on the one hand, the challenge of creating value in aggregated terms while respecting critical natural capital and, on the other hand, the challenge of assuring a fair allocation of this value. The compatibility of the weak-strong proposal has been tested in a concrete regional application, i.e. the sustainability study of the Spanish Costa del Sol between 2007 and 2015.

The process of defining the appropriate framework and the suitable indicators for energy sustainability analysis places particular emphasis on two specific aspects, namely understanding the role of exergy as a strong indicator of sustainability and the role of energy poverty as an equity variable representing energy affordability. With respect to the first, a critical analysis of the potential of this exergetic approach to the study of the sustainability of energy systems, in its different variants, has been carried out. With respect to the second, the main indicators of energy poverty in the literature have been critically reviewed and calculated for Spain. In addition, an alternative methodology has been proposed for the indicator based on the Minimum Income Standard (MIS) that corrects some of the issues identified.

Finally, a case study applying the proposed framework to the Spanish energy system is presented. To this end, a multi-objective computational model (MASTER.MC) has been developed which has made it possible to propose roadmaps for the transition towards a more sustainable model in Spain in 2030 and 2050.

Table of contents

List of figures

List of tables

Nomenclature

Acronyms / Abbreviations

AHP	Analytical Hierarchical Process
APC	Adjusted private consumption
CEC	Cumulative exergy consumption
CP	Compromise Programming
DPSIR	Driver-Pressure-State-Impact-Response framework
DRSA	Dominance-based rough set approach
EC	European Commission
ECEC	Ecological Cumulative Exergy Consumption
ECV	Encuesta de Condiciones de Vida
EEA	Expanded Exergy Analysis
ELCA	Exergetic Life Cycle Analysis
EPF	Encuesta de Presupuestos Familiares
EPOV	EU Energy Poverty Observatory
ESST	Energy Service Supply Technologies
GHG	Greenhouse Gas Emissions
GPEC	Global Primary Energy Consumption
GP	Goal Programming

GPI	Global Progress Indicator
GS	Genuine Savings
IGAE	Intervención General de la Administración del Estado
ISEW	Index of Sustainable Economic Welfare
LCEA	Life Cycle Exergy Analysis
MAUT	Multi-atribute Utility Theory
MCDA	Multi-criteria Decision Analysis
MCDM	Multi-criteria Decision-Making
MIS	Minimum Income Standard
MOP	Multi-objective Programming
OSE	Observatorio de Sostenibilidad en España
PC	Private consumption
RE	Reference Environment
SDG	Sustainable Development Goals
SD	Sustainable Development
SOHO	Self-organizing Holarcich Open Systems
SSA	Systemic Sustainability Analysis
SSM	Soft System Methodology
VSM	Viable System Model
SS	Strong Sustainability
WS	Weak Sustainability

Chapter 1

Introduction

1.1 Foreword

This document that you have in your hands concentrates the fruit of many years of study on the elusive concept of sustainability and the role of energy in it.

This study was based on the author's profound conviction that what we call sustainability is not primarily a technical challenge, but an ethical one.

With this light illuminating the way forward, I set out on a journey that could tentatively answer a fundamental question: how can the eminently technical debate in which the energy sector traditionally operates be moved to its fundamental ethical essence?

With that question in mind I approached Professor Dr. Pedro Linares, right after a lesson on Environmental Impact in which he led all of us who were there to that debate. In the first talk we had, we agreed to take up this challenge, and I have to say that it is thanks to his knowledge, patience and empathy that this document has finally seen the light of day.

This work is an unfinished effort. And surely it always will be. It will do so not only because of its scientific nature, always open to criticism and refutation, but especially because of the subject matter it deals with: sustainability. Any proposal for indicators or frameworks, although useful and necessary, must always be open to reformulations that adapt their pace to the dynamic evolution of the concept they intend to study.

Thus, the journey I started years ago began paying attention to the very beginning: what is sustainability? How can we conceptualize it so that we can objectively calculate how the energy sector is contributing to improving it or, on the contrary, to moving away from it? And that led me to discover the exciting discussion on the 1970s that gave rise to the two classic schools of sustainability: the weak and the strong sustainability paradigms. The first one is rooted on environmental economics and the second one in ecological economics.

At the beginning, more attention was paid to the latter. There I came across exergy, a thermodynamic variable used profusely in improving the efficiency of different energy processes, that some authors had elevated to a strong sustainability indicator. Much effort of this thesis was devoted to understanding to what extent that attempt was successful or not.

Once exergy had its place in the conceptualization of sustainability, it was the turn of weak sustainability to come into play. Strong approaches were focused on respecting environmental limits, a necessary consideration for sustainability but not sufficient. Important questions were pending that were not addressed by this strong approach. For instance how to be efficient and fair within the "safety zone"? Or going to the root of the matter, how to guarantee that well-being is not decreasing over time? On that questions, weak sustainability certainly had a word to say.

After reviewing the two approaches, strong and weak, it was the turn to investigate to what extent the two could collaborate in a comprehensive sustainability analysis. A study of the sustainability of one region, the Costa del Sol, was carried out. This study was based on the calculation of weak and strong indicators, in order to later analyse whether or not the results could be understood in a complementary way.

Then, it was time to propose a framework that would allow both aproaches to be integrated in an operational way. In order to do that, some approaches were analyzed, mainly multi-criteria frameworks and complexity theory, to finally decide to start from Professor Linares' proposal of an integrated framework and take a next step in its development and formalization. This framework proposes sustainability as a problem of creating value, i.e. ensuring that the environmentally adjusted net savings are positive (weak sustainability) subject to critical limits (strong sustainability) and finally incorporating the variable of equity in distribution (intragenerational sustainability).

Once the framework was clarified, it was time to put it into practice. To this end, it was decided to carry out a study of the sustainable energy transition of the Spanish energy sector towards 2030 and 2050. In order to do this, studying in depth how to incorporate the equity variable into the energy sector was a precondition. This led to the analysis of the concept of energy poverty and its calculation for Spain.

Then, in the process of developing the case study it was detected that it was necessary to develop a computational tool based on the proposed framework that could be converted into a concrete tool to aid decision-making. This is how the MASTER.MC model emerged.

It is an evolution of the MASTER.SO model developed at the IIT[1] by transforming a partial equilibrium, linear optimization model of the energy sector into a multi-objective model.

The path that has led to the achievement of this document is thus delineated. Now it is time to submit it to the academy for trial. The objective from now on is to continue pursuing sustainability, a concept that, like silence, when we talk about it, runs without leaving a trace...

1.2 Objective

1.2.1 General Objetive

The general objective of the thesis is to offer an operational framework for energy sustainability studies compatible with the capital-based definition of sustainable development[2]. This new framework will encompass in a complementary way the classical approaches (weak and strong) from which this problem has traditionally been addressed. In summary, this thesis wants to offer a consistent framework aimed at helping the structuring of the goal, i.e. moving towards a sustainable model, and the decision-making process in the energy sector.

More specifically, this is an integrated proposal for weak-strong sustainability analysis based on indicators that addresses, on the one hand, the need to set absolute limits that prevent critical constraints to be surpassed, and on the other hand, to guarantee adequate levels of welfare for present and future generations together with equity in distribution of capitals, i.e. provision of adequate energy services at affordable prices.

Once the integrated framework is defined, it is to be tested in a full case study, i.e. the energy transition in Spain towards 2030 and 2050, thus providing a concrete tool for energy policymaking.

1.2.2 Specific Objetives

Having introduced the main objective of the thesis, the specific objectives aimed at achieving the previous one are as follows.

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[1] The IIT, Institute for Research in Technology, belongs to the School of Engineering (ICAI) of Comillas Pontifical University of Madrid (Comillas). IIT is a non-profit Institute whose main aim is to promote research and postgraduate training in diverse technological fields through participation in specific projects of interest for Industry and the Government.

[2] In the next chapter devoted to presenting the context of the thesis, this approach to sustainability is introduced. However, I anticipate here that it is a proposal based mainly on the works of Solow [267], Pearce [214] and Neumayer [199].

1. Study of the different proposals for sustainability analysis frameworks. The first step is to analyze the state of the art of the various frameworks that have been proposed in this field, and then to analyze their suitability for the concrete system investigated in this thesis, namely the sustainability of energy systems.

2. Analysis of sustainability indicators from a strong and weak perspective. As in the previous point, it consists of a review of the state of the art of sustainability indicators that will allow us to identify the most appropriate proposals for the framework.

3. Sustainability study in a specific region, i.e. the Spanish Costa del Sol. As a first practical exercise, the aim of this analysis is to verify the suitability of the indicators chosen, or more specifically, the possibility of the schools of thought that these indicators represent, i.e. weak sustainability and strong sustainability, respectively, of working in a complementary manner on a proposal for an integrated sustainability analysis.

4. Development of a concrete proposal of an integrated framework. This will be the condensation of the previous exercise: once the most interesting proposals are identified, and the gaps to be filled in terms of research are highlighted, the formalization of the original framework of this thesis will be presented.

5. Energy poverty study in Spain. As a way to incorporate equity concerns in the energy sector, the most widespread proposals for energy poverty indicators in the literature will be investigated and applied to the Spanish case.

6. Development of the case study. The latter objective is to test all of the above. Thus the theoretical framework proposed will be applied to a specific case study for which the appropriate criteria-indicators are defined, the scenarios are proposed, a computer model is developed, and the results are obtained and discussed. It will consist specifically in the analysis of the energy transition in Spain towards 2030 and 2050.

1.3 Structure

The work is structured as follows: after Chapter 1, introductory, Chapter 2 contextualizes the thesis by introducing the problem to be addressed, namely, what is sustainability, what role energy plays in it and what characteristics a truly sustainable energy system should have.

Chapter 3 presents the main state of the art of the thesis, which has been divided into two parts: (1) weak and strong sustainability indicators and (2) sustainability frameworks. The first part includes a detailed study of exergy as an indicator of strong sustainability. The chapter ends by describing the gap detected in the literature and which the thesis seeks to fill.

In Chapter 4, a sustainability analysis of the Spanish Costa del Sol between 2007 and 2015 is carried out in order to test the compatibility or incompatibility of a combined weak-strong approach.

Chapter 5, presents and develops the proposed sustainability framework and Chapter 6 introduces the concept of energy poverty, analyses the main indicators used to date and calculates them for the Spanish case, proposing some improvements.

Then, Chapter 7 develops the case study of the thesis consisting of the application of the framework to the study of the Spanish energy transition towards 2030 and 2050.

Finally, Chapter 8 includes the conclusions, main contributions and future work.

Chapter 2

Context

2.1 The challenge of Sustainable Development

> "In the middle of the 20th century, we saw our planet from space for the first time. Historians may eventually find that this vision had a greater impact on thought than did the Copernican revolution of the 16th century, which upset the human self-image by revealing that the Earth is not the centre of the universe. From space, we see a small and fragile ball dominated not by human activity and edifice but by a pattern of clouds, oceans, greenery, and soils. Humanity's inability to fit its activities into that pattern is changing planetary systems, fundamentally. Many such changes are accompanied by life-threatening hazards. This new reality, from which there is no escape, must be recognized - and managed."

The text above is contained in the first chapter of the United Nations report "Our Common Future", better known as the Brundtland Report [41], which contributed in an extraordinary way to the popularization of the concept of Sustainable Development (SD)[1].

The report had two fundamental objectives: (1) to give as objective a vision as possible of the unsustainable path which human development was running through and (2) to emphasize the need for an international effort capable of reversing this situation.

The Brundtland report was a milestone. It opened the eyes of the international community to a problem that, if left unaddressed, could have fatal consequences for the planet and our way of life.

Today, 30 years later, we have much more information to help us understand the magnitude of the challenge of SD.

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[1] Although formally the concepts of sustainability and sustainable development are not identical, they will be assumed interchangeable in this text.

According to World Bank statistics [283], the world population grew from 3.01 billion people in 1960 to 7.53 billion in 2017, thus there has been a growth of more than 150% in less than 60 years. At the same time, the increase in world GDP (in constant 2010 dollars) went from $11.21 trillion in 1960 to $80.1 trillion in 2017 [281].

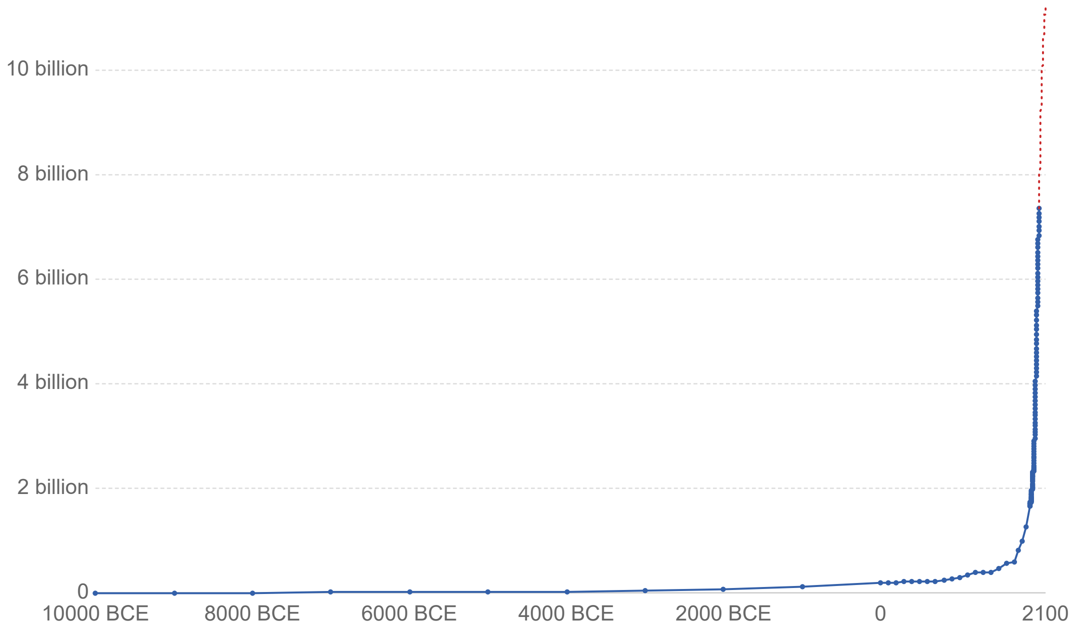

Fig. 2.1 Demographic evolution. Source [240]

Broadening the time frame of this evolution, Fig. 2.1 shows the World Population over the last 12,000 years and UN projection until 2100; whereas Fig. 2.2 shows the evolution of the World GDP over the last two millennia as the total output of the world economy adjusted for inflation and expressed in 2011 international dollars.

In short, these two graphs represent a scenario of unprecedented growth in human history. The question to be asked, and which the Brundtland Report already anticipated, is whether this growth is taking place in a sustainable manner, i.e. (1) respecting the limits of the planet and (2) assuring equity in the distribution of wealth for actual and future generations.

While there is no doubt that human progress has brought unprecedented levels of well-being in human history [2], unfortunately, there are signs indicating that these growth patterns are not actually being sustainable. One of the clearest examples is global warming. If greenhouse gas emissions (GHG) are not controlled, by the end of the 21st century we could

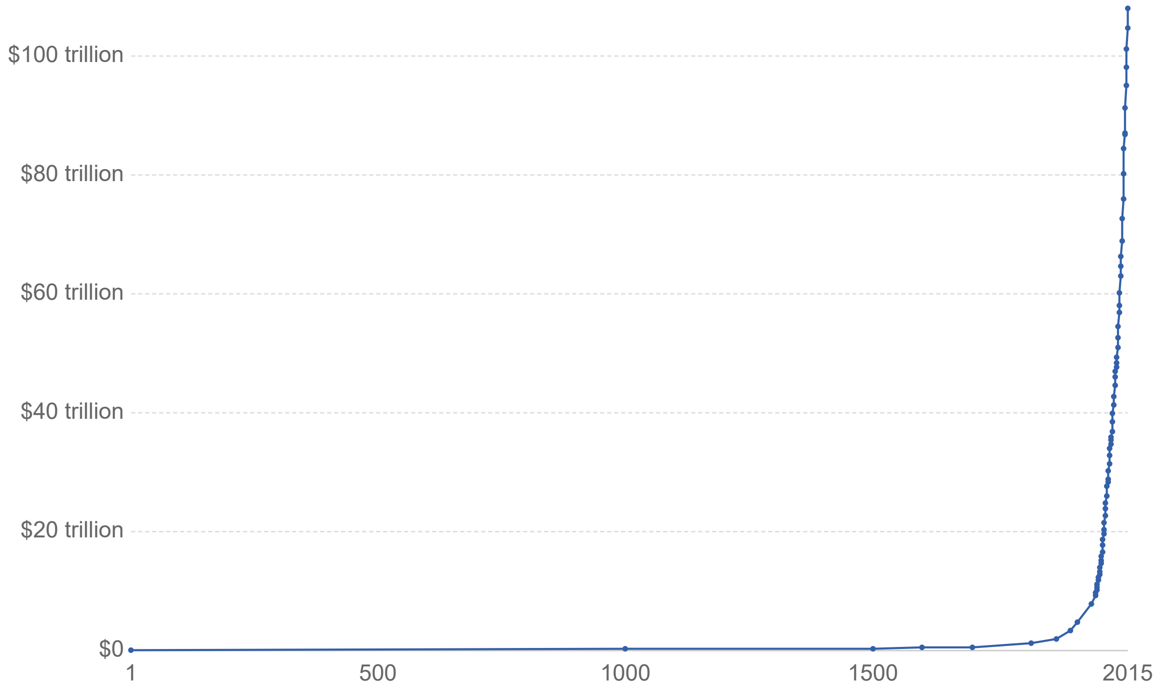

Fig. 2.2 Economic growth. Source [241]

be facing a scenario of global temperature rise of more than 2 degrees Celsius, which could be catastrophic for many ecosystems and societies [52].

However, although in the long term global warming is probably the greatest environmental threat we are facing, it is not the only one. In this sense, Rockstrom's proposal of the nine planetary boundaries [233, 234, 269] (see Fig. 2.3) helps to locate where the main sources of risk are in terms of the anthropogenic impact on the environment, namely, (1) Stratospheric ozone depletion; (2) Loss of biosphere integrity (biodiversity loss and extinctions); (3) Chemical pollution and the release of novel entities; (4) Climate Change; (5) Ocean acidification; (6) Freshwater consumption and the global hydrological cycle; (7) Land system change; (8) Nitrogen and phosphorus flows to the biosphere and oceans and (9) Atmospheric aerosol loading. According to Rockstrom, in three of them we have reached the very high risk zone, i.e. biogeochemical cycles of nitrogen and phosphorus, and genetic diversity.

It is therefore clear that the environmental risks we are incurring as a consequence of this growth scenario are disturbing. However, sustainable development does not stop there.

Ensuring that growth is distributed fairly is also an objective to be pursued. In this sense, we find contradictory realities. In terms of inequality within countries, and taking as a ref-

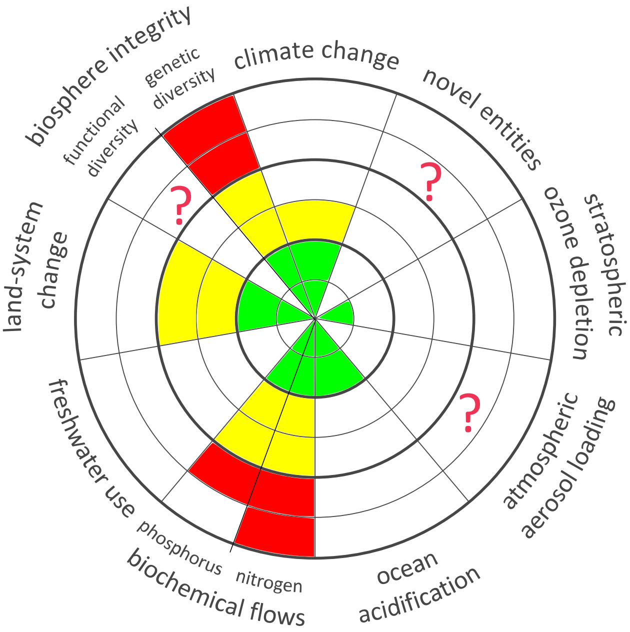

Fig. 2.3 Planetary boundaries. Source [269]

erence the world's leading economy, that of the United States, it may be seen that the Gini index [101], which measures the deviation of the balance in the distribution of income, grew from 0.346 in 1979 to 0.415 in 2016 [282]. That is to say that, despite the fact that US GDP doubled in this time frame, inequality in the distribution of GDP still remarkably increased (Fig. 2.4 shows the evolution of Gini index in EEUU before and after taxes and transfers[2]).

Conversely, if we look at inequality between countries, the indicators have remarkably improved. The income cut-off of the poorest 10% has increased in the last decades from 260$ to 480$, and the median income has almost doubled from 1,100 $ to 2,010$ [121]. However, even assuming that the improving trend in equity between countries will continue, there is uncertainty about the pace at which it will occur.

Finally, SD also encompasses other aspects related to human and social capital. They are well reflected in some of the SDGs[3] such as Goal 3 (good health), Goal 4 (quality education),

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[2] Higher values indicate higher level of inequality for equivalised household income

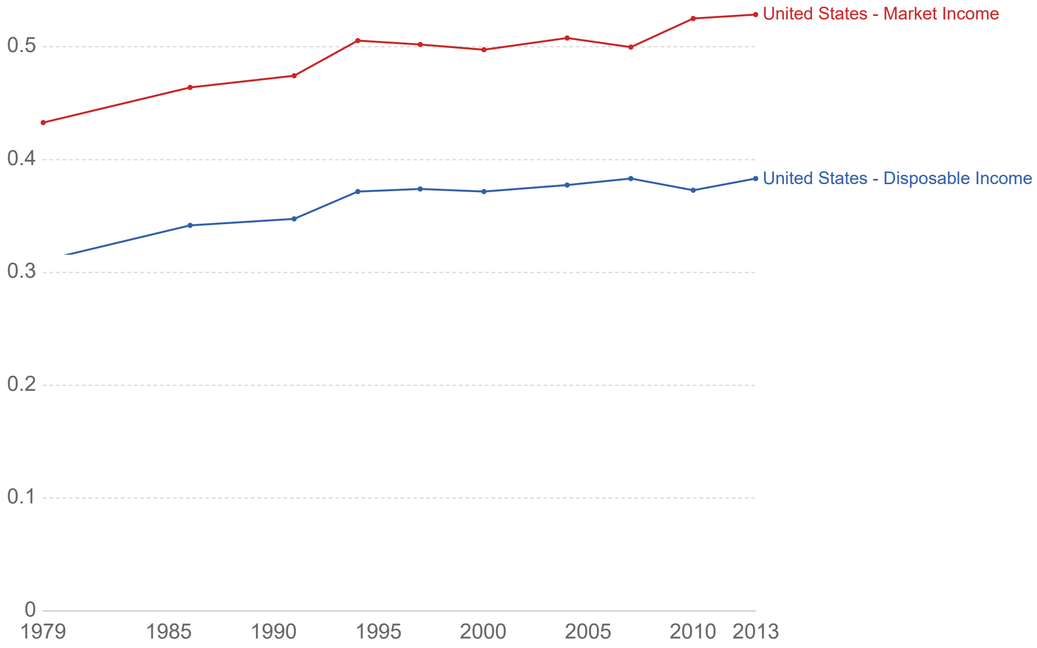

Fig. 2.4 GINI USA. Source [242]

Goal 5 (gender equality) or Goal 16 (peace, justice and strong institutions). In this aspect, in general terms it can be said that the trend is positive, although unequal [299].

Some other data could have been mentioned to illustrate that what the Brundtland Report anticipated was not a bad premonition, but a fact. The current growth model that is sustaining our welfare is to some extent unsustainable. One could say metaphorically that we are driving a limousine towards an uncertain abyss.

2.2 Energy and Sustainable Development

Once the scenario has been set out, namely that human progress presents unsustainable patterns that must be reversed, we can ask ourselves about the specific role that energy plays in it, since it is in this specific sector in which the contribution that this thesis aims to make will be focused.

According to economist E.F. Schumacher: “energy is not just another good, but the precondition of all goods, a basic factor such as air, water and land” [249]. Energy is something

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[3] In this context, the international community, represented at the United Nations, has embarked on an ambitious project that has sustainability as its long-term goal: the Sustainable Development Goals (SDG). Among them, Goal 7 has energy as its focus.

that every human being on the planet uses directly and indirectly on a daily basis. It is the raw material for all our activities and for our economic growth.

Let us have at look at the extent to which this is really so by looking at some data on energy uses around the world.

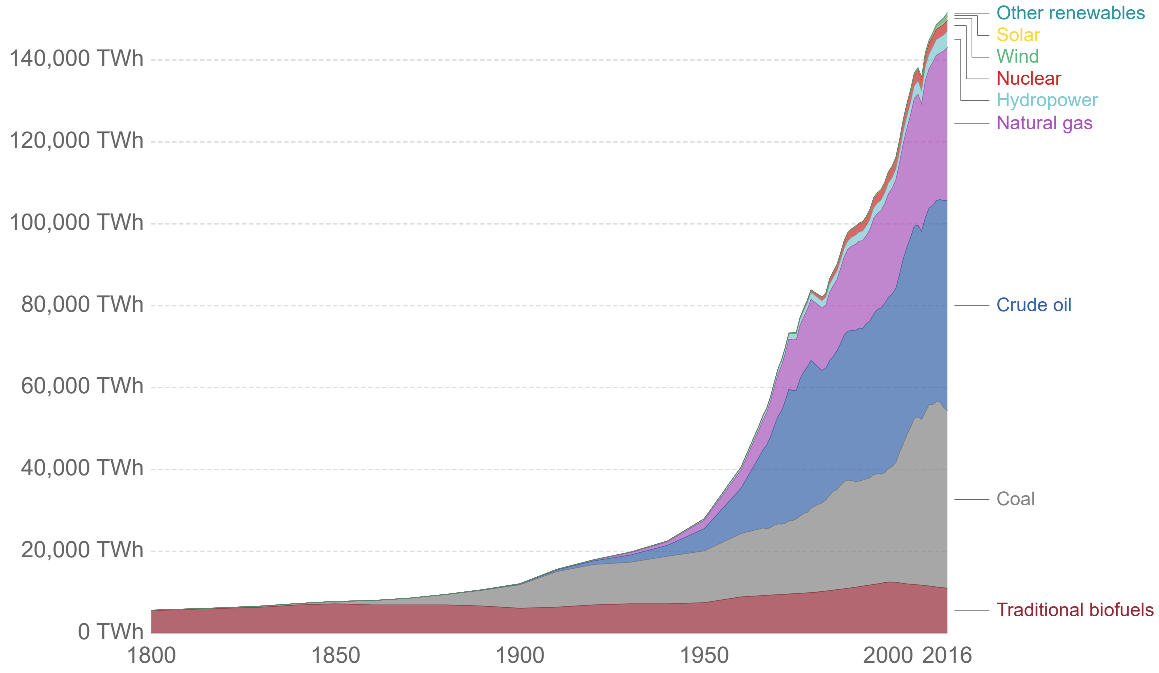

Fig. 2.5 Global Primary Energy Consumption (TWh). Source [293]

Fig. 2.5 shows the Global Primary Energy Consumption (GPEC), measured in terawatt-hours (TWh)[4].

According to these data, in 2015, the world consumed 146,000 TWh of primary energy, that is, more than 25 times more than in 1800. It is also worth highlighting that the total contribution coming from renewable sources was very small. Even including modern biofuels and hydropower, it was still less than five percent.

This data may suggest that the impressive economic growth of recent times shown in Fig. 2.2 has been based, to a large extent, on an ever-increasing energy consumption. Nevertheless, the link between energy consumption and economic growth has been a topic of wide discussion. A large number of studies have attempted to derive the causal relationship between energy consumption and economic growth, however no clear agreement has emerged.

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[4] Here 'other renewables' are renewable technologies not including solar, wind, hydropower and traditional biofuels

Chontanawat et al. [51] carried out a systematic study across 100 countries to try to reach a common consensus on the energy-GDP link. Besides, Akinlo [8] did similarly across eleven Sub-Sahara African countries. Neither found a direct causal relationship which was true in all contexts. Nonetheless, for most countries, an important relationship between energy and prosperity was found.

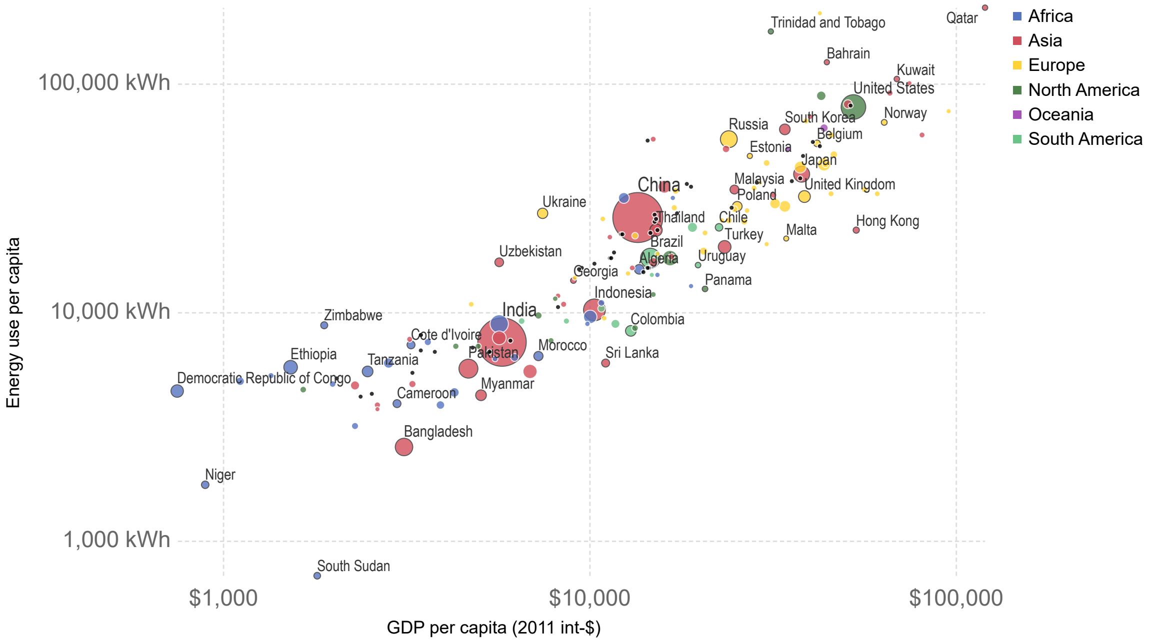

Fig. 2.6 Energy use per capita vs. GDP per capita. Source [294]

In Fig. 2.6 annual energy use per capita in 2015, measured in kilowatt-hours per person vs. gross domestic product (GDP) per capita, measured as 2011 international-$ is represented. A strong trend is shown, i.e typically the higher a country's average income, the more energy it consumes.

This fact in itself may not be a problem from an environmental point of view if the primary energy sources used were inexhaustible and clean, but this is not the case as clearly highlighted in Fig. 2.5.

Consequently, GHG emissions due to this pattern of energy use have increased. Focusing on CO_2 emissions due to fossil fuel use, these have risen from 15,458 Mtons in 1973 to 32,294 in 2015 [132]. Fig. 2.7 shows the evolution of the annual CO_2 emissions in million tonnes from solid fuel, liquid, gas, cement production and gas flaring.

In this regard, the IPCC has been particularly clear: if we want to limit the increase in the global temperature of the planet to 2 degrees by the end of the century (less than 450 ppm

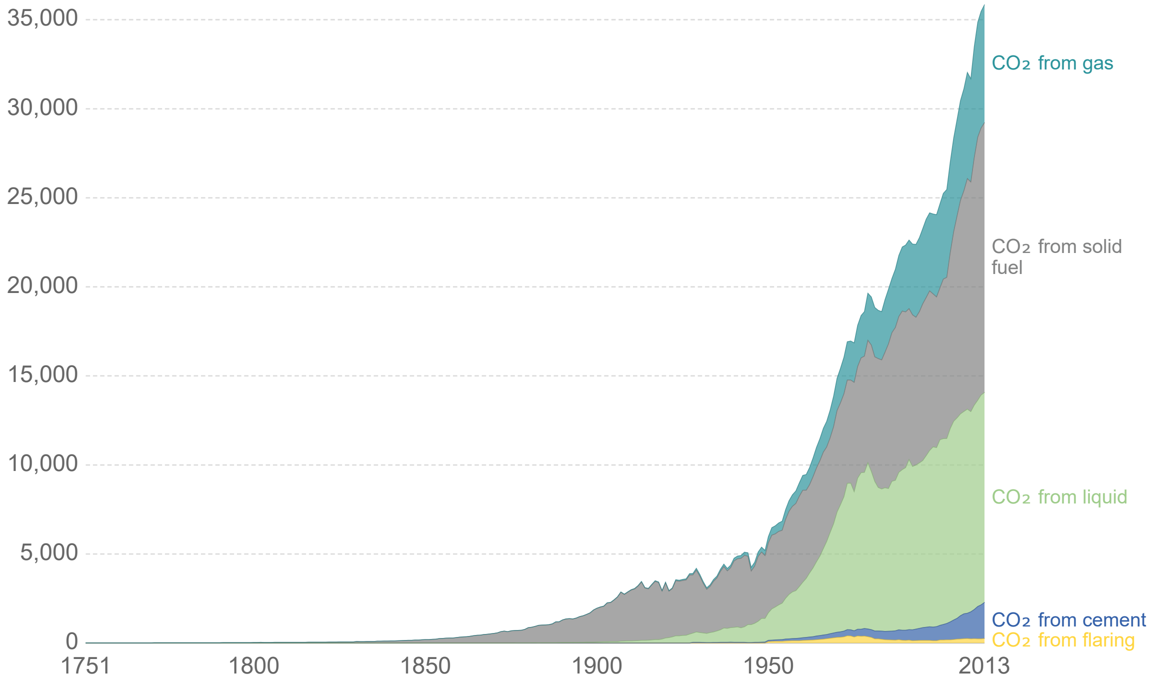

Fig. 2.7 Global GHG emissions. Source [243]

CO_2eq) it is necessary to reduce emissions by between 40% and 70% by 2050, and almost 100% by 2100, with respect to 2010 [52][5].

The consequences of not doing so may have a direct impact in the economy. The well known Stern Review on The Economics of Climate Change [270] estimated that, in a business as usual scenario (where average global temperatures reach around 5-6°C over pre-industrial values), the costs of climate change could imply a yearly global welfare loss equivalent to a 5% to 20% reduction in global GDP during the next two centuries. Another very relevant analysis in this regard, and of less extreme results, is that of Tol [288]. According to him, current estimates indicate that climate change will likely have a limited impact on the economy and human welfare in the twenty-first century. However, in the long run the negative impacts dominate the positive ones.

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[5] These data are included in the AR5, the last full report published by the IPCC in 2013. Nevertheless, new evidences [172] show that we should probably be much more ambitious in the decarbonization roadmap.

Additionally, atmospheric pollutants like NO_x, SO_2 and $PM_{2.5}$ emissions coming typically from combustion processes are increasingly affecting human health throughout big conurbations[6] in the world. This an issue that has been repeatedly highlighted by the WHO [325].

As in the case of the emissions just mentioned, energy plays a key role in the threat posed by the other Rockstrom's planetary boundaries mentioned in the previous section. Unfortunately, going deeper into each of them would require going beyond the limits of the present work.

It has become clear that the nexus between energy and environmental challenges is very direct, but as already anticipated, sustainability goes beyond this nexus.

To better analyze this relationship between energy and SD in all its dimensions, it is useful to rescue the classic definition of sustainability that divides it into three major poles, namely, environmental, economic and social, that is, the so-called triple bottom line, and to analyze the relations between energy and them.

Having already mentioned the first one, let us look at some data about the other two.

In terms of the energy-economy nexus, following [161] one issue is considered the most relevant, namely, the economic risk of high energy prices.

Energy is a very relevant input for our economies, allowing us to produce goods and services and to increase economic capital. However, the fact that our energy system is being based on non-renewable resources implies great challenges. Additionally, the global demand for fossil fuels is becoming tight, due not only to geological, technological or environmental reasons, but also to geopolitical ones: these resources are largely concentrated on a few countries and these facts have put much pressure during the last years on the prices of primary energy. This has large economic consequences, specially for consuming countries since higher prices imply higher expenditures on energy (unless consumption is reduced, which in a key economic input such as energy is not easy in the short term).

Fig. 2.8 shows the evolution of global crude oil prices, measured in 2016 US \$ per barrel, from 1861 to 2016. Although the evolution of these prices is uncertain, it is not excluded that they will continue to grow, mainly due to the foreseen increases in consumption, at least in the next decade.

When importing countries spend growing shares of their wealth in energy, it worsens their current account balances and affects their currency. In addition, as energy is a key input in their economies, growing energy prices are passed to the rest of the economy, increasing costs and hence reducing competitiveness. The reduced investment also implies that less

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[6] A city area containing a large number of people, formed by various towns growing and joining together.

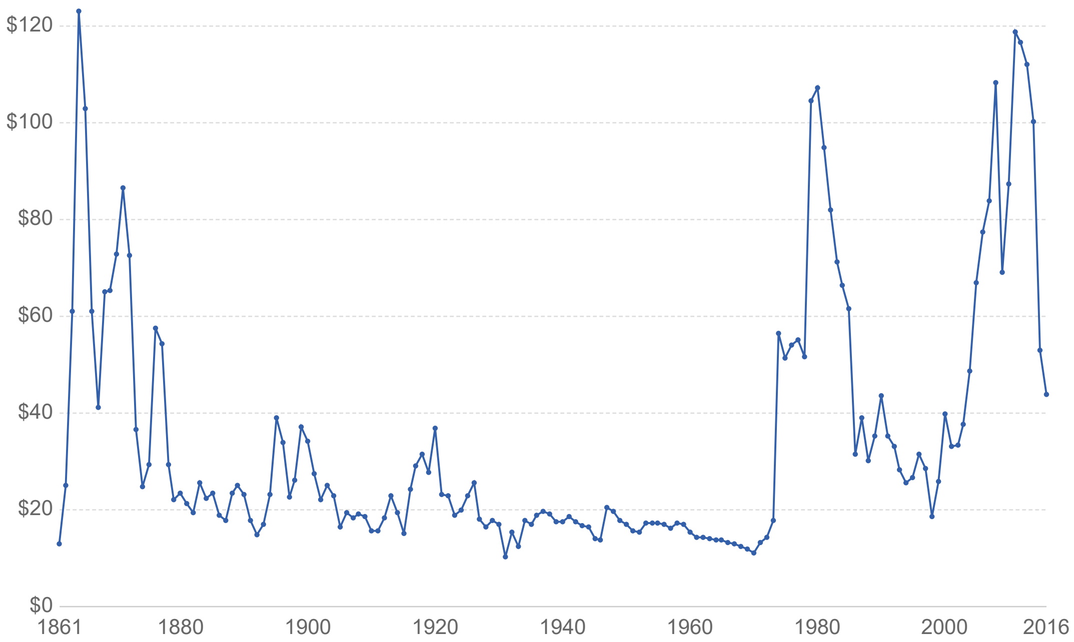

Fig. 2.8 Evolution of the oil price. Source [244]

economic capital is left for future generations. Interestingly, negative effects are not only derived from high price levels and expenditures, but also from fossil fuel price volatility, which implies greater uncertainty for many economic agents in their costs and in valuing their investments, which in turn increases risk premiums and financing costs, and require adjustment costs.

Regarding the energy-society nexus, it may be seen that linked to the patterns of energy production and use various social problems arise, such as geopolitical conflicts derived from the concentration of primary resources in certain areas of the planet, as well as the impact of this concentration on national policies, like the resource curse, dictatorships, etc [65].

Finally, in terms of equity, the most pressing issue is the need to provide universal access to energy at affordable prices (a fact that in developed countries is beginning to be recognized with the term "energy poverty" or "fuel poverty" [27]). The reality is that 1,06 billion people still do not have access to electricity, and 3,04 billion people still rely on solid fuels and kerosene for cooking and heating [280]. Besides, in developed countries such as Spain, although access is guaranteed, many households are unable to meet their energy costs. [237].

It therefore seems clear that there is also a problem of unsustainability in energy systems. What needs to be defined now is where to go, that is, what requirements must an energy system meet so that it is sustainable.

To do this, it is necessary to go back to the challenge of SD itself, to understand which proposals have been made to define the problem and to choose from among them the one that best suits the objective pursued in this thesis, namely to contribute to this global challenge of SD by providing an appropriate framework for the analysis of the sustainability of energy systems.

2.3 How to define a sustainable energy system

The first step in order to solve any problem, whatever its nature, is to define it. However, as Pezzey points out [219], in the case of SD this exercise has turned out to be almost unachievable:

> "A temptation when writing on "defining sustainability" is to try to distill, from the myriad debates, a single definition which commands the widest possible academic consent. However, several years spent in fitful pursuit of this goal have finally persuaded me that it is an alchemist's dream, no more likely to be found than an elixir to prolong life indefinitely."

Many definitions of sustainability have been presented to date [175], and many conceptualizations have emerged from them. Bruntland's report proposed the most famous one: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [41].

We cannot detract from a definition that has put the challenge of SD at the forefront of international politics, but we cannot ignore the difficulties it presents either. If we analyze the definition it can be seen that, to the question of what we want to sustain, the answer is: the human needs. This response is as powerfully intuitive as it is vague. Transferring this proposal to an operational framework is extremely difficult because, although we could perhaps agree on the needs that the current generation considers essential to be met, how can we replicate this exercise for future generations without affecting their ability to set their own preferences?

One possible solution to this difficulty is provided by Solow [265], who proposes to focus not on the needs themselves, but on the options for meeting them. Thus what is being proposed is to situate the definition in a previous step. This way, SD would be no longer a question of guaranteeing needs but of guaranteeing the raw material we need to cover them, whatever they may be. And this raw material is *capital*. Just as economic income is derived from capital, but in different and flexible ways according to the preferences of individuals, so can the rest of well-being be derived from other types of capital, namely, natural, human and social[7], as well.

This is the capital-based proposal to which I will refer later, but before that, let us present briefly a second candidate for the definition of SD. It is the classic proposal, already mentioned in the previous section, that divides up sustainability into different areas, i.e. ecological, economic and social and defines it as a kind of balance between the three. It is the so-called triple bottom line approach [188].

The problem with this definition is that the obvious interrelationship between the different dimensions or poles is not sufficiently explicit, so that it makes it difficult to operationalize them. And this is essential if we want to incorporate sustainability concerns in decision-making processes at different political levels.

Thus, with the capacity to become operational as the main guide, the capital-based approach mentioned above became the most interesting one.

Hartwick suggested that an operational conceptualization of the problem of SD should be based on capital theory extended to incorporate natural capital [112, 113]. That is the basis of the well know Hartwick's rule of sustainability. From this point of view, the sustainability of the development model would be guaranteed if a non-decreasing and equitably distributed stock of capitals, namely economic, social, human and natural, in space and time, were to be ensured, thus enabling human needs to be met in a sustainable manner.

Although this capital-based conceptualization represents a significant step forward in the operationalization of the problem of SD, it is not without its problems. The main one is probably found in the role that natural capital plays within the model. This is precisely the issue around which the two main schools of thought on SD, i.e. Weak Sustainability (WS) and Strong Sustainability (SS) paradigms, collide.

The WS paradigm, traditionally linked to environmental economics [190], was founded in the 1970s by extending the neoclassical theory of economic growth to include non-renewable natural resources as a factor of production. The key issue being investigated was whether economic growth could be sustained in perpetuity, in other words, whether a non-decreasing level of well-being over time in a context of finite resources was possible [216, 215, 267, 266].

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[7] Another possible way out of this difficulty is to shift the focus from the needs or the preferences to the capabilities proposed by Sen [259]. This is a topic that this thesis has not explored in depth, and which remains enunciated as a line of future work.

[8] Green investment = Net investment + change in natural capital; Genuine savings = Green investment + education expenditure; GSTFP = Genuine savings + Net present value of total factor productivity (i.e. technological change).

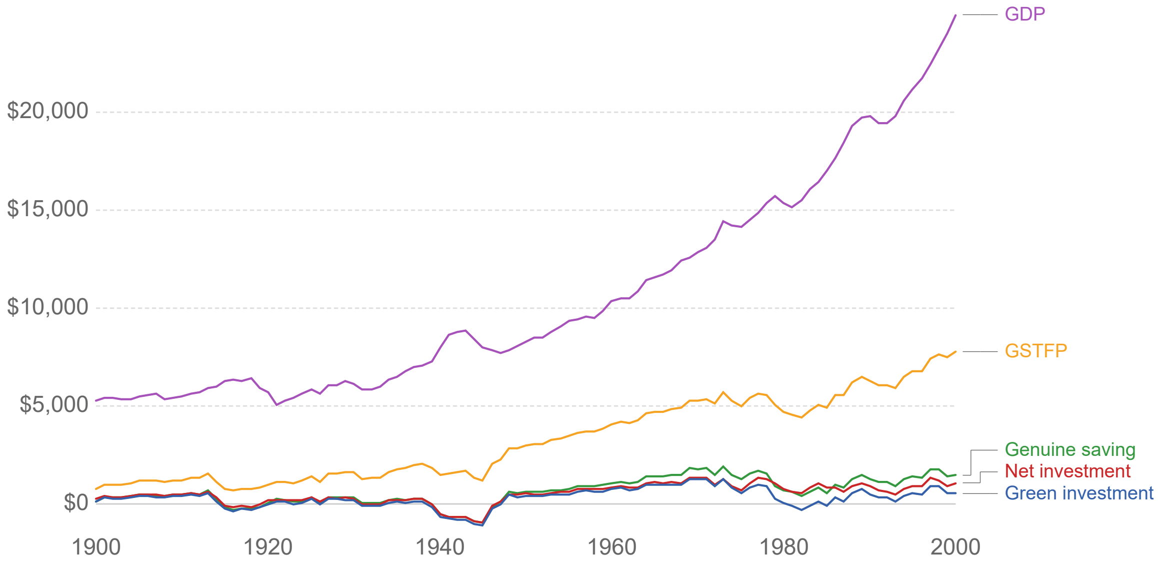

Fig. 2.9 Comparison GDP - National Savings[8]. Source [295]

This way, the condition for SD from a WS point of view implies ensuring that human well-being does not decline over time [213], or in other words, that *value* is not being reduced but created. How to measure well-being is the key issue around which many researchers have been working for decades. It will be further developed in the state-of-the-art chapter of the thesis but it can be anticipated here that GDP is not a good candidate for it. Corrected GDP indicators that are able to incorporate environmental elements will be the ones. This is more clearly understood if we look at graphs like the one in Fig. 2.9. In it we see various measures of national savings compared to GDP per capita (in international dollars) for the United Kingdom until the year 2000. Four indicators of net savings are included. It can be observed that, while GDP growth is exponential, these indicators, at best, grow very slowly, and at worst have periods when they become negative, i.e. income grows at the expense of savings.

The concept of SS, rooted on ecological economics [190], was strengthened by the works of Georgescu-Roegen and Daly [98, 63]. One underlying idea in those studies was the urgent need to define absolute limits to human activity that would safeguard the conditions that make life on earth possible, or from a capital perspective, the urgency to define a critical natural capital.

The difference between the two paradigms, strong and weak, is in general terms the possibility or not of substitutability between capitals and, in particular, the treatment of natural capital. For WS, natural capital is no different from other capitals and can be substituted without limitation. On the contrary, proponents of the SS paradigm argue that natural capital is by no means substitutable with other capital.

Ultimately, both approaches suffer from particular limitations that prevent them from covering all aspects of energy sustainability on their own. That is why, in my view, it could be of interest proposing an integrated approach that included both contributions. This idea will in fact be the main thread of this thesis.

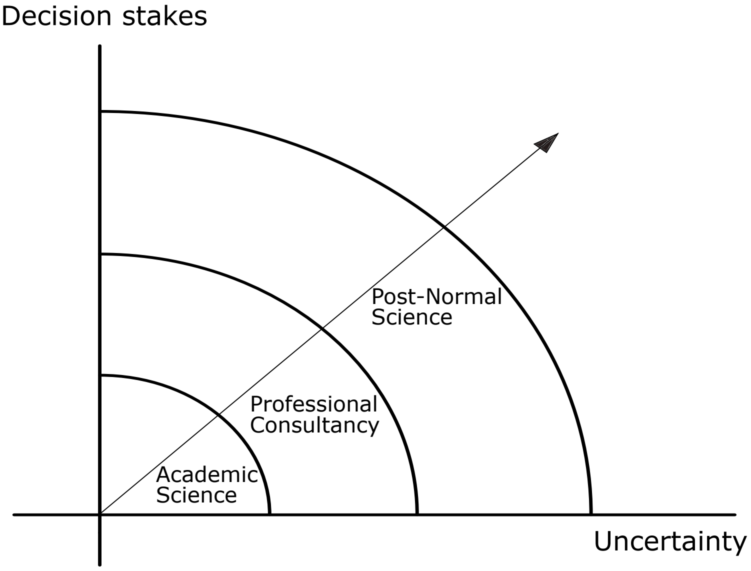

Fig. 2.10 Post-Normal-Science (own elaboration based on [91])

When we delve deeper into this division between schools of thought, namely, the environmental economics school of thought represented by the WS and the ecological economics developed by the SS, we discover that beyond the formal differences between them, there is a deep epistemological chasm that separates them, so I think it is important to reflect here in a very concise way on the extent to which this integration is really possible or not. For this, it is necessary to dive into the roots of both schools and its relationship with other classic controversies in the world of economics.

It is always risky to make watertight classifications because few proposals can be classified strictly as belonging to one or the other side. However, it can be said without too much fear of ambiguity that there are other controversies in economics that in a way are twinned with this one presented between SS and WS. Next, some of them are mentioned. If we unify all those who are in tune, we find ourselves with a concrete epistemology, perhaps not explicit, but very recognizable.

First of all, it is worth mentioning the Post-Normal-Science (PNS) paradigm proposed by Funtowitz and Ravetz [91]. According to them, PNS is a new conception of the management of complex science-related issues. It focuses on aspects of problem solving like uncertainty, value loading, and the inclusion of other legitimate perspectives, that are typically neglected in traditional scientific practice. PNS considers these elements as integral to science, so providing a coherent framework for an extended participation in decision-making. We can understand post-normal science by means of a diagram (see Fig. 2.10), where the axes are "system uncertainties" and "decision stakes". When both are low, we find applied science, that is, normal (in Kuhn's sense [142]) scientific approach. When they are average, we have the professional consultancy, as a veteran engineer using normal science tools that must deal with uncertainties. But there is a third level, the PNS level, where uncertainty and risks are so high that an extended community of peers is needed in order to address the issue.

The links of this proposal with ecological economics are very direct. It was not for nothing that the first ideas about the former emerged during the gestation of the latter. Many of the proposals currently developed for sustainability analyses are inspired by this new PNS paradigm. Its main raison d'être is to react against a way of doing science that, according to its practitioners, is inadequate to face the great problems that confront humanity in our time, such as SD.

Another interesting dispute that, in my opinion, links in with the previous ones is that of substantive rationality versus procedural rationality. This approach was presented by Simon [262] in the 1970s. What Simon brought up was the different way of understanding what "rational" means in economics and psychology. Classic economics based on the homo economicus assumption, has been concerned with substantive rationality, that is, with the appropriateness of human behavior to the achievement of given goals within the limits imposed by given conditions and constraints. On the contrary, psychology has been mainly concerned with procedural rationality, that is, with the processes that human beings use in order to discover and choose behaviors that will be effective for reaching their goals. Pulling on this thread, authors such as Giampietro and Munda [99] stress the need to integrate both rationalities into the sustainability analysis process itself. Classic economic approaches (we could say that purely WS approaches) as mentioned above, that ignore the "process" variable in decision making, will inevitably fail when it comes to analyzing complex processes such as decision making for a transition to sustainability in our societies.

In this particular case, it can be said that there is some convergence in the two schools. Environmental Economics has long incorporated the procedural economics dimension into its own analysis, while Ecological Economics is partially rooted in the doubt about the capacity of a purely substantive economic approach to confront the problems inherent in SD.

Finally, it is worth mentioning the proposal of transdisciplinarity [201], as a reaction to the probably excessive compartmentalization of scientific knowledge. According to Max-Neef [174], the sustainability problematique cannot be adequately tackled from the sphere of specific individual disciplines. They clearly represent transdisciplinary challenges. By this he refers to the integration of knowledge not merely as juxtaposed proposals, but in an organic way and anchored in the reality it intends to analyze. Again, ecological economics is very closely aligned with this conception of scientific work. In fact, it considers itself a transdisciplinary science.

These brief insights on such interesting disputes serve as an introduction to what we will see later in the section on the state of the art, namely, that the study of sustainability has put science itself in the context of questioning its capacity to tackle this challenge with the tools it has had to date. And a possible solution to this challenge for the science of sustainability comes from integrating schools of knowledge traditionally antagonistic, such as the WS and the SS.

At this point, we are already in a position to answer the question that introduced this section: what requirements must an energy system meet in order to be sustainable?

It has been shown above how any possible response to that question requires starting from a certain conceptualization of SD. Guided by the need to be operational it was decided to focus on a capital-based approach. Thus, being consistent with this proposal, a sustainable energy system must:

1. Ensure a non-declining level of well-being, or in other words, ensure that the aggregated stock of capital increases or at least does not decrease in time[9];
2. Guarantee intra and inter-generational equity, i.e. fair allocated welfare within and beyond the present generation, respectively, and
3. Respect the resilient limits of the socio-environment.

As we will see later on, the first two objectives are more easily approachable from WS, while the third is better treated by SS.

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[9] The author is aware that there are schools of thought that advocate the need to turn towards degrowth models that would apparently clash with this interpretation of sustainability [145, 171]. It is important, however, to highlight that the definition does not mention growth, but well-being, which are not necessarily synonymous. Therefore, degrowth positions that do not question the need to guarantee well-being, far from being incompatible would also have a place within this framework.

This is where the concrete contribution that this thesis seeks to make to the achievement of global sustainability goal (focusing on its energy dimension) begins.

Starting from a capital-based approach to the very concept of SD, and taking into account the particularities of one of these capitals, i.e. natural capital, which is key to the energy sector, the present work aims to offer a framework for the analysis of energy systems compatible with this specific approach to SD. Then, once the framework is set, proper indicators representing WS and SS are to be chosen in order to monitor the sustainability transition.

In addition, it is important not to forget an implicit requirement for the framework: that it is scalable, i.e. that is replicable at various scales. I will return to this point in the Chapter 3 on the state of the art.

The two first steps of the thesis, that is (1) selecting a conceptual approach to our problem and (2) defining the conditions for an energy system to be truly sustainable, have already been assessed in this chapter, yet two more steps are pending, i.e. (3) to choose the appropriate framework and indicators to design and develop energy sustainability analyses and (4) to test it in a concrete case example.

Therefore it is time to move into the third phase and core of the thesis, namely defining the tools that effectively allow us to make this journey. In my view, these tools are basically the two already mentioned, that is, on the one hand, (1) an adequate framework of analysis or assessment and, on the other hand, (2) a proper indicator or a set of indicators to work within that framework. Reviewing the current developments in the literature regarding these two areas constitutes the main state-of-the-art analysis of the thesis.

Chapter 3

State of the art: frameworks and indicators

This chapter presents the revision of the state of the art carried out during the thesis. It focuses on two aspects, (1) sustainability frameworks that can ultimately be applied to energy sustainability analyses and (2) sustainability indicators based on WS and SS.

They are the two most important areas in terms of reviewing the state of the art, but they have not been the only ones. Particularly important is the state of the art of energy poverty indicators which, for clarity purposes, has been incorporated directly into Chapter 6.

3.1 Sustainability frameworks

Bibliographical references to this topic of frameworks for sustainability are extremely extensive and diverse. I was therefore forced to narrow the field of search, and it was decided to focus on two specific methodologies, namely (1) multi-criteria methods and (2) methods based on complex systems. This choice was fundamentally due to the fact that both strategies fulfilled the main requirement we were asking for, that is, that they allowed the different dimensions of sustainability, and their corresponding capitals, to be integrated within the same operational and scalable framework.

Moreover, given that the thesis moves continuously in that dichotomy between environmental economics and ecological economics following the two classic schools of sustainability, WS and SS, these two methodologies have shown themselves to be good candidates to deal with this apparent contradiction in a creative way. On the one hand, the multi-criteria methods, as will be explained below, are techniques that seek to place different criteria on an equal footing in which each one can adequately affect the decision to make. These methodologies are therefore perfectly compatible with the capital substitution proposal by WS. In fact, they have been widely used to quantify and incorporate economic externalities into decision-making processes. That said, multi-criteria techniques also allow for the incorporation of criteria from the SS into SD decision-making. This is in fact the reason that led us to adopt this approach as the basis for the concrete framework proposal presented in the thesis (see Chapter 5).

On the other hand, the methods based on complex systems are in principle open proposals typically focused on the relationship between the system under study and the environment that sustains it. They are, in most cases, proposals rooted on an ecological understanding of the reality (SS) where what prevails is not the balance of criteria but the care of the environment, or, in the words of Pope Francis, of the common home [89].

However, before presenting the two sets of selected framework proposals, it is important to note that some authors would also consider multi-criteria techniques as a system-based proposal. Partially agreeing with this assessment, it was decided to separate them because, in my opinion, the multi-criteria techniques have reached a level of development that make them worthy of being treated in an individualized manner.

3.1.1 Multi-criteria frameworks

Multi-criteria Decision-Making (MCDM)[1] or Multi-criteria Decision Analysis (MCDA) encompass a set of different existing techniques suitable for addressing problems featuring high uncertainty, conflicting objectives, different forms of data and information, multiple interests and perspectives [316].

Thus, these techniques are suitable when dealing with a multiple criteria decision problem. When there is only one criterion, a technological problem is being faced in which no election is to be done but rather just find the optimal solution. When there are indeed several criteria, the decision becomes a decision problem, and that implies a real problem of choice.

3.1.1.1 Introduction

The general formulation of a MCDM problem is as follows:

$$Opt \quad z = (z_1(x), z_2(x), ..., z_n(x)) \quad x \epsilon F \tag{3.1}$$

where z is the vector of n criteria functions (objective functions), x is the decision variable and F is the feasible set.

Let us introduce now some basic concepts in MCDM theory:

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[1] The content of this section is mainly adapted from [74] and [151].

- *Solution*: This is the result of the analytical process chosen. It is important to note that a solution may be optimal under one criterion, but not under another. A solution is efficient or Pareto optimal if an improvement in one of the criteria always leads to a worsening in one of the others. The set of Pareto optimal solutions is called the efficient set.
- *Trade-offs*: It is the amount of achievement in one criterion that must be sacrificed to achieve a unitary increase of another criterion. It has a double interest within MCDM. On the one hand, it is an index to measure the opportunity cost of a given decision that includes several criteria, and on the other hand it is a key parameter to provide information and interact with the decision-maker.
- *Attribute*: It is the observed (measured) value of a decision independently of the decision-maker.
- *Objective*: Improvement direction of an attribute.
- *Aspiration level*: Acceptable level of achievement for an attribute.
- *Goal*: Combination of an attribute with its aspiration level.
- *Criteria*: Attributes, objectives or goals relevant to a decision problem.

As mentioned above, MCDM encompasses different techniques. They can be classified according to the space of solutions, i.e. continuous or discrete. Within the former, the most commonly used methods are: (1) multi-objective programming (MOP); (2) compromise programming (CP) and (3) goal programming (GP). The first two are considered optimization problems while the third belongs to the so-called “satisfacing problems”.

Besides, in the discrete side, the most popular techniques are (1) the theory of multi-attribute utility (MAUT), (2) the analytical hierarchical process (AHP) and (3) the outranking methods, such as the Electre or Promethee.

Next, a brief description of the most relevant techniques, with special emphasis on those most relevant to this thesis, are presented.

MOP is a technique that seeks to establish the set of efficient solutions without incorporating the preferences of decision makers. This efficient set can be, in turn, finite or continuous.

Within MOP, obtaining a payoff matrix is a necessary first step. The payoff matrix is a squared matrix built by optimizing each criteria separately and calculating the values of the other ones for this mono-criterion optimal solution. This is the first approach to the problem and serves to assess the level of conflict between the different criteria. It is also used to check if there are dominated criteria, that is, if any criteria is redundant.

In the payoff matrix the ideal point, i.e. the optimal values for each criterion, can be found in the main diagonal of the square matrix. Besides, anti-ideal (nadir) points can be found elsewhere in the matrix, since they are made up of the worst values. These two points define the range of variation of the attributes. This payoff matrix, as we shall see, is also the necessary first step in other techniques, like the compromise programming methodology.

A second phase of MOP is the generation of the efficient set (that consisting of the set of Pareto optimal solutions), a task that is not always easy and that sometimes may not be essential. The most common techniques for this task are: (1) Restrictions (ϵ - restrictions); (2) Weights; (3) Non-inferior set estimation (NISE) and (4) Simplex multi-criteria[2].

The main drawback of MOP is that, in most cases, the information in the efficient set is excessive, and this implies a very high computational cost together with the possibility that biases may arise in the treatment of the criteria by decision-makers.

Faced with this difficulty, the most preferred approach is to incorporate the preferences of the decision-maker in order to reduce the efficient set. The two techniques most commonly used for this are those mentioned above, i.e. (1) compromise programming (CP) and (2) goal programming (GP).

CP tries to find, within the efficient set, the solutions that best suit the preferences of the decision-maker. It is based on Zeleny's axiom of choice: "Given two possible solutions, the preferred one will be the one closest to the ideal point". These solutions are called compromise solutions, and the set including all the solutions is called compromise set.

$$L_p = \Big[\sum_{i=1}^{n}[w_i \frac{f_i - f_i^*}{f_{i*} - f_i^*}]^p\Big]^{1/p} \tag{3.2}$$

Eq. 3.2 indicates the objective function to be minimized, where p represents the metric defining the family of distance functions; n is the number of criteria considered; w_i is the preferential weight of the i_{th} objective; f_{i*} is the ideal value for the i_{th} objective and f_i^* is the anti-ideal (nadir) value for the i_{th} objective.

The distances of greatest interest for CP are those corresponding to the metric $p = 1$, or Manhattan distance, and the metric $p \to \infty$, or Tchebycheff distance.

The Manhattan distance, or L_1, is defined by the following expression:

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[2] Profuse explanations of these techniques can be found in [74].

$$L_1 = \sum_{i=1}^{n} w_i \frac{f_i^* - f_i(x)}{f_i^* - f_{i*}} \tag{3.3}$$

That is, the normalized and weighted sum of the deviations of each attribute from its ideal value.

Besides, Tchebycheff's distance is defined as

$$L_\infty = max_i \left| w_i \frac{\left|f_i^* - f_i(x)\right|}{\left|f_i^* - f_{i*}\right|} \right| \tag{3.4}$$

that is, Tchebycheff's distance corresponds to the greatest deviation of the attributes from their ideal value.

In terms of mathematical programming, the L_∞ minimization can be expressed as follows:

$$\begin{aligned} \min L_\infty = D \\ s.t. \\ f(x) \in F \\ \left| w_i \frac{\left|f_i^* - f_i(x)\right|}{\left|f_i^* - f_{i*}\right|} \right| \leq D, \forall j \end{aligned} \tag{3.5}$$

where D represents the largest deviation, and F the set of feasible solutions.

According to [15], it can also be verified for this L_∞ distance that:

$$W_1 \frac{f_1^* - f_1(x)}{f_1^* - f_{1*}} = \ldots = W_i \frac{f_i^* - f_i(x)}{f_i^* - f_{i*}} = \ldots = W_n \frac{f_n^* - f_n(x)}{f_n^* - f_{n*}} \tag{3.6}$$

This shows that the L_∞ solution represents a perfect balance between the different criteria once they have been normalized and adjusted with their corresponding weights.

In summary, from a preferential point of view L_1 and L_∞ solutions represent two opposite poles. The L_1 solution implies the maximum aggregate achievement, i.e. maximum efficiency, whereas the L_∞ solution implies maximum equity.

In addition, these two distances represent the edges of the whole compromise set. In order to get some other intermediate solution, the following optimization problem can be solved:

$$\begin{aligned} \min(\lambda L_1 + (1-\lambda) L_\infty) \\ s.t. \\ f(x) \in F \\ \left| w_i \frac{\left| f_i^* - f_i^* \right|}{\left| f_{i*} - f_i^* \right|} \right| \leq D, \forall j \end{aligned} \tag{3.7}$$

From the above, it is clear the capacity of this technique to adapt to the resolution of decision problems with efficient sets so large that they need to be simplified, and at the same time, problems that must incorporate the criteria of different stakeholders. For these reasons, CP has been the main technique chosen for the development of the case study of this thesis. The application of the methodology to it is presented in the Chapter 7.

Besides, goal-based programming (GP) states that in complex situations, with incomplete information, limited resources, multiple objectives or conflicts of interest, we may not be in a position to optimize, so that it may be sufficient to achieve certain levels of achievement. It is based on the "satisficing" philosophy [261].

A goal is the combination of an attribute with an aspiration level. It is formulated as follows:

$$\begin{aligned} f_i(x) + n_i - p_i = t_i \\ n_i p_i = 0 \end{aligned} \tag{3.8}$$

where n_i represents the lack of achievement, p_i the excess of achievement (both deviation variables), and t_i the aspiration level.

GP technique is focused therefore in minimizing unwanted deviation variables, subject to the constraints of the original problem and the soft constraints of each target. Depending on the type of minimization, different type of goals can be used, namely, weighted goals, lexicographic goals or MINIMAX goals[3].

Although this is not the main technique chosen for the case study of this thesis, there is a small application of it in the calculation of the inconsistency of the decision-makers (see Chapter 7).

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[3] Again, the reader interested in these techniques is encouraged to revise [15].

Finally, let us introduce some basic principles of the most popular discrete technique, namely the AHP, developed by Thomas Saaty [246]. It is a widely used methodology. In fact, many software applications that implement it have been developed in the last decades.

The main advantage of the method is that, as CP or GP, it does not require the generation of the efficient set, so it does not involve much calculation and is also easy for decision makers to understand. The main drawback is that, by not considering the range of variation of the criteria, it is not valid according to neoclassical economic theory.

The philosophy of AHP can be summed up by the fact that when a problem is too complex, it is necessary to (1) break it down; (2) make decisions on small problems; and (3) add solutions to sub-problems. It is therefore based on the innate human ability to make reasonable decisions about small problems. It is interesting to note the reductionist inspiration of the methodology that does not problematize the division of the problem into its simplest parts to solve them individually. The reaction against this approach will be one of the key elements of the complex thinking that will be presented in the next section.

Thus, the phases of the AHP methodology are (1) the hierarchization of the problem; (2) the issuance of value judgments; (3) the translation of value judgments and finally (4) the calculation of a coherent set of weights.

As CP and GP, this technique has been used in the development of the case study of the thesis, this time for the hierarchization of the criteria and for obtaining the weights assigned by the decision makers to them. A detailed description of this process can be found in the corresponding Chapter 7.

3.1.1.2 Applications

As mentioned above, the purpose of this review of multi-criteria frameworks is to find or to define a framework applicable to the study of the sustainability of energy systems, since it is a crucial sector for achieving the global goal of SD.

From this perspective, the state-of-the-art review was divided into two parts. The first concerned the use of the multi-criteria techniques as a general framework for addressing the challenge of SD in all its complexity. The second dealt with the use of multi-criteria proposals to support decision-making specifically in the energy sector.

In relation to the first one, Munda's work stands out [193, 190, 195, 191, 192, 194]. According to him, MCDM evaluation supplies a powerful framework for the implementation of the incommensurability principle, namely "the absence of a common unit of measurement across plural values since it meets several goals at the same time".

To overcome this difficulty, Munda proposes a series of requirements that such an analysis should have, namely, (1) being inter/multi-disciplinary, (2) participatory[4] and (3) transparent. And precisely all these requirements are fulfilled by MCDM, which lead him to propose it as an adequate assessment framework for aiding sustainability policy-making.

This question of incommensurability is the result of the classic disputation between weak and strong comparability [170] and reflects the clear position of Martínez-Alier et al. for rejecting reductionist economic proposals that, according to them, fail from their very conception of the problem, i.e. reducing all the criteria exclusively to monetary variables. Surely no one has raised the issue better than economist Kapp [136]:

> “To place a monetary value on and apply a discount rate (which?) to future utilities or disutilities in order to express their present capitalised value may give us a precise monetary calculation, but it does not get us out of the dilemma of a choice and the fact that we take a risk with human health and survival. For this reason, I am inclined to consider the attempt at measuring social costs and social benefits simply in terms of monetary or market values as doomed to failure. Social costs and social benefits have to be considered as extra-market phenomena; they are borne and accrue to society as a whole; they are heterogeneous and cannot be compared quantitatively among themselves and with each other, not even in principle”.

So far the introduction of Munda’s works on multi-criteria applied to SD, which have been of enormous inspiration for this thesis.

Another proposal that has addressed the convenience of using multi-criteria techniques applied to sustainable development is Boggia’s [23], who developed a methodological approach based on multi-criteria analysis aimed at ranking areas (municipalities) in order to understand the specific technical and/or financial support that they needed to develop sustainable growth. He applied it to a case study in different areas of an Italian region.

Besides, Cinelli’s [53] analyzed the performance of five MCDA methods related to ten crucial criteria, among which are a life cycle perspective, thresholds and uncertainty management, software support and ease of use.

Beyond the academia, international institutions have also promoted the use of MCDM for SD. The United Nations Framework Convention on Climate Change (UNFCCC) includes them as one of the most important tools in assessing impacts, vulnerability and capacity to adapt to climate change. The Tyndall Centre report in 2003 [32] is another good example of a framework proposal for energy sustainability analysis based on these techniques.

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[4] In this sense, Popa’s reflection on trandisciplinarity and “reflexion” understood as including different actors in the participatory process is particularly interesting [222].

In addition to the above, there are a huge number of articles and technical reports that present MCDM sustainability analyses focused on specific sectors, technologies or areas. Among them, I will focus on those that are most relevant to this thesis, that is, those that have to do with energy systems.

The number of publications on MCDMs applied to energy is also very high. Therefore it was decided to focus on the most significant state-of-the-art reviews on the issue in recent years, starting with Pohekar's work in 2004 [221]. There, a review of more than 90 published papers is presented in order to analyze the applicability of various MCDM methods, i.e. weighted averages, priority setting, outranking, fuzzy principles and their combinations. The 90 articles were classified according to their application area, being the most popular renewable energy planning followed by energy resource allocation. Regarding the techniques, AHP is the most used followed by outranking techniques: Promethee and Electre.

In 2009, Wang et al. published another state-of-the-art review of MCDM applied to energy systems [324]. In it they reviewed the corresponding methods in different stages of MCDM, i.e., (1) criteria selection, (2) criteria weighting, (3) evaluation, and (4) final aggregation. The criteria are summarized from technical, economic, environmental and social aspects. In this regard, investment cost was the most used criteria followed closely by CO_2 emissions. The weighting methods were classified into three categories, namely, subjective weighting, objective weighting and combination weighting methods. Here equal criteria weights were found to be the most popular ones. Eventually, several methods based on weighted sum, priority setting, outranking, fuzzy set methodology and their combinations applied to energy decision-making were analyzed. Among those, AHP was the most popular.

More recently, Strantzali and Aravossis [274] developed another review focused on Decision Support Systems applied to renewable energy. They analyzed 183 studies and classified them according to the year of publication, method used, energy type, application area, criteria and geographic distribution. The methods that were found to be the most popular were those based on AHP techniques.

In 2017, Kumar et al. [143] summarized the essential aspects of MCDM techniques applied to energy issues and outlined various performance indicators. According to the authors, no single MCDM model can be ranked as best or worst, each method has its own strength and weakness depending upon its application in all the consequence and objectives of planning. They also highlight the need for a process of hierarchy so that sustainable energy planning can be evaluated not only considering a single scenario based on multiple criteria but also considering multiple scenarios based on multiple criteria. This work by Kumar et al. is particularly illuminating in terms of the need to transcend substantive rationality when addressing sustainability issues[5]. This is what the complexity-based proposals in the next section will be about.

Mardani et al. [168] selected and reviewed 196 published papers, from 1995 to 2015 in 72 journals related to energy management. They were categorized into 13 different fields: environmental impact assessment, waste management, sustainability assessment, renewable energy, energy sustainability, land management, green management topics, water resources management, climate change, strategic environmental assessment, construction and environmental management and other energy management areas. Furthermore, papers were categorized based on the authors, publication year, nationality of authors, region, technique and application, number of criteria, research purpose, gap and contribution, solution and modeling, results and findings. Hybrid MCDM and fuzzy MCDM in the integrated methods were ranked as the first methods in use. And environmental impact assessment was ranked as the first area in which decision-making approaches were applied.

Finally, it is worth mentioning a very recent work whose subject fits perfectly with the focus of this thesis, that is, the proposal of a sustainability analysis framework applicable to energy systems. This is Volkart's work in Switzerland [316].

In the context of the Swiss energy system, where nuclear power will be phased-out and greenhouse gas emissions are to be dramatically reduced, she developed her research aiming at supporting prospective Swiss energy policy-making by providing a detailed sustainability analysis of possible energy system transformation pathways. For this purpose, she used an energy system model to quantify the variables in different future scenarios and coupled it with a MDCA. Twelve interdisciplinary indicators were used. The results of the analysis showed that implementing a stringent climate policy in Switzerland was associated with co-benefits such as less fossil resource use, less fatalities in severe accidents in the energy sector or less societal conflicts and higher resource autonomy. Regarding CSS technologies, the availability and implementation of them allowed for achieving the GHG emission reduction target at lower costs, but at the expense of a more fossil fuel-based energy system.

This work was especially inspiring for this thesis in the development of its case study. The system to be analysed, i.e. the energy system of a nation, coincided with the one proposed for the present work, so the way in which it was dealt with was very helpful. In addition, Volkart identified a gap in the literature that she suggested as future work: "the full integration of the MCDA and partial equilibrium energy system modelling by for example endogenising

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[5] A brief introduction to this interesting discussion between substantive and procedural rationality was included in the Chapter 2.

the indicators". That is precisely the effort made by this thesis in its Chapter 7, and one of its main contributions.

3.1.1.3 Conclusion

This brief overview of MCDM as a possible framework applicable to the SD study in general, and to energy sustainability in particular, is concluded here by analyzing its pros and cons in this sense.

To the credit of these proposals, their theoretical solidity and broad development should be highlighted. These consolidated methodologies have been widely used in recent decades as tools to aid decision-making in many areas.

On the debit side, some critics of the MCDM point to one of its main features as its main weakness, namely that it has a subjective component. However, this is precisely why it is more realistic than the classic decision framework. It helps to formalize complex decision problems, and to make more coherent decisions.

Finally, with regard to its capacity to adapt to the concrete approach sought in this thesis, i.e. an operational framework that would be compatible with a capital-based definition of sustainability and capable also of integrating the two main schools, SS and WS, it can be said that the evaluation is positive.

Munda's works show that multi-criteria methods, besides containing pure analytical tools inspired by a neoclassic economic rationality, also integrate proposals where uncertainty and bounded rationality play a fundamental role [189].

Thus, I agree with Martínez-Alier [170] that MCDM is a good tool for sustainability assessments since it is multidimensional in nature and allows us to take into account economy-environment interactions. Additionally, according to the aggregation procedure chosen, weak or strong sustainability concepts can be operationalized. This depends on the degree of compensability allowed by the aggregation procedure.

This crucial point in the aggregation that allows both approaches to be integrated will be the key to be addressed in the proposed framework presented in Chapter 5.

3.1.2 Systemic frameworks

It has been already highlighted the consensus in the literature regarding the complex nature of the sustainability challenge. This has led many authors to propose methods that go beyond a reductionist way of doing science, starting with the immediate rejection of any attempt to simplify it from the narrow view of a single discipline, be it economics or ecology. According to them, if we want to achieve a level of understanding of the very goal of sustainability that allows us to move towards its achievement, we need Funtowitz and Ravetz's "orchestration of sciences" collaborating for this in a transdisciplinary way, as mentioned in Chapter 2.

These authors have seen in the complex nature of the challenge of sustainability a not accidental but rather essential characteristic of the concept, and therefore they have claimed that only by using a complex system paradigm we will be able to provide solutions that will guide us along the path of SD.

Thus, this part of the state-of-the-art review focuses on presenting these proposals based or inspired by the theory of complex systems.

This section, probably the most unknown, requires in my opinion a more in-depth explanation. I will begin by introducing the very concept of complexity, or more specifically, of complex thinking. Then I will focus in defining what we mean by complex systems. Finally, some concrete applications of complex systems to SD will be presented.

3.1.2.1 Complex thinking

Delving into the very root of complex thinking brings us to the figure of Edgar Morin [184], a French philosopher and sociologist (with Sephardic Jewish ascendancy) who is considered the father of this complex thinking epistemic paradigm.

The best way to present this thought is to do so in contrast to the dominant thought, which Morin catalogues as "simplifying thinking".

Such simplifying thinking is characterized by the following four basic principles [183]:

1. The *disjunction* that tends to isolate, to consider the objects independent of their environment.
2. The *reduction* which tends to explain the reality by only one of its elements: whether psychic, biological, economic, spiritual, etc.
3. The *abstraction* which establishes general laws regardless of the particularities of the phenomenon.
4. The *causality* which sees reality as a series of causes and effects, as if it were a linear path.

Conversely, the basic principles of complex thinking are as follows:

1. *Dialogic*: It is a reaction against mono-logical reductionism and also against the dialectics, since in dialogic thinking there is no overcoming of opposites, but the two terms coexist without ceasing to be antagonistic, i.e. "Contraria sunt complementa".

2. *Recursiveness*: Effect becomes cause, cause becomes effect; products are producers, the individual becomes culture and culture becomes individuals.

3. The *hologrammatic principle*: This principle seeks to overcome the principle of holism and reductionism. Holism sees only the whole; reductionism sees only parts. The hologrammatic principle sees the parts in the whole and the whole in the parts. This is a characteristic that, in my opinion, is often misunderstood in some proposals that confuse holistic with complex. A complex approach to any problem requires a complementary look between the holistic and the particular.

It can thus be observed that this paradigm[6] of thought presents an amendment to the whole to the way science is done today. The attempt to divide complex problems into non-complex sub-problems presupposes a linear causality that does not reflect the reality of things. In complex thinking heterogeneity and interaction are always considered; every object of knowledge, whatever it may be, cannot be studied in itself, but in relation to its surroundings; precisely because of this, every reality is a system, because it is in relation to its surroundings.

After this brief introduction to the key aspects of complex thinking, we can see what we anticipated in the Chapter 2: the Post-Normal Science proposal, on which many sustainability researchers rely, has a clear complex inspiration.

In summary, complex thinking proposes a deep epistemological reformulation based on (1) non-linearity; (2) non-reductionism; (3) openness; (4) inter and transdisciplinarity; (5) recursivity; (6) focusing more on the links than in the nodes, (7) emergence and (8) transformation.

The reader may be wondering what sense this introduction to complex thinking makes, perhaps more appropriate for a thesis in epistemology than in engineering. It was decided to add this introduction because it will help us to identify the presence or absence of elements based on complexity in the different complex system-based framework proposals found in the literature. Eventually, we will see that although the main technique on which the framework proposal of this thesis is based is multi-criteria theory, some elements inspired by this complex paradigm are also present.

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[6] According to Morin, a paradigm is a mental and cultural structure under which reality is perceived.

3.1.2.2 Complex systems

In the same way that complex thinking was presented as opposed to simplifying thinking, I now present here the characteristics that differentiate complex systems from simple systems. Bell and Morse's work [19] will be the main reference for this.

1. Predictable behavior. Simple systems exhibit a behavior pattern that is easy to deduce from knowledge of the external inputs acting upon the system. Conversely, complex processes display counter-intuitive, seemingly acausal behavior full of unpredictability. It can be observed that this characteristic of complex systems is again closely related to the recursiveness (non-linear causality) characteristic of complex thinking.

2. Few interactions and feedback/feedforward loops. Simple systems generally involve a small number of components, with self-interaction dominating the mutual interaction of the variables. Involving only a few variables, simple systems generally have very few feedback/feedforward loops. Such loops enable the system to re-structure, or at least modify, the interaction pattern of its variables, thereby opening-up the possibility of a wider range of potential behavior patterns. The hologrammatic principle of complex thinking, although not explicit here, works through the relationship between these parts.

3. Centralized decision-making. Power in simple systems is generally concentrated in one or, at most, a few decision-makers. By contrast, complex systems display a diffusion of real authority. This is particularly important when it comes to designing decision support tools in the energy sector. It is not enough to empower the regulator or the utility when dealing with global sustainability goals.

4. Decomposable. Typically, a simple system involves weak interactions among its constituent components. Conversely, a complex process is irreducible. Neglecting any part of it or severing any connection destroys essential aspects of the system's behavior or structure. Again, the non-reductionist characteristic of complex thinking is present here.

In summary, complex systems are characterized by (1) counter-intuitive unpredictable behavioral modes; (2) relatively large numbers of variables interacting through a rich network of feedback/feedforward connections; (3) decentralized decision-making structures and (4) a high level of functional indecomposability.

It is easy to understand from this introduction that the system put into play in the sustainability analyses, namely the anthroposphere were the interaction between the three classical dimensions: economic, ecological and social (or their associated capitals) occurs, responds to this complex system profile. Moreover, complex is not only the global system under study when it comes to proposing strategies for sustainable development in the broadest sense, but also the different sub-sectors that contribute to this development. One such sector would be the energy sector under consideration in this thesis.

3.1.2.3 Applications

We already know what complex thinking is, how complex systems are defined and that the system at stage in a sustainability analysis belongs to this category; let us now look at some concrete framework proposals based on complex systems theory that try to apply these principles to the study of sustainability[7].

3.1.2.3.1 SSA - Imagine

Systemic Sustainability Analysis (SSA) is defined by Bell and Morse [19] as the participatory deconstruction and negotiation of what sustainability means to a group of people, along with the identification and method of assessment of indicators to achieve that vision of sustainability. Their belief is that participation, although difficult and problematic in itself, is preferable to projects that are determined top down. It is worth recalling here the requirements of Munda for any sustainability assessment, namely, inter-disciplinarity, participation and transparency. The alignment of Bell and Morse's proposal with Munda's is clear.

SSA may be achieved by employing a variety of specific participatory methods depending upon who the stakeholders are and the broad context of the analysis.

"Imagine" is a concrete SSA focused on projects that deal with sustainability. To develop the Imagine approach a number of stages must be undertaken, namely, (1) identify the stakeholders and the system; (2) identify the main sustainability indicators; (3) identify the reference condition; (4) the development of the AMOEBA diagram[8]; and (5) the extension of the AMOEBA over time.

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[7] This section will not delve into all the tools based on dynamic systems (soft-computing) that have been developed and applied directly or indirectly to the resolution of problems related to sustainability [88, 49, 126]. The reason for not stepping into this world is because the primary objective of the thesis is not to provide a specific tool but rather a framework for analysis. Once presented, and depending on which family this framework belongs to, it might be discerned which concrete tool should be used in each concrete application of it.

[8] This was presented as a method to represent multiple sustainability indicators [31] in one diagram and has since been developed in a systems manner.

This methodology has been applied to the sustainability analysis of Coastal zones in the Mediterranean [19] and to a Coastal Area Management Programme in Slovenia [167]. Although, to my knowledge, there is no application of Imagine framework to energy sustainability studies, the methodology is potentially applicable to these cases.

It is worth noticing the similarities in the steps of this methodology with the steps of the multi-criteria AHP described in the previous section. This reinforces the idea that multi-criteria methodology, understood not only as an analytical tool, but as a complete framework for the assessment of sustainability issues, also draws on the tradition of complex thinking presented here.

Although the Imagine framework proposal has not been very well developed to date, I would like to highlight its potential, especially in its participatory nature, which is defined as an open dynamic-recursive process. I also find the visual instrument used to show the results very interesting, i.e. the AMOEBA diagrams. A version of these diagrams has been used in this thesis for the comparison of the results in the case study (see Chapter 7).

3.1.2.3.2 DPSIR

The Driver-Pressure-State-Impact-Response (DPSIR) framework is a causal model for sustainability analysis. It is the model used by the EEA and the UN, based on the classic PSR proposed by the OECD in 1992. It has been used in numerous analyses related to the issue of energy sustainability. One of these applications can be found in the BP Observatory of Energy and Sustainability, which used this framework in its 2008 edition to integrate its proposal based on indicators [64].

The DPSIR framework divides the problem into 5 interrelated factors, namely:

- Driving forces: A driving force is a need. Examples of primary driving forces for an individual are the need for shelter. For a nation, a driving force could be the need to keep unemployment levels low [141]. In the case of the energy sector, it would be the need to cover the demand of energy services by the society.
- Pressures: Driving forces lead human activities to exert pressures on the environment, as a result of production or consumption processes. They can be divided into three main types: (1) excessive use of environmental resources, (2) changes in land use, and (3) emissions to air, water and soil.
- State: As a result of pressures, the state of the environment is affected; that is, the quality of the various environmental spaces in relation to the functions that they fulfill. The state of the environment is thus the combination of the physical, chemical and biological conditions.

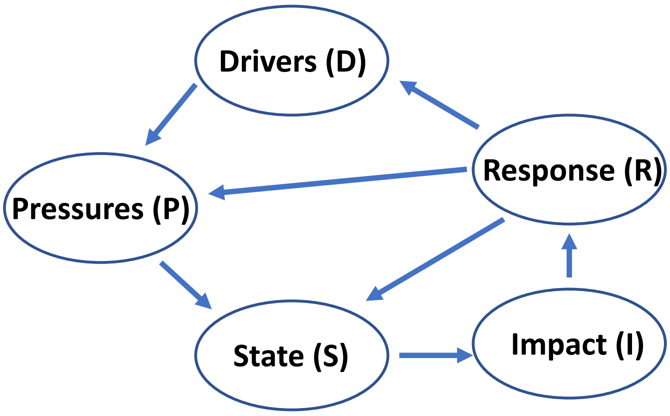

Fig. 3.1 DPSIR model. Adapted from [141]

- Impacts: Changes in the state may have environmental or economic impacts on the functioning of ecosystems, and ultimately on human health and on the economic and social performance of society.

- Responses: A response by society is the result of an undesired impact and can affect any part of the chain between driving forces and impacts.

A basic distinction between pressure, state and response was employed by the United Nations for their Indicators for Sustainable Development (ISD), proposed in the 1992 Rio Earth Summit. The UN published the results of its third revision of them in 2006. Interestingly, it abandoned the DSR framework in favor of a theme-based approach: the Sustainable Development Goals, proposed in 2015.

This DPSIR framework is included here since it incorporates non-linear causality across feedback loops between the responses and the drivers, pressures and state, as is shown in Fig. 3.1. This way it can be considered, at least partially, as a complex framework for SD analysis.

Various applications of the method for environmental analysis can be found in the literature [11, 173, 139]. One of them is NERI's (National Environmental Research Institute) methodology in which environmental problems are defined and structured using this framework.

3.1.2.3.3 VSM

The Viable System Model (VSM) proposal is probably the complexity-based approach that has been applied most broadly and in the most depth to the SD challenge. That is why I will go into more detail on its presentation.

The VSM is a second-order Cybernetics application developed by Stafford Beer which tries to offer a holistic form of observing collective behaviours in today's societies [76]. Its history goes back into the late 1950s. Stafford Beer created it in the context of the earlier work in cybernetics by Norbert Wiener, Warren McCulloch and Ross Ashby, especially his studies on viable systems.

According to Ashby, a viable system is one "capable of maintaining an independent existence - not one that is completely separate from the environment, but one where structural changes take place without loss of identity and without separation from the niche" [10].

The challenge that gave rise to this model was how to deal with the complexity between the viable system and its niche[9]. Such systems have their own problem solving capacity. If they are to survive, they need not only the capacity to respond to familiar events, but the potential to respond to unexpected events, to the emergence of new eco-social behaviours and even to painful catastrophes.

Ross Ashby's Law of Requisite Variety is at the core of the VSM. Broadly speaking, this law states that a "controller" has requisite variety, i.e. has the capacity to maintain the outcomes of a situation within a set of desirable states, if and only if it has the capacity to produce responses to all those disturbances that are likely to take the outcomes out of the set. In other words, the Law of Requisite Variety suggests that the variety of responses produced by the system should at least equal those emerging from its environment, and the variety of responses of management should at least equal those of the system (see Fig. 3.2).

Beer's model of such a viable system is composed of a set of operations, a meta-system, and the environment within which it impacts and sustains itself.

Thus, the VSM is a particular method in which those different parts of the system relate each other, one that is derived from studying biological systems. In these systems, hierarchy is replaced by structural recursion. Living (viable) systems, from the most elementary cells to human beings, are self-organising and self-regulatory systems where cells' functional differentiation and connectivity may produce more complex living systems, without cells losing their self-organising and self-regulatory characteristics. This produces viable systems

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[9] That is, in sustainable terms, between the human socio-economic system and the environment that sustains it.

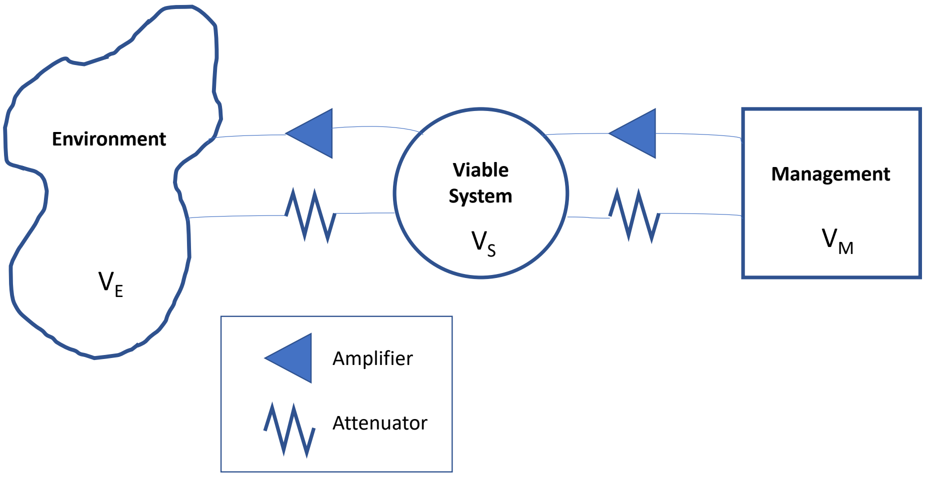

Fig. 3.2 VSM - Managing complexity. Adapted from [76]

within viable systems, at increasing levels of complexity. Fig. 3.3 shows the unfolding of a viable system complexity based on this principle.

For instance, if we are to apply this model to the analysis of the electricity system in a region, these levels would go from the simpler cells, namely, the consumers managing the households, to the top-level viable system, namely, regulators managing the interconnected power system.

Several applications of VSMs to SD studies can be found in the literature.

First of all, Espinosa's proposals [77], who revisited the work of Stafford Beer in organisational cybernetics to help researchers and practitioners in the field of SD understand how it could help in the re-design of social structures and institutions, in forms that are better prepared to foster sustainability.

Thus, from this perspective, sustainability would be an ongoing process constituted through the dynamic relationships between viable organisations. Additionally, sustainability had to be a term constantly open to negotiation and local definition in dialogue. It should be more a fruit produced by procedural rationality than by substantial rationality [262][10].

Besides, viability is clearly very closely linked to sustainability: both result from the organisation dealing with the environmental complexity in the course of its own dynamic

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[10] The reader is invited to review the presentation of this interesting discussion in the Chapter 2.

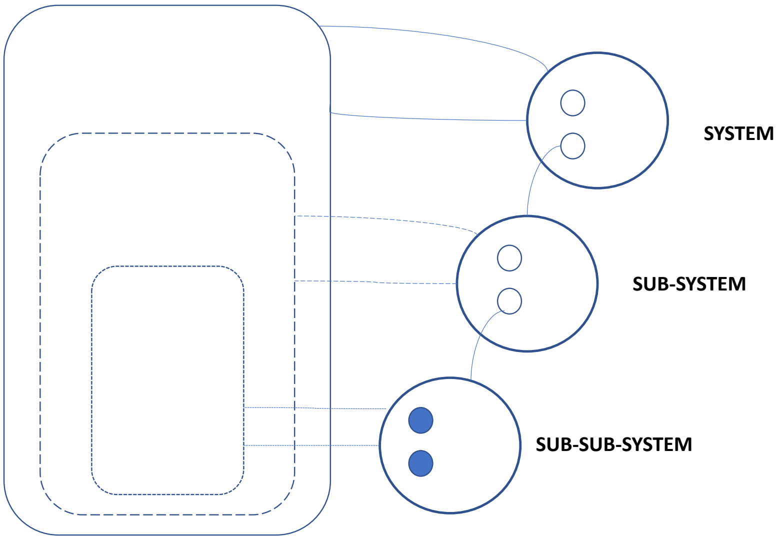

Fig. 3.3 VSM - Unfolding complexity. Adapted from [76]

changes and development. Lack of viability or severance from its niche, as defined by Santiago's school[11], indicates death or cessation of that life form.

Developing the previous ideas, Espinoza indicates a number of reasons why the VSM might be of particular value to support sustainability, in comparison with more traditional organisational approaches.

1. Autonomy and Cohesion. According to Espinoza, this is particularly relevant to implementing sustainability agendas, as it is precisely the cohesion of structurally coupled autonomous systems at every recursive level that will eventually produce sustainability (understood from a strong perspective where the weight lies in guaranteeing the resilience of the environment). It may be seen that this feature comes naturally when the system is defined as viable.

2. The Role of Higher Management. In the VSM, management is not top-down. The role of the highest level in the model is not to decide but rather to provide a meta-

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[11] The Santiago theory of cognition by Maturana and Varela, based on autopoiesis principle [109], has demonstrated the intimate relationship between an organism's cognitive domain and its interaction with the niche it inhabits, as distinct from simply talking about and exploring the organism and 'the environment'. In this usage, the niche is a subset of the total environment, that aspect of the environment that the organism is structurally coupled to in its realization of life.

understanding of the entailed issues that ensures the cohesion that constitutes the system. This point highlights the novelty of the VSM compared to other decision models. The hierarchy obeys the very logic of the viable system, being its structure organic rather than pyramidal.

3. Structural coupling with the Environment. It is by mapping the interaction between the environment and the various parts of the system (at all levels) that we can take account of the viability of their interactions with their ever-shifting niches. This characteristic was a first key factor in the development of this thesis. If what we were looking for was a framework that would allow us to tackle the challenge of SD in all its complexity, that framework could not be closed, it had to be open, that is, it had to be integrated into a supporting framework that is none other than the biosphere, or the anthroposphere, if we look at it from a purely anthropocentric perspective. This clue also led us to the concept of exergy, which will be discussed in the next section on sustainability indicators.

4. Variables and Metrics for Sustainability. Instead of designing metrics and measures to control the systems from above, the VSM suggests the need to design meta-systemic tools to monitor self-regulation of embedded viable systems. The connection to the first point is clear. Additionally, it also suggests the idea of eudemony as a measure of people's well being[12].

5. Participation and Re-engagement. Variety balancing between all operations at all levels require empowered, engaged individuals/communities/organisations, and the only way effective organisation can be articulated is to devolve power to the level that get things done.

The summary of Espinosa's proposal for the use of VSM as a tool for sustainability ends here. Yet while it is perhaps the most elaborated contribution, it is not the only one.

Similarly, Leonard's proposes another application of VSM to sustainability analyses [148]. In her paper she explores the use of Stafford Beer's proposal to design human communities that foster adaptation to criteria of sustainability in eco-social environments using three levels of recursion, namely, the household, the neighborhood and the city.

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[12] This issue, which may seem anecdotal, reflects the ethical rationale behind this proposal. Unfortunately, delving into this idea exceeds the limits of the present work but will be indicated as a possible future line of research.

Another interesting application is Schwaninger's [253]. Moved by the fact that, in his opinion, the quest for the ecological sustainability of planet Earth at this stage is not at all successful, he presents an integrative concept for sustainable renewal based on Beer's VSM. He develops a structure that enables agents at all recursive strata to generate variety in balance with the complexities they face. According to him, the VSM cybernetic model organizes the efforts for sustainability in a more effective way than conventional approaches.

In relation to VSM proposal applied to energy sustainability, few references were found. One of the most interesting is Herzog's [123]. He developed an approach for a scalable battery storage system based on VSM. Results show a high efficiency even in partial load operation, fault tolerance and availability in error cases, maintainability and a high flexibility.

To my knowledge, an application of VSMs to study the sustainability of energy systems from the perspective of aiding decision-making in energy transition has not yet been developed.

VSM framework is in my opinion a very powerful conceptual tool that could not only help much in the ex-post analysis (monitoring) of key variables in sustainable energy transition but could also help in the design of appropriate policies for SD. This recursion level-based design makes VSM well suited to address problems that have traditionally required top-down and bottom-up approaches. The VSM integrates both in a coherent way, thus giving practical expression to the principle of subsidiarity, and to the hologrammatic principle of complex thinking.

That said, as with the other complex approaches presented, we cannot forget the difficulties inherent to their real implementation, as will be discussed later.

3.1.2.3.4 SOHO

Kay [137], is one of those authors mentioned in the introduction of this section that believes that the dynamics of ecosystems and human systems are much better addressed in the context of Post-Normal Science grounded in complex systems thinking [91]. In this sense, he proposes to portray these systems as Self-Organizing Holarchic[13] Open (SOHO) ones and interpret their behaviours and structures with reference to non-equilibrium thermodynamics.

Self-organizing holarchic dissipative processes emerge whenever sufficient exergy is available to support them[14]. Once a dissipative process emerges and becomes established it

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[13] According to Kay, a holarchy is a generalized version of a traditional hierarchy with reciprocal power relationships between levels rather than a preponderance of power exerted from the top downwards.

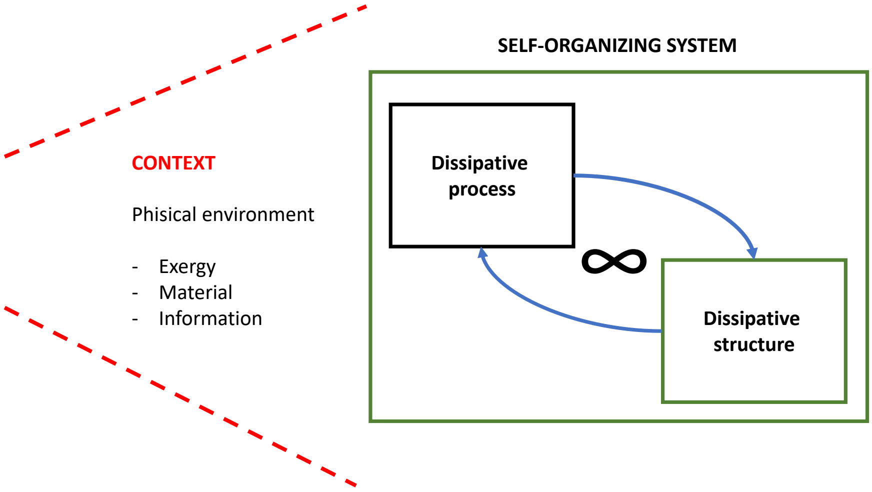

Fig. 3.4 SOHO system. Adapted from [137]

manifests itself as a structure. These structures provide a new context, nested within which new processes can emerge and so on. Thus emerges a SOHO system, a nested constellation of self-organizing dissipative process/structures organized about a particular set of sources of exergy, materials, and information, embedded in a physical environment (see Fig. 3.4).

In his approach, he emphasizes, as Martínez-Alier, that conventional science approaches to modelling and forecasting are inappropriate, given that linear misleading causality and stochastic properties prevails in them. Instead, narratives in the form of scenarios to depict morphogenetic causal loops, autocatalysis, and multiple possible pathways for development must be considered.

This SOHO proposal includes almost all the characteristics that define an approach based on complexity: open system, non-linear, recursive, etc. In this regard, it is closely related to the VSM proposal presented in the previous section. Not for nothing they are both inspired in the biological analogy for the definition of their system.

Although, as far as I know, concrete applications of the SOHO framework to case studies are very limited, I believe that it has the potential to be developed. Among these possible case studies, of course, the analysis of the sustainability of the energy systems could be one of

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[14] In this sense, Kay's proposal is clearly aligned with that of May [196] who proposed a definition of SD as "the increase of the exergy content and exergy buffering of human society, not provoking a measurable decrease of exergy content and exergy buffering of the ecosystem".

them. In this case, the global, national or regional energy system, depending on the scale on which the study were focused, would have to be defined according to a SOHO. The present thesis does not develop this model, but indicates it as a possible future line of work.

3.1.2.4 Conclusions

After this presentation of various approaches based on complex systems, it is time to assess the extent to which they serve the purpose in question, which is none other than to propose a suitable framework for the analysis of the sustainability of energy systems. However, before going into this analysis, I would like to mention a proposal for an analysis framework applicable to the study of energy sustainability which, as it is closer to a linear rather than a systemic approach and is not really a multi-criteria proposal, has run out of space of its own. It is the proposal of the economist Munasinghe ”Sustainomics” [186]. The reader interested in knowing more about it can find a brief description in the Appendix A.

Three are, in my opinion, the most relevant characteristics of these proposals for our purpose.

Firstly, they are non-reductionistic approaches rooted more on a procedural rationality than in a substantial rationality [262], that is to say, they go beyond the pure rationality that classic economics assigns to the profit maximizing subject, towards a deliberative rationality in the sense of Simon [262], much more appropriate for dealing with complex and uncertain problems such as the one at hand. Secondly, their dynamic character: they are designed to describe systems that vary over time. Thirdly, the type of relationship between the variables, since some of them allow for the integration of environments and sub-environments with recursive relationships of dependency among them in the same framework, they are well suited to model real eco-social environments, i.e. those involved in sustainability analyses.

However, the main limitation of these proposals is the difficulty to make them operational. Many of these systemic approaches run this risk, that is, they may remain mere proposals that are interesting from a conceptual point of view but are unable to be translated into concrete operational tools that aid decision-making.

To be fair, this limitation cannot be seen as an accidental flaw in the proposals, but as an essential feature of them. If we divide the challenge of energy sustainability into, on the one hand, creating the right narrative, i.e. modelling the system, and, on the other, translating that narrative into concrete analyses, these systemic approaches are perfectly equipped to undertake the first very well, but unfortunately the second not so well.

For this reason, not only practical but also theoretical approaches to the goal of sustainability are needed, since it is as important to measure well as to ensure that we are measuring what we need to measure.

3.2 Sustainability indicators

While the choice of a good framework for analysing sustainability ensures that all areas of the problem are well covered, we still need to choose indicators capable of reflecting the behaviour and evolution of the model that this framework represents.

3.2.1 Introduction

As with the frameworks, the literature on sustainability indicators is extremely large. In recent decades, plenty of sustainability indicators have been proposed with the aim of being used as measures of the sustainability of various systems. The UN proposal of the SDG alone contains more than 200[15], and so happens with many other proposals of families of indicators by other international agencies.

Along with the above, an extensive set of aggregate indicators, or sustainability indices, have been proposed that seek to capture in a single value the degree of alignment with the SD objectives of a given system, these systems being fundamentally countries.

The above was referred to indicators of SD in general, but when we focus specifically on indicators of energy sustainability, the picture is similar. Since concerns about energy sustainability issues rose to the top of the agenda of international institutions in the 1970's and 1980's, many contributions have been presented, most of them being based on particular sets of indicators [3, 4, 1, 314]. Two of them are highlighted here.

Firstly, Afgan proposed four sets of energy indicators regarding four different sectors, namely, resources, economic, environmental and social. In that proposal, the indicators within each sector were aggregated in order to provide a single figure regarding four different electricity generation technologies, i.e. solar, wind, biomass and oil. These values represented a degree of sustainability according to a scale that was built during the aggregation process.

Secondly, Vera's proposal, who guided the program by the International Atomic Energy Agency (IAEA) on indicators for sustainable energy development, is also remarkable. This program involved two different phases. In the first one, 41 energy indicators were chosen which were reduced to 30 in the second phase [4]. They were divided in three groups according to the DSR framework (a simplified version of the DPSIR presented in Section 3.1.1). As Vera emphasizes, this set is intended as a reference point or basis upon which users can

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[15] With regard to this UN proposal, some authors have highlighted the need to deepen into the conceptualization of this great set of indicators through the adoption of an appropriate framework [128].

develop their own specific indicators. It means that further manipulation and aggregation of data would be needed.

This incursion into the purely energy sustainability indicators proposed in the literature made us understand that it would be difficult to select a closed set of indicators that would allow us to undertake any type of energy sustainability analysis, whatever it might be. As Vera points out, any proposal of a generic set of indicators will always be illustrative. Each specific application should identify which of these indicators are most appropriate for the case study.

Thus, if it was not possible to find a set of generic energy sustainability indicators applicable to the chosen framework, someone might think that there was no point in further exploring this general state-of-the-art review in indicators; instead what had to be to done was to directly define the specific case study and then to carry out the exercise of choosing indicators.

However, I was not at ease with this sudden closure of the state-of-the-art review of a field as fundamental to this thesis as that of indicators. While I concluded that the specific choice of energy indicators could not be anticipated and should be taken up again in the case study (see Chapter 7), there was a great deal of knowledge gap to be filled in terms of what generic characteristics these indicators should ultimately have if they were to perform their work within the final framework proposal. This, therefore, asked for a review of the proposals of SD indicators in the literature in an attempt to identify these functionalities in them. So we were back to square one, an almost unapproachable square one indeed because of it extension and complexity.

Luckily, to clear up this complex picture, I had a good guide, which is none other than the requirements for a sustainable energy system compatible with the capital-based definition of SD already introduced in Chapter 2. If we remember, there were three such requirements, namely (1) that it should ensure that welfare does not decrease in time; (2) that its distribution is equitable; and finally (3) that it does all of the above without jeopardizing the resilient limits of the environment.

The framework, as discussed in the previous section, should allow all these requirements to be addressed in an organic way, but it was still needed to define measures to help monitor the process. That is where the indicators come in.

Following this common thread, three types of indicators were necessary in this scheme, namely (1) indicators that measure well-being or, ideally, capitals whose aggregation guarantees that this level of well-being is not decreasing; (2) indicators of equity in the distribution of wealth and (3) indicators that set absolute limits to the activity that safeguard the integrity of the environment.

Table 3.1 Strong and weak indices

Strong sustainability	**Weak sustainability**	**Partially strong**	**Undefined**
EF, HANPP, eMergy, EVI, LPI	CDI, ISEW, GPI, GS	EPI, FEEM	HDI

As soon as I set out to review the literature on indicators using the previous guide as a reference, I immediately reached a very interesting point: the discussion between the two sustainability schools, i.e. WS and SS, had a very direct influence on the proposals for sustainability indicators, specially in relation to the role of natural capital. This fact seemed to me to be of great relevance for the thesis itself, since it was in its first inspiration the proposal to integrate two schools that, although apparently antagonistic [312], were in my opinion called to collaborate within a common framework.

Therefore I set myself the objective for this state-of-the-art review on the literature on indicators based on WS and SS, to identify how different indicators representing both schools could contribute to the objectives sought.

In this search, I basically focused on proposals of aggregated indicators (indices). To this end, I specially relied on the work of Bell and Morse's on this topic [19].

The most widespread sustainability composite indicator was found to be the Ecological Footprint [273, 82], but there are many others, such as: Human Appropriation of Net Primary Production (HANPP) [107]; eMergy indicators [206]; Environmental Performance Index (EPI) [78]; FEEM Sustainability Index (FEEM SI) [47]; City Development Index (CDI) [182]; Human Development Index (HDI) [61]; Environmental Vulnerability Index (EVI) [134]; Living Planet Index (LPI) [158]; Index of Sustainable Economic Welfare (ISEW) [197]; Genuine Progress Indicator (GPI) [146] or Genuine Savings (GS) [111].

It is interesting to note that all these proposals, although intended to bring together all the complexity of the sustainability phenomenon, in practice are biased towards some specific aspect (some even fail to fulfill fundamental scientific requirements [24]). In that sense, as mentioned above, it is easy to associate them according to their inspiration by one of the two classical conceptions of sustainability[16]. A summary of these affiliations is presented in Table 3.1.

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[16] It is also important to stress that we are referring here to the use of these indicators as sustainability measures. Needless to say, if these indicators are used in other partial contexts, such as, for instance, the ISEW within a purely economic analysis, it would make no sense to link them to one of the two schools of thought on sustainability.

At this point, I considered trying to better understand the basic characteristics, if any, of each family of indicators and how they could contribute to this thesis. A distillate of this process is presented below.

1. Weak indices:

   Traditionally linked to the disciplines of welfare economics and environmental economics, in these proposals all the factors involved in the calculation of the indicator are typically transformed into monetary units. This presents obvious difficulties, since for many of the elements to be measured, especially those that have to do with the natural capital, there is no market that assigns price[17].

   Within this group we find well known proposals such as the Index of Sustainable Economic Welfare (ISEW), the Global Progress Indicator (GPI) or the Genuine Savings (GS). They belong to a group of indicators which try to correct GDP as a welfare indicator by taking into account expenditures and incomes related to social, economic and environmental sustainability [111]. There are few differences among them [260][18], being the ISEW the most extended alternative. Several ISEW analyses can be found in which this indicator has been calculated for countries and regions all around the world [271]. Although the controversy regarding the drawbacks of this approach is also extensive [200], it is a consolidated weak proposal worth of being analyzed, in particular because of its social orientation including equity concerns.

   Thus, it can be observed that these weak indicators, given that they are oriented towards the measurement of well-being, can contribute decisively to this framework of sustainability analysis sought where the non-decreasing evolution of welfare is a necessary condition. Additionally, some of these indicators include equity concerns, so in principle they can incorporate this dimension as well. Unfortunately, they are limited when it comes to setting absolute limits to human activity that safeguard environmental resilience. For this purpose, other approaches will be necessary.

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[17] The different proposals for alternative environmental valuations in the absence of markets are well known. They are not going to be evaluated here, but it is worth pointing out that all of them try to obtain the willingness to pay (accept) for an improvement (worsening) in environmental features, which in practice also consists of a monetary reduction.

[18] However, although the similarities are very notable, it should be noted that the GS indicator differs from the ISEW and the GPI in the calculation basis. While the last two are based on private consumption, the first one is based on net savings. This aspect of the GS indicator has led some authors to propose it as the most accurate indicator of weak sustainability [111, 110, 212], as it measures added value. Unfortunately, although the World Bank collects GS statistics by country, its practical development has been very limited.

2. Strong indices:

   Anchored in positions closer to ecological economics, they suggest that the only real sustainability indicators are those "coming from the ground", i.e. bio-physics. Most of these proposals are based on the exergy concept, a thermodynamic variable that links the first and second principles of thermodynamics. The exergy of a system operating in an environment measures the amount of useful energy (work) which that system is capable of developing within that environment [321]. The direct linkage of this concept with energy efficiency can be intuited, but it goes beyond it. Proposals based on the concept of exergy, such as the eMergy one [206] which follow the opposite path to WS proposals by translating all socio-economic activity into thermodynamic values, takes the use of exergy to its limits [236]. Other proposals based on exergy are: Cumulative exergy consumption (CEC), Life Cycle Exergy Analysis (LCEA), Exergetic Life Cycle Analysis (ELCA), Exergonomics, Ecological Cumulative Exergy Consumption (ECEC) or Expanded Exergy Analysis (EEA). Each of these methodologies presents its own set of exergetic indicators that reflect in different ways the burden that human activity is exerting on the environment under study.

   By their very nature, these thermodynamic proposals are very close to an eco-centric or bio-centric understanding of sustainability. Although some proposals are complete, that is, they seek to analyze the global eco-social system from an ecocentric perspective, where, in my opinion, their contribution is most relevant is in identifying the limits of the interaction between the socio-economic and the ecological spheres, or in other words, identifying critical natural capital. Rockstrom's proposal of planetary boundaries[269] is perhaps the best example of what we mean by critical natural capital.

Eventually, although each of the two families of indicators is able to cover some of the aspects sought after, none of them does so completely. On the one hand, weak approaches, especially the economics ones, are not effective in addressing the problems of setting absolute limits to human activity that safeguard the integrity of the environment. On the other hand, strong proposals have more difficulty in integrating social and equity aspects of energy distribution. Hence, I consider that there is a great way forward in this integration between two perspectives that, rather than being incompatible, could eventually be understood as complementary.

In summary, there are multiple proposals of sustainability indicators in the literature that attempt to capture its complexity. It is easy to see that such proposals can be classified according to their strong or weak inspiration. Both schools provide absolutely relevant information for the achievement of the desired goal, therefore, we cannot dispense with either of them. Weak approaches will help us to measure fair well-being, understood as aggregation of capitals, while strong approaches will help us to measure the resilient limits of the environment.

Guided by this idea, I proceeded to identify among all the weak and strong proposals those that came closest to what we were looking for. Hence, one of the alternative indicators of well-being to GDP, namely, the ISEW, was chosen as the weak indicator; and exergy, in its many variants, was chosen as the strong indicator.

In the case of WS, ISEW was selected not only for being the most widespread alternative to GDP as a measure of well-being, but also for its attempt to incorporate equity concerns within the indicator itself. On the SS side, the choice was even clearer. Exergy is a totally consolidated indicator in the strong sustainability literature.

In the following sections, both are discussed in more detail.

Nevertheless, before introducing these two proposals, it is convenient to bring up a key issue when it comes to monitoring systems with multiple variables and, therefore, multiple indicators. We are referring to the problem of aggregation. This issue has a special impact (but not only) on the WS approach, since it will be asked to be responsible for measuring well-being. It must not be forgotten that this well-being, from a capital-based approach to sustainability, is defined as an aggregation of capitals. This is precisely where the problem arises since, how can capitals be added in a coherent way without falling into misleading reductionism?

3.2.2 The problem of aggregation

The aggregation of indicators is a very complicated issue but of crucial importance in decision-making. The first condition that these aggregations have to meet is mathematical consistency. Ebert's contributions on this area are relevant [71]. He concludes that certain indexes are not to be used as aggregated sustainability indicators because of the variety of their disaggregated scales. In our case, having opted for a multi-criteria strategy, this problem is solved as long as the multi-criteria theory itself provides the required mathematical consistency (see Section 3.1.1).

A second issue to consider when aggregating is the question of *value*. Aggregation requires dealing with similar, or at least comparable units. As mentioned above, many approaches to sustainability, although accepting the division of sustainability in three poles (economic, social and environmental), usually tend to reduce all kind of indicators, whatever type they belong to, to their equivalent monetary values. This is a controversial issue where, once again, weak and strong sustainability paradigms collide. Martínez-Alier and Munda reflections on this topic are remarkably inspiring [170].

From the WS side, several approaches have been proposed to cope with these conflicts. Most of them have their roots in Utilitarianism [177] and are based on the assumption of complete commensurability (substitutability without restrictions). For these economists, the environment is a place of conflict between competing values and interests, and different groups and communities that represent them. Thus the different dimensions of value can conflict with each other and within themselves, and any decision will distribute different goods and bads across different groups both spatially and temporally. That is to say, the conflict of value is assumed to be inherent to the economic activity itself and their homogenization by means of their transformation into monetary units (prices) is not excessively problematized by the WS.

In turn, SS generally view the reliance on prices as primary expression of values with skepticism. They view economic activity as “taking place within a larger context of material flows which originate in the environment, are processed in economic activity and released back into the environment as high entropy waste” [170]. This approach is specially well summarized by O’Hara’s discursive ethics [210]. According to O’Hara, “it is not enough to ask how social and environmental functions can best be assigned monetary value so as to correct prices, what is needed instead is an understanding of the complex social, cultural, physical, biological and ecological system themselves. It demands relinquishing the centrality of the subsystem monetary market exchange and internalize economics into the material and non-material context of human lives and the environment”.

Thus SS requires a methodology that allows the complexities of all systems to be explicitly admitted to the valuation process rather than being implicitly considered in corrected market prices. In the end, this is the main gap in WS identified by SS practitioners, i.e. simple analytical frameworks to sustainability cannot cope with its vast complexity.

It is worth highlighting how a discussion of the problem of indicator valuation has led us to the need to clarify the framework of analysis we are using. It is not for nothing that the answer this thesis offers to this difficulty of aggregation, especially with regard to the calculation of well-being, does not come in the form of the choice of indicators, but rather from the chosen framework itself. As described in the previous section, both multi-criteria and systemic techniques have this difficulty very much in mind and offer technical alternatives to solve it without falling into reductionism.

3.2.3 Weak sustainability approach: ISEW

Having described this important problem that any type of indicator-based sustainability analysis faces, namely the problem of aggregation, let us look in more detail at one of the weak sustainability alternatives to the measure the well-being: ISEW.

It is important to stress again that ISEW is not presented as the only possible WS alternative, but rather as an indicator that allows us to understand what well-being we are referring to when we identify it as the value to be sustained for our generation and the subsequent generations.

As mentioned above, over the last couple of decades, environmental and welfare economics have proposed several sustainability and welfare indices as alternatives to Gross National and Domestic Product (GNP/GDP) which are not welfare indicators, although sometimes they have been wrongly used as such.

According to Neumayer, there are four main critiques related to GNP/GDP in its attempt to become a welfare indicator [198]: (1) it does not include household and volunteer labor; (2) it does not weigh the effects on welfare of unfair income distribution; (3) it does not include effects of environmental degradation due to economic activity and (4) it considers defensive expenditures wrongly as contributions to welfare[19].

In order to fix these drawbacks, several indices were proposed [111]. The Index of Sustainable Economic Welfare (ISEW) is one of them [17]. Although is not without controversy, it is a consolidated weak sustainability approach worth of being analyzed, in particular because of its social orientation by including inequality distribution issues.

The calculation process of ISEW was established by Daly and Cobb in 1989, but has been modified by different authors in several studies. ISEW accounting starts with Private Consumption (PC), which is a sub-component of GDP. Afterwards, PC is adjusted according to an index of income distribution, typically the Atkinson index [12] or the Gini index [101]. Once PC has been corrected by income distribution, all the remaining items are calculated and allocated a certain sign, according to their positive (services) or negative (costs) contribution to welfare. Finally, the items are added or subtracted to the adjusted PC in order to obtain the final figure for the ISEW. Therefore, the ISEW is the sum of adjusted personal consumption expenditures and all its corrections [197].

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[19] According to Daly and Cobb, “defensive means a defense against the unwanted side effects of other productions” [63]. Hence, these expenditures should not be considered as positive contributions to welfare, but as protections against side effects of economic activity (i.e, illnesses due to pollution).

Next, the full list of items (services and costs) involved in ISEW calculation is included following Pulselli's proposal [225]. He used a particular division of the items assigning a letter to each one in alphabetical order.

- *Item A*. Year
- *Item B*. Private consumption (PC)
- *Item C*. Index of income distribution
- *Item D*. Calculation of adjusted private consumption
- *Item E*. Services - Domestic labor and volunteer work
- *Item F*. Services - Consumer durables
- *Item G*. Services from public infrastructure
- *Item H*. Public health care and education costs
- *Item I*. Costs - Consumer durables
- *Item J*. Private defensive expenditure for education and health care
- *Item K*. Local advertising costs
- *Item L*. Costs of commuting
- *Item M*. Urbanization costs
- *Item N*. Costs of road accidents
- *Item O*. Cost of water pollution
- *Item P*. Cost of air pollution
- *Item Q*. Costs of noise pollution
- *Item R*. Loss of wetlands
- *Item S*. Loss of agricultural land
- *Item T*. Depletion of non-renewable resources
- *Item U*. Long-term environmental damage

- *Item V.* Net capital growth
- *Item W-X-Y-Z.* Absolute and per-capita ISEW and GDP

The ISEW, as Lawn points out [146], is based on the Fisherian concept of income, in contrast to the traditional Hicksian definition which is the basis for GDP calculations. According to Fisher, national dividend consists not of the goods produced in a particular year, but of the services enjoyed by the ultimate consumers of all human-made goods [146]. In Fisher's view, since the stock of human-made capital depreciates through use, its maintenance is a cost not a benefit. Therefore, it is necessary to produce a throughput of matter-energy by exploiting natural capital to keep human-made capital intact. This is the idea under the inclusion of environmental items in the calculation of the ISEW, i.e. long-term environmental damage, and the separation between *services* and *costs*.

Nevertheless, as mentioned before, the ISEW is not devoid of controversy [198, 197]. Three facts condense the criticism to this indicator that can be found in the literature: (1) the lack of a theoretical foundation for it; (2) the ambiguity of being presented sometimes as a sustainability indicator and others as a welfare indicator; and (3) the arbitrary election of the items used to correct GDP.

I am persuaded that Daly and Cobb were not blind to the limitations of the index they had presented. In fact, as Daly himself stated: "the ISEW is like putting a filter on a cigarette. It is better than nothing" [225].

As mentioned above, the literature of ISEW studies is vast. Most of the studies have been developed over national territories [271].

It can thus be observed that, without the need to make it explicit, this indicator of sustainable well-being, the ISEW, is clearly inspired by the capital-based approach to sustainability. Each of the items that this analysis incorporates represent capitals, whether economic, social or environmental. And the way in which it manages them, namely by translating them all into monetary values, clearly links it also to WS.

The question that needs to be asked at this time is how ISEW serves our purpose. The answer is simple: while accepting that both the items chosen and the methodology used to calculate them should be revised, the measure of well-being to which the ISEW points out is precisely the one that the capital-based approach seeks to sustain. Thus, any concrete application of any capital-based framework analysis must be directly or indirectly aligned with the achievement of this objective. Thus, for example, the ISEW could become the variable to be optimized in an ex-ante sustainability analysis proposal applied to a state (modeled as general equilibrium). Or ISEW could be used as the WS indicator of an ex-post regional sustainability analysis that assessed the evolution of welfare and the environmental burden this development is imposing on the environment. A concrete application of this second case has been developed and is presented in Chapter 4.

3.2.4 Strong Sustainability approach: Exergy

Bearing in mind the previous discussion on problems and limitations on sustainability assessments, it is time to summarize the path that led some pioneer researchers to propose exergy as a useful tool in sustainability studies.

Although it has already been anticipated that what will be asked mainly of the strong indicators would be for them to measure critical capitals[20], this review of exergy as a sustainability indicator goes beyond that area. We will see how the proposals are very diverse: from being used merely as an indicator of efficiency in processes, to being proposed as the unifying variable in eco-social models.

It was decided to devote a lot of space and effort to this analysis of exergy because of the wide interest shown in the community of sustainability practitioners and because of the relevance I consider that an essentially energetic indicator has in an engineering thesis.

Thus, this Section[21] starts with an introduction followed by a rigorous definition of the concept. Subsequently, the different proposals for the use of the concept within sustainability studies are presented followed by a discussion. The Section ends with some general conclusions.

3.2.4.1 Introduction

Now, our attention will be placed in thermodynamics. This discipline offers the basic knowledge needed to deepen into the roots of sustainability problems at a physical level. Energy, heat, power, entropy and technical efficiency, are thermodynamic concepts whose clear definition is critical in order to offer accurate measures and guidelines for improving industrial processes as well as global energy policies. Within this broad world of thermodynamics, a powerful concept was proposed by Gibbs two centuries ago: *exergy*.

Since the second thermodynamic principle was formulated by Clausis in 1856 [54], a fruitful research has been developed in this area, and exergy has emerged as a crucial concept to be taken into account when trying to formulate the relationship between systems and their respective environments in thermodynamic terms.

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[20] Not only critical natural capital, also other critical capitals might be measured (economic, social, etc).

[21] This Section is based on the paper “Exergy as a global energy sustainability indicator. A review of the state of the art” developed by the author and Pedro Linares and published in *Renewable and Sustainable Energy Reviews* [236].

The research by Gibbs and followers was guided by a basic premise: energy did not properly reflect the elusive relationship between the system under study and its environment. The second law of thermodynamics (entropy), dictated that irreversibilities produce a continued degradation of energy. Exergy emerged then as the portion of energy which remained available after subtracting the effects of irreversibilities. Thus, exergy is the distilled result of a basic inquiry: which is the available energy resulting from the interaction between natural and artificial systems with the environment they belong to. Thanks to this characteristic, some authors started to propose exergy as an alternative measurement unit which could substitute, or at least complement, classic economic approaches[22] to sustainability.

Unfortunately, Gibbs also acknowledged that uncertainties regarding the exergy calculation would never be fully analytically solved. Hence, the full potential of the inquiry which guided those researchers toward exergy, that is, a common measurement unit that could be the bridge between physics and economy, was not finished, for a pure thermodynamic approach would never be fully capable of covering it. Some other disciplines should offer their own achievements in order to complete the scene. The roots of the necessary complementary work in sustainability science are hidden behind this previous assertion.

Broadly speaking, exergy appears as a powerful concept describing the sustainability issue in a double way: firstly, it can be proposed as that common physical measurement unit which can complement classic economic approaches under a weak sustainability paradigm. Secondly, exergy also condenses a very rich conceptual approach to sustainability by linking *systems* and *environment* in a single movement, and thus addressing also part of the strong sustainability concerns.

Exergy refers to the available, or useful energy, but it is not a property of a material or process itself. It is the portion of energy which is susceptible to be used, i.e. transformed in work, *within a defined environment*. If the connection between the process and the environment is broken, the richness of the exergy concept disappears and becomes another chemical potential whose usefulness is limited to the efficiency improvement of certain industrial applications.

The next step will consist of precisely defining the exergy thermodynamic concept. This definition will clarify possible misuses and will focus our attention on its thermodynamic properties. Afterwards, different uses of exergy regarding sustainability studies will be pre-

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[22] As mentioned above, although using exergy means a step forward in the way of dealing with global sustainability concerns, it is barely capable of dealing with some dimensions of sustainability related to social issues, i.e. equity or wealth allocation, a limitation inherent to all the thermo-economical proposals indeed. Hence, the contribution of exergy to sustainability assessments is normally restricted to the environmental pole.

sented and discussed, taking into account its precise thermodynamic definition as well as its rich conceptual potential already highlighted during the present introduction.

3.2.4.2 Definition of Exergy

Exergy is often confounded with energy. “Exergy is work, or ability of work, whereas energy is motion or ability of motion, not necessarily work” [320]. Exergy relates to the second law of thermodynamics and the works of Sadi Carnot who in 1824 stated: “the work that can be extracted of a heat engine is proportional to the temperature difference between the hot and the cold reservoir” [46].

Some years later, that famous quotation became the second principle of thermodynamics which was profusely debated and redefined during the next years. Gibbs was one of the prominent researchers in this area. He was also the conceptual father of exergy. In 1873, following a previous definition of *available energy*, he introduced the notion of *available work*:

“We will first observe that an expression of the form

$$-\varepsilon + T\eta - Pv + M_1 m_1 + M_2 m_2 + ... + M_n m_n \tag{3.9}$$

denotes the work obtainable by the formation (by a reversible process) of a body of which $\varepsilon, \eta, v, m_1, m_2, ..., m_n$ are the energy, entropy, volume, and the quantities of the components respectively, within a medium having the pressure P, the temperature T, and the potentials $M_1, M_2, ..., M_n$. (The medium is taken to be so large that its properties are not sensibly altered in any part by the formation of the body)” [100].

Gibbs’ contribution was extremely important for thermodynamics theory. In fact, thermal optimization was conceptualized through his work.

However, several decades went by until the Slovenian Zoran Rant, at a scientific meeting in 1953, suggested that the term *exergy* should be used to denote *technical working capacity*, which is the natural evolution of Gibbs’ *availability*. As Rant explained, energy literally means *internal work* from the Greek ‘en’ and ‘ergon’, and the prefix ‘ex’ implies instead an *external* quantity.

By adopting this name, all previous expressions, such as *available energy, availability, available work, potential work, useful energy, potential entropy* and later introduced terms such as *essergy*, could in principle be abandoned.

Nevertheless, in practice, it took 50 years for Rant’s denomination to become accepted worldwide.

Energy	Exergy
Dependent on the parameters of matter or energy flow only, and independent of the environment parameters	Dependent both on the parameters of matter or energy flow and on the environment parameters.
Motion or ability to produce motion	Work or ability to produce work
Always conserved in a process, so can neither be destroyed or produced	Always conserved in a reversible process, but is always consumed in an irreversible process
In equilibrium with the ref. environment, its value is different from zero	In equilibrium with the ref. environment, its value is equal to zero

Table 3.2 Energy versus exergy

A further description of this interesting historical evolution of the exergy concept, from the proposal made by Rant to its final consolidation, can be found in [258]. It is noteworthy that this debate continued in the sixties, and led to the modern efficiency definitions we are using today.

Two modern definitions of exergy were proposed by Szargut [278] in the eighties:

- "Exergy is the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with the above mentioned components of nature".
- "Exergy is the shaft work or electrical energy necessary to produce a material in its specified state from materials common in the environment in a reversible way, heat being exchanged only with the environment at temperature T_0".

Similarly, Sciubba and Wall defined exergy as "the maximum theoretical useful work obtained if a system 'S' is brought into thermodynamic equilibrium with the environment by means of processes in which 'S' interacts only with this environment" [258].

It should be noted that, in all these definitions, the role of the environment in calculation of exergy is clearly highlighted. In order to obtain exergy, defining the system is not enough, a Reference Environment (RE) must be chosen.

Since, as mentioned before, exergy is commonly confounded with energy, some authors focused their academic contribution on resolving this conflict by clearly setting the difference between both concepts.

Table 3.2, based on Dincer [69], shows these differences.

For clarity purposes, a further elaboration on the thermodynamic roots of the exergy concept has been moved to Appendix B.

Type	**Origin**	**Exergy approach**	**Source**
User-side	Life Cycle Analysis (LCA)	Life Cycle Exergy Analysis (LCEA)	[322]
		Exergetic Life Cycle Analysis (ELCA)	[58]
	Exergoeconomics	Cumulative Exergy Consumption (CEC)	[278]
		Exergoecology	[301]
Donor-side	Ecosystem ecology	eMergy	[204]
		Ecological Cumulative Exergy Consumption (ECEC)	[114]
		Extended Exergy Accounting (EEA)	[257]

Table 3.3 Exergy applications to sustainability analyses

3.2.4.3 Applications of exergy to the assessment of sustainability

Exergy has been extensively used in the technical literature for the optimization of industrial processes. Some of these areas where exergy have been successfully used are: efficiency improvement in thermal and chemical processes, development of designing tools for thermodynamic optimization, studies of material properties related to a pre-defined reference environment, improvement of thermodynamic cyclic applications (steam power cycles, gas turbine cycles, renewable energy cycles), heat exchangers, cryogenics, chemical processes and agricultural and biological system analysis.

Some interesting reviews can be found in the literature where these applications of exergy are presented [258, 238, 239].

In summary, exergy is universally recognized as an optimization tool. Yet, the inquiry presented in this research is a more specific one: can exergy be properly used as a global energy sustainability indicator?

In order to give a sound answer, different contributions to energy sustainability studies in which exergy already represents a key concept have been reviewed and are presented next. They are grouped in two sets based on two different systems of energy valuation: user and donor side. Table 3.3 collects the results.

3.2.4.3.1 User-side contributions

When energy is evaluated according to its usefulness to the end user, it belongs to a receiver (user) system of value [296]. In these approaches, exergy will become the common measurement unit enriching classic thermodynamic techniques, i.e. Life Cycle Analyses and Thermoeconomics, traditionally linked to weak sustainability studies.

Life Cycle Exergy Analysis. Environmentally-oriented Life Cycle Analysis or Assessment (LCA) became a very popular technique in the last two decades to analyze environmental problems associated with the production, use and disposal or recycling of products [102].

From a sustainability point of view, Life Cycle Assessment is a methodological framework that has offered a new and more precise means to estimate the environmental impacts attributable to the life cycle of a product [231].

According to Gong and Wall, the main drawback of LCA is related to its multidimensional approach, which causes large problems when it comes to comparing different substances. In order to solve this problem, they proposed exergy as the common measure needed, and formally created a new LCA, the *Life Cycle Exergy Analysis* (LCEA).

LCEA has been widely used in the analysis of different kind of supply systems. Following Wall's scheme, the exergy flow through a supply system, such as a power plant, consists of three separate stages. First, we have the *construction stage* where exergy is used to build a facility and put it into operation. During this time some exergy is spent and some is accumulated or stored in materials. Secondly we have the *maintenance* of the system during time of operation, and finally the *clean up stage*. These time periods are analogous to the three steps of the life cycle of a product in a classic LCA.

The condition for sustainability in LCEA is expressed in Eq. 3.10

$$E_{pr} \geq E_{in} + E_{indirect} \tag{3.10}$$

where E_{pr} represents produced exergy and E_{in} expresses input exergy. As Wall emphasizes, only when E_{in} comes from a pure renewable source, the sustainable condition of the process can be ensured.

Another proposal of exergetic-LCA is due to Cornelissen and Hirs, the *Exergetic Life Cycle Analysis* (ELCA) [58]. It uses the same framework of the LCEA [56], but a different criterion, which is now the *life cycle irreversibility*, i.e. the exergy loss during the complete life cycle of the product [57]. In the ELCA it is shown where the losses of natural resources take place. According to their authors, with this information, better proposals for reducing the loss of natural resources can be obtained.

The differences between Wall's LCEA and Cornelissen's ELCA are not very relevant. They can be found in their respective level of aggregation. The level of the former is high, i.e. it directly aggregates all the exergetic contributions in every step, whereas the latter tend to disaggregate every exergetic contribution in the three different steps in order to highlight local irreversibilities. Nevertheless, both approaches share the main advantages and disadvantages of applying exergy to classic LCA. On the one hand, measuring all the inputs and outputs in exergetic terms makes possible to calculate the global efficiency of the process under study and to set some exergetic limits to certain activities (wastes). On the other hand, difficulties in setting a comprehensive reference environment along with uncertainties on the exergetic valuations, in particular of waste products, limit its applicability.

Finally, it is worth mentioning Valero's contribution to this area. He suggests that the traditional framework of LCA, *from-cradle-to-grave*, should be modified for *from-the-cradle-to-the-cradle*.

According to Valero, to complete the calculation cycle it is necessary to calculate also the exergetic cost of replacement of materials which have been degraded throughout the life cycle of a product. He proposed to calculate that value also in exergetic terms. Therefore, the value of the total cost measured in units of exergy is called the exergoecological cost and the larger for a product or service is, the more unsustainable it will be.

Actually, the exergoecological cost is a derivation of the exergetic-cost-analysis studies developed by CIRCE during the last three decades, contributions which are rooted and linked to the works of Szargut [277], Bejan [18] and other researchers in exergy accounting and thermoeconomics.

Thermoeconomics. According to Valero, "Thermoeconomics is that science which explains the physical bases of the cost and which unites the cost with the physical processes in which the sacrifice of physical resources is located, causalised and quantified in terms of thermodynamic irreversibility" [301].

A vast literature can be found regarding this issue. The first idea of linking thermodynamics and costing was explored by Lotka [163] and Keenan [138] who clearly realized that entropic issues were to be taken into account in monetary cost considerations.

Besides, the word Thermoeconomics was first used by Myron Tribus in his MIT lectures. Later contributions were due mainly to El-Sayed [73], Tribus and Evans [291], and especially to Gaggioli [92] in the US.

At the beginning of the sixties, almost simultaneously and by independent investigators, the joint application of exergy analysis and engineering economics was presented under the name of *Exergoeconomics*. The basic idea of this method was to apply the usual procedures of Engineering Accounting linking the prices of components to their operating parameters and to their exergetic efficiency, and pricing not the unit mass, but the specific exergy content of a (material or energy) stream.

Szargut proposed the *Cumulative Exergy Content* (CEC) [278] method as a first conceptualization of this strategy. More recently, Valero, Lozano and others developed a new formalization: *Exergoecology*, or the exergy cost of a product, that is, the quantity of exergy which is necessary in order to produce it once the limits of analysis have been fixed [166, 306, 308, 307, 289, 305].

Ultimately, CEC and Exergecology share the same advantages and disadvantages of LCEA and ELCA approaches. Exergy is a valuable common measurement unit capable of unifying heterogeneous flows, but the difficulty in setting a comprehensive reference environment and to evaluate waste impacts in exergy terms generates uncertainties about the results.

3.2.4.3.2 Donor-side contributions

Unlike the previous user-side approaches, in the donor-side ones the energy valuation is done through a hierarchy of aggregated (donated) levels [296]. These methods focus on the environmental performance of the system under study on the global scale, including not only direct energy inputs but also economic and work flows, all of them transformed and evaluated in exergetic units. Although an aggregation of different kind of natural capitals is used by these methods, the role that the environment plays in them places these methods within the strong sustainability paradigm.

Regardless of their drawbacks which will be highlighted below, it is worth noting the courage of these donor-side contributions and the fresh air they bring to the sustainability research arena, in which the role of the environment has traditionally been relegated to a second place.

eMergy. eMergy is the most extended exergetic donor-side approach to sustainability. Citing H.T. Odum's words: "eMergy is the *available energy* of one kind (usually solar) that has to be used up directly and indirectly to make a product or service" [207, 203, 208, 202, 205, 209, 204]. More recently, eMergy has been defined as exergy of all types used up (in solar equivalent terms) to make a product or service.

According to Odum, since solar energy is the main energy input to the Earth, all other energies could be scaled to solar equivalents to obtain common units. Other kinds of energy existing on the Earth can be derived from these main source through a *transformity*, which is the main concept in eMergy analysis. Transformity, or Unit eMergy Value (UEV), is "the solar eMergy required to make one joule of a service or product". Hence, the solar transformity of a product is equal to its solar eMergy divided by its available energy (exergy), that is:

$$M = T * E \tag{3.11}$$

where M is eMergy (measured in solar eMergy joules seJ), T is transformity and E is available energy (exergy).

eMergy analysis introduces an energy basis for the quantification or valuation of ecosystems, goods and services. According to Odum, valuation methods in environmental and ecological economics estimate the value of ecosystem inputs in terms that have been defined anthropocentrically, while eMergy tries to capture the ecocentric value. It attempts to assign the correct value to ecological and economic products and services based on a theory of energy flow in systems ecology and its relation to systems survival. A fundamental principle of eMergy analysis is the *Maximum Empower Principle*. It states that "systems that will prevail in competition with others, develop the most useful work with inflowing eMergy sources by reinforcing productive processes and overcoming limitations through system organization" [34].

Odum asserts that this principle should be able to determine which ecological and also which economic systems would survive over time and hence would contribute to the development of future systems. The maximum empower principle suggests that designing *adaptive* systems rather than *effective* ones should be the final aim of sustainable policies.

eMergy has encountered a lot of resistance and criticism within the scientific community, but also enthusiastic support. Next, some advantages and drawbacks of Odum's contribution are presented. According to Hau [115], among the most attractive characteristics of eMergy analysis are:

- It provides a bridge that connects economic and ecological systems. Since eMergy can be quantified for any system, their economic and ecological aspects can be compared on an objective basis that is independent of their monetary perception.
- It compensates for the inability of money to value non-market inputs in an objective manner. Therefore, eMergy analysis provides an ecocentric valuation method, opposed to an anthropocentric/economics-based approach.
- It is scientifically sound and shares the rigour of thermodynamic methods.
- Its common unit allows all resources to be compared on a fair basis. eMergy analysis recognizes the different qualities of energy or abilities to do work.
- eMergy analysis provides a more holistic alternative to many existing methods for environmentally conscious decision making. Most existing methods ignore the crucial contribution of ecosystems to human well being.

Although it is not the only ecological approach, it is noteworthy that these features of eMergy analysis are particularly impressive since eMergy was developed many decades before the more recent engineering and corporate interest in sustainability.

The major criticisms of eMergy analysis are shown below:

- *eMergy and economics.* According to Ayres [13], the eMergy theory of value focuses on the supply side and ignores human preference and demand.
- *Maximum Empower Principle.* The criticism is centered in Odum's claims about the general applicability of this principle to all systems.
- *Combining disparate time scales.* Accounting for solar inputs over geological time scales is problematic since it is difficult to know the total inputs and processes over such a long period.
- *Representing global energy flows in solar equivalents.* Ayres questions such conversion since there is no simple way to discover how much of any one form of energy might have been needed to produce another in the distant past.
- *Problems of quantification.* Some authors [13, 55] claim that eMergy analysis has not considered the uncertainty in many of the numbers used to calculate the transformities.
- *Problems of allocation.* The method used for partitioning or allocating inputs between multiple outputs makes the eMergy algebra quite challenging.

In summary, it is easy to see that the most important drawbacks shown are related to the calculation of transformities. Not surprisingly, eMergy researchers are centering their efforts in refining and systematizing these calculations [33, 40, 36, 39, 90, 116, 228, 297].

H.T. Odum's eMergy was a groundbreaking proposal still needing further developments, which are to be able to solve the uncertainties about its scientific soundness. An enthusiastic community of developers, led by Mark T. Brown from Florida, is working hard to bring eMergy to the fore in global sustainability studies. Its complementary nature opens a very fruitful landscape of cooperation among different disciplines in order to obtain more accurate results. Nevertheless, as Hau emphasizes, the biggest challenge yet for eMergy is to overcome some preconceived misunderstandings to legitimate it as a sound thermodynamic approach.

Ecological Cumulative Exergy Consumption. eMergy is the most important donor-side exergetic application to sustainability studies, but it is not the only one. Hau and Bakshi [114] proposed an expansion of Szargut's CEC (described in Section 3.2.4.3.1), called *Ecological Cumulative Exergy Consumption* (ECEC). It starts with the basic premise that available energy (as used in eMergy analysis) and exergy are equivalent when three conditions are satisfied: the analysis boundary for both methods are identical, the allocation method is the same at each node and the same approach is used for combining the global energy inputs.

According to Hau and Bakshi, these conditions are usually easy to satisfy, which implies that eMergy transformities of ecological goods and services can be used to readily include their contribution in CEC analysis. Therefore, if the ECEC framework is used, CEC studies would be greatly enriched by Odum's holistic model becoming not only a thermoeconomic approach but also a complete open framework for sustainability assessments referenced to solar eMergy.

Since ECEC is a combination of CEC and eMergy approaches, it shares all the advantages of disadvantages of these approaches already presented above.

Extended Exergy Accounting. A third exergetic donor-side approach to sustainability studies comes from Sciubba's studies. Extended Exergy Accounting is a method developed by him [254] in the 90s. As ECEC, this method is a standard exergy analysis in which Szargut's CEC (see Section 3.2.4.3.1) is enriched by additional exergy flows that represent the exergetic equivalents of the Capital, Labor and Environmental Remediation Production Factors.

EEA condenses some key features of the pre-existing theories and procedures described in previous sections:

- The time span of an EEA assessment covers the entire life of the facility and/or product, as it is based on life-cycle assessment methods (see Section 3.2.4.3.1) [58].
- In EEA, all of the inputs that contribute to the formation of a product are accounted for on an exergetic basis. The basic input is a given set of raw materials, as in cumulative exergy analysis [278].
- EEA, like thermoeconomics [301, 18], uses exergy cost balances to quantify the value of every flow of matter and energy that interacts with the system under consideration.
- EEA assigns labor an intrinsic primary resource-based value depending on the local exergy resource flow, with a method in principle very similar to that proposed by eMergy analysis [204].

EEA is based on two fundamental assumptions. Firstly, the cumulative exergy content of any product is equal to the sum of the raw exergy of the original constituents that form the input to the production process plus a properly weighted sum of all the exergetic inputs into the process itself. And, secondly, labor, capital, and non-energy externalities can also be reformulated in terms of exergy. EEA proposes to assign to labor and to human services an exergetic value computed as the total (yearly averaged) exergetic resource input into a portion of society divided by the number of working hours generated therein.

Besides, EEA proposes a new means of measuring environmental impact by including in the exergetic cost of a product an environmental pollution avoidance cost, calculated as the additional extended exergy expenditure that is required for bringing all environmental discharges down to the exergetic equilibrium state.

Clearly, this approach is closely related to Valero's exergetic cost of replacement of materials [301] and to Cornelissen's abatement exergy of emissions [58].

It is specially controversial in these approaches the calculation of the environmental impact by means of non-conventional economics methods. Calculating the non used exergy in effluents is possible, yet stating that all that exergy is potentially harmful is not evident at all. Once again, this important drawback of exergy applied to sustainability studies, already highlighted in LCEA and CEC applications, appears.

Sciubba also reformulated Wall's definition of exergy as:

$$EE = CEC + E_{Capital} + E_{Labor} + E_R \tag{3.12}$$

where CEC stands for the cumulative exergy content of every raw material whereas $E_{Capital}$, E_{Labor} and E_R represent the exergy equivalent of monetary, labour and environmental remediation cost flows, respectively.

Sciubba developed an application of the EEA to the complex system of a entire Nation: Italy [255]. This proposal was adapted by Ertesvåg [75] and Chen [50] to Norwegian and Chinese societies, respectively. In order to do so, he proposed a disaggregation level in which seven sectors were considered, i.e. extraction, conversion, agriculture, industry, transportation, tertiary and domestic. Additionally, seven extended exergy fluxes connected the seven sectors to one another, i.e., Resources fluxes (R), Natural resources fluxes (N), Product Fluxes (P), Trash fluxes (T), Discharge fluxes (D), Human work flushes (H) and Capital fluxes (C).

After revising these interesting applications of exergy proposed in the literature (summarized in Table 3.3), it may be concluded that exergy has already emerged as an alternative valuation method in sustainability studies. It makes an important contribution to sustainability assessments by intimately linking the system under study to the environment which supports the productive system, a key factor usually underestimated by conventional approaches. Nevertheless, some drawbacks have also been highlighted. It is time to summarize the advantages and disadvantages in order to finally answer the question which opened this section: can exergy be considered a comprehensive energy sustainability indicator?

3.2.4.4 Discussion

As was explained in the introduction, evaluating the appropriateness of exergy as a global energy sustainability indicator was our final aim. In the previous sections, the thermodynamic roots of exergy were presented as well as the main applications that have been proposed in the literature where exergy is used as an energy indicator (or a key tool) in a complex sustainability framework. They have been summarized in Table 3.4.

Besides, some advantages as well as some limitations have already appeared, and they have been summarized in Table 3.5. In this section they are presented and discussed systematically.

Revising the advantages of using exergy as a user-side or donor-side sustainable indicator summarized in Table 3.5, it is easy to acknowledge that all of them are rooted in two main characteristics of exergy:

1. Exergy links the system under study and the environment that supports its activity. Exergy cannot be defined if a reference environment is not chosen and justified. This way the dyad system-environment is transformed into the new study object in exergetic sustainability analyses, thus avoiding the main drawbacks of traditional economic approaches to sustainability in which the environment plays a secondary role.

2. Exergy can be used as a common measurement unit susceptible to be aggregated in a single indicator, either using a user-side approach (see Section 3.2.4.3.1) or a donor-side one (see Section 3.2.4.3.2). Thus, all the flows present in a sustainability analysis can be measured or transformed in exergetic terms.

Regardless the merits of exergy exposed above, the relevance of its drawbacks will decide the appropriateness or not of using it as an energy sustainability indicator, thus answering the question which guided this research. Nevertheless, at this point of the discussion it is worth splitting the question in two different lines. In Section 3.2.4.3 two different groups of exergy applications based on two different valuation methods were introduced: user and donor side. These two methods are closely linked to the WS and SS paradigms. In Table 3.5 all the drawbacks are included, indicating if they affect to weak or strong exergy-based sustainability approaches. It is noteworthy that they are additive, that is, those applicable to LCEA and ELCA are also present in exergoecology and in donor-side applications, likewise, limitations of exergoecology are also present in eMergy, ECEC and EEA. Let us give a brief insight into them, summarizing and separating them according to its weak or strong nature.

Type	Origin	Method	Features
User-side (weak sustainability)	LCA	LCEA	Based on classic LCAs, oriented to designing sustainable (renewable) supply systems
		ELCA	LCA extended to determine the consumption and depletion of natural resources
	Thermoeconomics	CEC	First conceptualization of exergetic cost
		Exergoecology	Based on the calculation of the exergetic cost of replacement of materials (from-the-crade-to-the-cradle)
Donor-side (strong sustainability)	Ecosystem ecology	eMergy	Provides an ecocentric valuation method based on the Maximum Empower Principle
		ECEC	Algorithmic method that extends classic CEC to include the contribution of ecosystems
		EEA	Classic CEC including exergetic fluxes equivalent to labor, capital and environmental damage remediation cost

Table 3.4 Summary of features of exergy applications to sustainability assessments

Type	Origin	Method	Advantages	Limitations
User-side (weak sustainability)	LCA	LCEA	- Rigorous scientific soundness based on classic LCA - All energy and material streams are measured in the same unit: exergy - Native distinction between renewable and non-renewable resources	- Attempt to characterize waste impact in exergy terms - Attempt to characterize exergy onf non-working resources
		ELCA	Same as LCEA (+) More extensive inventory analysis	Same as LCEA
	Thermoeconomics	CEC	- Links physics with economy using exergy as the nexus - Introduce a theory of cost formation based on exergy - Sound algorithmic implementation	- Problems in the standardization of the reference environment - Uncertainties due to non-linear irreversibilities
		Exergoecology	- Solid exergy calculation of capital of earth (standard reference environment) - Introduction of ”from-the-cradle-to-the-cradle” framework	Same as CEC
Donor-side (strong sustainability)	Ecosystem ecology	eMergy	- Provides a bridge that connects economic and ecological systems - Use a common exergy-based unit which allows all flows (energy, monetary, labor) to be compared on a fair basis - Scientifically sound and shares the rigour of thermodynamic methods	- Focuses on the supply side and ignores human preference and demand - Uncertainty in the calculation of transformities of non-energetic inputs (monetary and labor) into exergy units - Difficulty in the definition of proper time scales in global sustainability assessments
		ECEC	Same as eMergy (+) Extends classic CEC to a global donor-side evaluation	Same as eMergy
		EEA	Same as eMergy (+) Sound algorithmic extension of CEC focused on the role of environment in sustainability studies	Same as eMergy (+) strong assumptions made in the calculation of the Conversion Factors

Table 3.5 Summary of advantages and limitations of exergy applications to sustainability assessments

3.2.4.5 Limitations of using exergy as a weak sustainability indicator

1. *Problems with the reference environment.* Some authors proposed to define comprehensive exergy reference environments in order to deal with extensive environmental problems by means of exergetic analysis. However, the requirements of an ideal reference environment can severely limit the applicability of exergy. By way of example, it may be highlighted the inconsistency of using exergy to measure the waste impact of a system linked to an environment which has been defined infinitely large and subjected just to internally reversible processes. Hence, if no comprehensive reference environment could be defined, the attempt to use exergy as the common unit in sustainability analyses could not succeed.

2. *Attempt to characterize exergy of non-working resources.* For work-producing resources such as fossil fuels or biomass, exergy is often an appropriate measure of how much work can be extracted from these resources. However, useful work is not a relevant characteristic of a mineral. This criticism is directed against all those attempts which try to characterize the mineral capital of Earth (sse Section 3.2.4.3.1). According to Gaudreau, determining exergy and useful work based on the *concentration exergy* (as was proposed by Valero [309]) is “simply not realistic”.

   If so, the use of exergy as an indicator of sustainability would become very difficult given that, as discussed in the previous section, all proposals are based on exergy aggregations derived from various energy and non-energy inputs to the system-environment.

3. *Uncertainties due to non-linear irreversibilities.* The previous criticism was related to the very definition and calculation of exergy, which affected every attempt of using exergy in weak sustainability analyses. Now, the relation between exergy and cost is put under exam. Valero and coworkers have been analyzing these issues for decades. They have focused in the problem of the cost-formation and the role that exergy could play in that crucial debate. Some of these issues were introduced in Section 3.2.4.3.1.

   In a very interesting article [302], Valero describes the advantages and disadvantages of using exergy methods for cost allocating and accounting. In a fascinating search for Aristotelian causality in thermoeconomics terms, Valero states that irreversibility is the *causa efficiens* of cost.

   Eventually, Valero is proposing a global consensus for the exergy use. That consensus would imply the definition of a comprehensive standard reference environment which would objectively solve the problems related to chemical exergy derivations. If that consensus were obtained, exergy could be that universal link between physics and economy in a static scenario.

But even if we agree in the fact that an static exergy evaluation of a system, calculated over a comprehensive standard reference environment, comprises the total complexity (causes) of irreversibility within natural and artificial processes, linearity is a hidden assumption that has not been put under exam. It may be assumed that linear causes of irreversibilities, i.e. causes that can be analytically predicted and measured, can be traced through exergy-cost evaluation, but non-linear causes still occur in nature which cannot be analytically calculated in exergetic terms.

4. *Attempt to Characterize Waste Impact*. That is the aspiration of some of the exergy methods described in Section 3.2.4.3. For instance, Cornelissen's ELCA and Wall's LCEA (see Section 3.2.4.3.1) in the analysis of the clean-up process, propose an exergetic method for the evaluation of the emissions.

   Besides, Valero and coworkers, in their from-the-cradle-to-the-cradle LCA proposal (see Section 3.2.4.3.1), quantify the footprint that mankind imposes on Earth based on its exergy cost.

   Gaudreau emphasizes the lack of agreement among researchers in this point [96, 97, 95]. According to him, although several attempts have been presented, there is no empirical evidence that there is a direct correlation between the amount of exergy present in the wastes of a process and the potential harm that this exergy is able to inflict to the environment.

3.2.4.6 Limitations of using exergy as a strong sustainability indicator

As was indicated above, the drawbacks included in Table 3.5 are additive. Hence, the strong sustainability (donor-side) approaches described in Section 3.2.4.3, share the same drawbacks explained above plus a new one related to the calculation of transformities in eMergy, ECEC and EEA methods. These values are used to transform not only energetic and material inputs but also monetary and labor flows into the system under study. Strong assumptions are made during the calculation process of transformities which affect the accuracy of the sustainability analyses in different ways [13].

3.2.4.7 Conclusion

Along the previous sections, exergy has been defined and examined in the different uses proposed in the vast existing literature regarding the assessment of sustainability. As was emphasized in these sections, exergy inextricably links the system and its environment, as well as unifies different measures (materials, funds, processes, etc) constituting a single weak or strong figure which can be easily measurable and comparable. The strength of exergy relies on these relevant characteristics. Yet, at the same time, its main drawbacks are related to these same features, for problems in the exergy evaluation, in the non-linear thermodynamic cost-value formation process and in the calculation of transformities appear.

Therefore, the question is still open: what can exergy offer to this global framework? Will it just be a useful tool for thermal optimization of industrial processes as stated by Gaudreau [96]? Could we use it as a reliable thermoeconomic variable in charge of measuring irreversibilities, as argued by Valero? Could exergy be used as a donor-side measurement of the memory of energy present in any product, as Odum states? In short, could exergy be used as an overall scientifically sound weak or strong sustainability indicator?

Regarding the last question, different weak sustainability approaches in which exergy is a key element have been analyzed. All of them are widely used and accepted by the scientific community. Problems in the calculation of exergy really exist, especially those related to the calculation of waste impact in exergy terms, but this limitation is also present in non-thermodynamic sustainability approaches. Therefore, there is no doubt that exergetic LCAs and exergoecological studies will still offer a valuable contribution for sustainability assessments.

Strong exergy-based sustainability studies have important drawbacks, as has been clearly highlighted above, yet this limitation is not a resigned acceptance of uncertainty. The accuracy of the reference environment used will define the accuracy of the global sustainability analysis. We are not referring only to the definition of the bio-physical environment, but also to the social and the economic environment, which is needed to calculate the transformities in strong sustainability approaches.

Proposals like eMergy, ECEC and EEA, regardless their limitations highlighted in section 3.2.4.3, are partially successful in their attempt to offer alternative sustainability studies based on the second law of thermodynamics. These donor-side holistic approaches to sustainability studies are rooted over this conviction: exergy is not only a static thermodynamic indicator but an open door to a new way of counting with the environment.

Gaudreau's criticism regarding the inability of exergetic methods to accurately measure the environmental impact of human activity is relevant, yet the objective of these methods might not be that pretentious. eMergy as well as ECEC and EEA analyses, although will never reach a deterministic result regarding the global sustainable situation of a pair system-environment, will rather offer an alternative thermodynamic insight into them.

Another issue has to do with the uncertainties in the calculation of transformities, which have cast a lot of doubts among classic sustainability researchers. Nevertheless, as Hau highlights [115], some of these doubts come from very extended misunderstandings. The community of researchers around eMergy and other approaches is continuously improving the calculation methods of transformities that increase our confidence in the capacity of these approaches to occupy an important role in future sustainability studies.

From the author' point of view, these strong approaches can play a key role in a sustainability framework designed in order to obtain sustainable policies which are able to maintain homeostatic[23] relations between the system under study and its environment (those same relations in which VSM or SOHO system framework proposal presented in Section 3.1.1 are based), thus complementing traditional economic approaches which are mainly focused on the economic and social poles of sustainability.

This way, exergy can be not only a static *weak* indicator of the efficiency of a system but also a *strong* conceptual tool to be taken into account in the very definition of the framework. Since exergy relates environment and systems, using it into sustainability studies forces the researcher to define not only the system under study but also the environment in which it operates. This is a critical point. Once the boundaries of the system are accurately set, the limitations of the research are set as well.

Eventually, exergy may teach us an important lesson regarding the trandisciplinar condition of sustainability studies. As already highlighted above, the nature of the relationship between system and environment is intrinsically undetermined. This does not mean that partial analytical approaches cannot be proposed, they are absolutely necessary indeed, but they cannot cope with the uncertainties inherent to its irreducible relationship. Therefore, as stated by Munda [192], since no pure analytical solution for this issue will be found, a wider framework is to be adopted including social and ethical thinking. By deepening into its complementary system-environment nature, these other disciplines may find in the exergy concept an open door to a collaborative effort along with physics.

Thus, the circularity of the proposal is clearly established: from physics to ethics (from the indicators to the framework), and vice versa.

Sustainability is a complex issue. No matter how sophisticated linearities we invent, they cannot cope with its elusive condition. Hence, complementary contributions coming from different fields are welcome and can constitute a transdisciplinar effort which will offer a new insight into real problems regarding our limited, fascinating real world.

Within that framework, exergy is already providing a valuable contribution in a double way: from a weak sustainability point of view, by offering solid thermodynamic insights

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[23] Homeostasis is the property of a system that regulates its internal environment and tends to maintain a stable, constant condition [45].

into sustainability issues, and from a strong sustainability perspective, by formally reminding that system and environment, i.e. humankind and Earth, are inextricably linked.

After this extensive review of exergy as an indicator of sustainability, it is now easier to fully understand the introduction that was made to it. We have indeed understood that exergy-based proposals are very diverse: from being used merely as an efficiency indicator in processes (WS), to being proposed as the unifying variable in eco-social models (SS) in general and as carrying capacity indicator which set absolute limits on natural capital in particular.

Thus, in the choice of energy sustainability indicators for the case study, both possible uses of exergy will be investigated. In practice, as will be seen in Chapter 7, exergy is proposed as a possible indicator of eMergetic dependence, both in terms of its participation in well-being within the aggregate multi-criteria framework, and as a critical limit to be set for that dependence variable.

3.3 The gap to be covered

The end of the state-of-the-art review of the thesis has been reached with an amalgam of proposals for both frameworks and indicators.

Although it has been repeated many times throughout the text, let us remember once again the aim of this thesis so that it can help us summarize all the information presented: We are aimed at proposing an operational framework for sustainability analysis, together with its proper indicators, that is applicable to the study of the extent to which energy systems are actually contributing to the global challenge of SD. This framework will have to meet a number of requirements:

1. Be operational. That is to say, it is not enough for us to have a mere conceptual approach that is interesting but incapable of being applied to a specific case study and of obtaining concrete results that are useful for decision-makers.
2. Be compatible with the capital-based approach to sustainability. We are therefore looking for a framework that moves from the triple bottom line sustainability definition to the capital-based one, by proposing as the real challenge of sustainability the optimization of a fairly distributed well-being while respecting the resilient limits of the environment.

3. Be scalable. In other words, the chosen framework must be applicable to the various scales involved in the challenge of sustainability. By this we mean not only geographical or temporal scales, but also sectoral ones, like energy.

This was the guide in the process of the review of the state of the art of frameworks. It was done by dividing the section into two proposals, namely multi-criteria and systemic frameworks.

In the multi-criteria frameworks a set of very consolidated methodologies and certainly with the capacity to face the challenge sought was found. Particularly interesting was the discovery of some multi-criteria applications to aid decision making in energy transition at states level. In the systemic frameworks different proposals were found that had enormous potential but which were much less developed and with serious difficulties to be implemented in real cases.

In relation to the indicators, it was decided to investigate two specific proposals, a weak one (ISEW) and a strong one (exergy). Both have a great theoretical background behind them and are ductile enough to be adapted to different case studies. However, it is important to emphasize again that there can be no prior choice of indicators to the definition of the case study. While the sustainability analysis framework is a conceptual tool that can be chosen beforehand, the indicators will necessarily have to be chosen once the case study has been modelled according to the chosen framework. As mentioned above, this important fact does not, in my opinion, detract from the state-of-the-art of indicators presented in this chapter. The ISEW, insofar as it serves as a welfare proxy, as well as the exergy in its different variants, insofar as it helps to set absolute bio-physical limits, will be very useful approaches in any specific application within an integrated assessment of the energy sector.

Having said all the above, the main gap detected in the literature was already present in the search criteria that guided the entire state of the art: "A formal development of a conceptual framework which is coherent with a capital-based approach to sustainability that combines WS and SS approaches, and its application to a real case on energy sustainable transition is certainly a gap to be explored".

Of all the proposals analyzed, the most suitable for the intended purpose was found to be the multi-criteria decision making framework. It will, therefore, be the basis on which the case study of this thesis will be developed. Additionally, even though no concrete complex proposal was chosen as the basis for this contribution, some hints coming from complex thinking definitely were inspiring in its development.

Chapter 5 will introduce the framework proposal, but before that, an analysis of the real capacity of WS and SS to cooperate in a same environment is still pending. The study introduced in Chapter 4 will try to shed some light into this issue.

Chapter 4

Combining weak and strong sustainability indicators

Two indicators were analyzed in the state-of-the-art section as representatives of WS and SS. In order to see to what extent the two proposals collide or, on the contrary, are capable of complementing each other, it was decided to calculate them in a specific application and analyze the results. This chapter presents this development.

This study consists of an analysis of the sustainability of a region over a specific period of time. The purpose is to test this collaboration between the two schools of sustainability (WS and SS) in a real situation: a mixed strong and weak sustainability study of the conurbation of the Costa del Sol in Spain from 2001 to 2015.

Thus, the goal of this exercise is to show the extent to which both paradigms provide complementary[1] information about the sustainability of the area. It can be anticipated here that the results of the research are promising in this sense.

The study then is focused on the period from 2001 to 2015 in the Costa del Sol, a coastal region located in the Province of Málaga (Spain). This region is an important tourist destination in Spain, and therefore a very good example of the conflict between economic development, ecological pressures and cultural challenges.

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[1] I am aware that there is a broad debate in the economic field around this concept of complementarity (applied above all to capital, as was mentioned when the SS school was introduced) and other related concepts such as substitutability or comparability. I have already referred to them in the state-of-the-art-section. In this case, however, the complementarity to which I refer is far from this discussion. I am using here the interpretation of complementarity in the dialogical sense proposed by Morin as one of the defining characteristics of complex thinking. That is to say, complementarity in this case would imply that both schools of thought in conflict (WS and SS; thesis and antithesis) do not become a synthesis that contains them and in a way overcomes them (I think that this is not possible in this case since the differences are irreconcilable), but rather keeps both of them active in a permanent creative tension.

The reader may be wondering why a local application has been chosen rather than a national or international one. The reason is due to the strong role that local approaches are playing in the quest for sustainability (such as the one promoted within the Agenda 21 movement) [108], as cities and their surrounding areas have become the basic units of human interaction with the environment and economic development.

According to the World Bank, in 2017, 54.7% of the world population live in cities [284], and according to estimations of the UN, in 2050, 68% will do so [298]. Therefore, I believe that assessing the sustainability of urban areas is a very relevant topic, although special attention needs to be paid to scaling up the results so that they compute on a global scale.

When dealing with the sustainability of urban areas, several technical approaches have been proposed [62, 59, 318]. However, this exercise started from the previous reflection that came up with the justified choice of indicators that adequately represent the SS and the WS in the previous chapter.

As mentioned above, some authors have already proposed [264, 118] that the strong indicator can represent the carrying capacity or resilience of the ecosystem under study, whereas the weak one is better equipped to offer a figure representing the level of welfare in the society dwelling in that area. This has in fact been the basis on which the framework proposal presented above was built (see Eq. 5.2).

This is precisely the proposal put forward in this application. A weak indicator, namely the ISEW was calculated along with and a battery of strong indicators, namely eMergetic and EEA-based (see Section 3.2.4.3) on the region under study in the given period. The first will seek to measure sustainable well-being and the second the carrying capacity of the region.

Eventually, the drawbacks and advantages of each indicator, that is, of each paradigm, and also their level of conflict or compatibility, will be highlighted.

The results show that effectively both approaches provide information that cannot be subsumed into one another. That is, there is no direct or inverse correlation between them that indicates dominance. This opens the door to further exploring possibilities for true integration. That is precisely what the case study proposal in the Chapter 7 is aimed at.

The chapter proceeds as follows. Firstly, the empirical study (Section 4.1) of the Costa del Sol and the methodology used (Section 4.2) are described. Then the results are presented and discussed (Section 4.3). Finally, in Section 4.4 some conclusions are presented[2].

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[2] This chapter is based on the working paper "Strong versus weak sustainability indexes in a conurbation context. A case example for Spain" developed by the author and Pedro Linares initially sent to *Ecological Economics* [235].

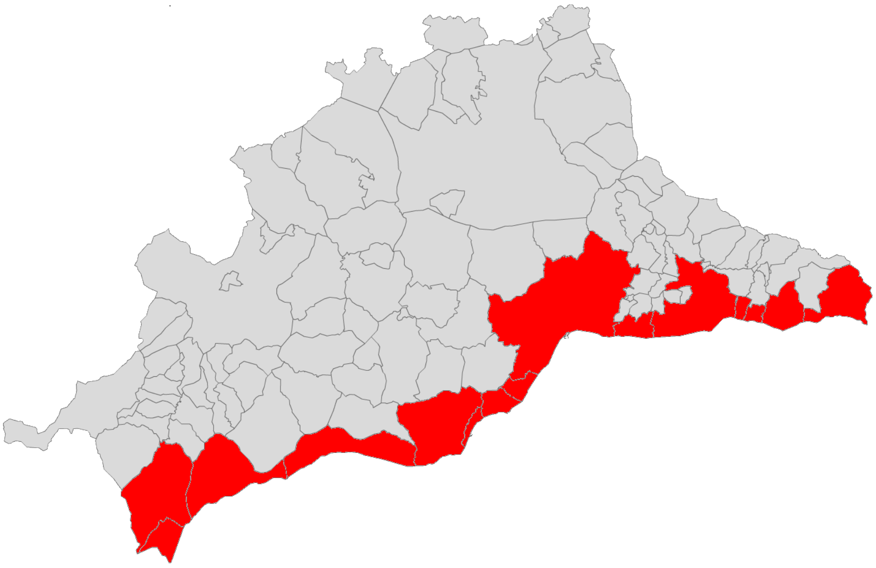

Fig. 4.1 Malaga province (grey) and the Costa del Sol (red) [Own ellaboration]

4.1 Introduction

The Costa del Sol is a coastal region located in the Province of Malaga, one of the eight provinces that comprise the region of Andalusia, southern Spain. It is a popular tourist region that emerged as an international travel destination in the second half of the twentieth century. Although before this date it was made up only of a several small villages devoted to fishing and local agriculture, the region was completely transformed during the latter part of the previous century. This transformation into an international tourist destination meant an important economic growth in the region, as well as an increase in the pressure on the environment.

Thus, the fast urban development that the Costa del Sol has experienced during the last sixty years provides an excellent opportunity to investigate how such a quick development has influenced the ecosystem which is supporting it.

From the point of view of the distribution of the population, the concentration of inhabitants in the area is significant, which is a recurrent tendency in modern urban areas, i.e. the coast is the most densely populated area while the hinterland is virtually unpopulated. Regarding the economic activity and its relation with the environment, the Costa del Sol is situated in a privileged area in terms of renewable capabilities, i.e. hours of direct solar irradiation, wind and ocean energy possibilities. Nevertheless, its dependence on fossil fuels is very high.

The Costa del Sol extends from the cliffs at Maro in the East, to Punta Chullera in the west, along 161 coastal kilometers of conurbation (see Fig. 4.1); and is divided in three physical areas: Eastern Costa del Sol, Malaga (capital city of the province) and western Costa del Sol. It comprises a total area of 1,700 km^2, a 23.28% of the extension of the province.

The population of the Costa del Sol in 2001 was 1 million inhabitants, 77.91% of the total population of the province, whereas this figure increased to 1.21 million inhabitants and a share of 79.48% in 2007, and to 1.3 million and a share of 79.79% in 2015. Moreover, according to local estimations, around 2 million tourists per year visit the Costa del Sol and stay there for a mean value of 4 days [130]. The present research has been based on data regarding registered inhabitants; although some figures are included which offer an estimation of the impact of this heavy touristic activity. A future sustainability research particularly focused on the influence of tourism on the Costa del Sol would be a very interesting complement to this study.

Table 4.1 Data sources for the sustainability analysis of the Costa del Sol

Institution	Source	Scope	ISEW	eMergy	EEA	Interpolation method
INE	Spanish Regional Accounts	Regional	B, E, F, H, I, J, L			Weighted by population
INE	Spanish National Accounts	National	G		K	Weighted by population
DGT	Statistical Yearbook of Accidents	Local	N			Not needed
AAE	Info-Energy	Local	T, U	R, F1	R, D	Not needed
MEIC	DataComex	Local		M1, G1, SS1	N, P	Not needed
SEPE	Anual Employment Report	Local			W	Not needed
MADECA	PRISMA	Local			T	Not needed

Table 4.1 summarizes the main data sources used for the calculations. Column ‘Scope’ indicates the scale of the source of the data used. Unfortunately, some data are not available at local scale, specially for the ISEW, therefore some interpolations using regional or national data had to be done. The method used for interpolations when needed is included in column ‘Interpolation method’ This is a limitation of the calculation that will be addressed in the conclusions. Then column ISEW, eMergy and EEA refer to the different components or indicators included in each proposal. These elements are further explained in Tables 4.2, 4.3 and 4.6, respectively.

4.2 Methodology

This section summarizes the methodology used to calculate the strong and weak indicators, with special emphasis on those methodological adaptations that have been proposed according to the particularity of the case study.

4.2.1 ISEW

In the State of the Art Section (see Section 3.2.3), the ISEW was introduced, including a brief description of its methodology. Part of this introduction is replicated here for clarity purposes.

ISEW accounting starts with Private Consumption (PC), which is a sub-component of GDP. Afterwards, PC is adjusted according to an index of income distribution. Once PC has been corrected by income distribution, all the items are calculated and are allocated a certain sign, according to their positive (services) or negative (costs) contribution to welfare. Finally, the items are added or subtracted to PC in order to obtain the final figure for the ISEW.

Pulselli, in his study of the ISEW for the province of Siena [225], used a particular division of the items involved in ISEW analyses, assigning a letter to each one, following an alphabetical order. That strategy was used here as well. Below, each item is presented and explained, indicating the method used to calculate it along with the assumptions adopted in the present study.

- *Item A*. Year: It stands for the year under study.
- *Item B*. Private consumption (PC): Similarly to GDP, ISEW's basis is the total private consumption for the region under study in a year.
- *Item C*. Index of income distribution:

  According to Daly and Cobb, PC does not indicate the real economic and social welfare of society [63]. One of the main reasons behind this fact is the unequal distribution of income. Thus, they proposed to correct the PC figure using an index of income distribution. Two different approaches have been used in ISEW studies. Some authors have used the Gini index while others have proposed to use the Atkinson index. According to Neumayer, the latter approximation should be preferred to the former, since it is able to reflect the estimation of society's aversion to inequality, through a parameter. Nevertheless, the calculation of this preference index lacks enough data in most occasions, and also requires the assumption that personal utilities can be aggregated. Thus, the Gini index was chosen for this research.
- *Item D*. Calculation of adjusted private consumption: This item is calculated by solving the equation:

$$APC = PC/(1+G) \tag{4.1}$$

where APC is the Adjusted Private Consumption (item D), PC is the Personal Consumption (item B), and G is the Gini coefficient.

According to Daly and Cobb, APC will be the basis to which all other positive and negative modifications will be applied. Nevertheless, as Neumayer highlights, this is again a controversial step. Once the PC is adjusted using this inequality index, no coherent comparison can be done with GDP, since both indices are rooted on different bases. Thus, APC is not a real value which can be compared with real data since it is an artificially weighted PC value. Furthermore, if this index is to be taken into account, Neumayer proposes not to apply it to the PC, but to the final ISEW index. Nevertheless, this proposal is also problematic since we would be assuming that income distribution affects the ISEW as a whole, which is not necessarily true. Assuming that the dispute is not closed, respecting the original formulation, in our calculations the first strategy represented by Eq. 4.1 was used.

- *Item E.* Services - Domestic Labor and volunteer work: Since domestic and volunteer labor are not remunerated work, they are not accounted for within the GDP. However, there is no doubt that this labor contributes in a positive way to global welfare. Therefore, Daly and Cobb decided to include these elements in the correcting items for the calculation of the ISEW. Depending on the available data, several methods have been used for this calculation. In the present research, an estimation of 27 hours of non remunerated work per citizen between 18 and 70 years old in Andalusia in 2000 [70] was used. This value, together with the minimum wage in Spain in every year, were used to account for the domestic and volunteer work in the Costa del Sol.

- *Item F.* Services - Consumer Durables: Daly and Cobb proposed a double way of dealing with the contribution of consumer durables to welfare. First, services arising from the stock of consumer durables acquired during the accounting period should be considered a positive contribution, whereas costs of consumer durables acquired in the present year should be subtracted in order to avoid double counting (see item I). Data from the “Encuesta de Presupuestos Familiares” (EPF) survey compiled by the Spanish Statistical Institute (INE) were used.

- *Item G.* Services from public infrastructure: According to Daly and Cobb, services from public infrastructure, as well as health and education costs must be considered a component of economic welfare. They argue that growth of administration costs keeps economic welfare from declining. The data were obtained from the “Intervención General de la Administración del Estado” (IGAE).

- *Item H.* Public Health Care and Education Costs: These public costs should be included in the ISEW calculation since they clearly affect welfare and sustainable development in a society. How to include them is, however, much more complex than it seems. According to the first revision of the ISEW calculation by Daly and Cobb (1994), 50% of this expenditure during the present year is a defensive cost, and should not be added. Thus, according to them, just 50% of global public expenditure in health and education would constitute a positive effect on welfare. Data from Andalusian Statistics Office were used.

- *Item I.* Costs - Consumer Durables: As was explained in item F, Daly and Cobb considered that consumer durables expenditures during the year of study should be subtracted from PC given that their contribution to welfare would be taken into account during the next years.

- *Item J.* Private Defensive Expenditure for Education and Health Care: In item H, 50% of public health care and education expenditure was considered as a non defensive cost that increased economic welfare. In order to be consistent with this hypothesis, 50% of private consumption in health and education was considered as defensive costs as well, hence subtracted from Private Consumption. The EPF survey in 2001, 2004, 2007, 2010, 2012 and 2015 provided the necessary data.

- *Item K.* Local advertising costs: Local advertising contribution to ISEW in all the studies reviewed was found to be negligible. Moreover, accurate data regarding this issue for a local region are not normally available. Hence, we decided not to include this item in the present research.

- *Item L.* Costs of commuting: Daly and Cobb estimated that 30% of the costs related to private cars and public means of transport were directly related to commuting costs. Only private cars uses have been included in the present research. Data were also obtained from the EPF (INE).

- *Item M.* Urbanization costs: Following some authors that had excluded this item from calculations of the ISEW in different studies, it was decided not to include them. Lack of consensus on the right way of computing the equivalence between the level of urbanization and the welfare related to this fact prevented us from including this item. In any case, its relative contribution was found to be less than 1% for most ISEW studies.

- *Item N.* Costs of road accidents: This item comprises the total costs related to road accidents. An average cost for casualties (€ 47,400) and serious injuries (€ 328,000) taken from an AEPO survey were used [250]. Data of accidents, casualties and injuries in 2001, 2004, 2007, 2010, 2012 and 2015 were obtained from the "Dirección General de Tráfico" (DGT) in Spain.

- *Item O.* Cost of Water Pollution: Unfortunately, finding an accurate methodology for measuring this concept is extremely difficult. Nevertheless, an option was to be chosen, and total costs for water purification was the one we selected, following Pulselli's proposal [225]. An estimation of the total costs of purification of water supply was obtained from data on a standard purification plant: € 17.35 per equivalent inhabitants (E.I.) of the area.
- *Item P.* Cost of air pollution: Daly and Cobb divided their estimation of this item in six different categories: (1) damage to agricultural production; (2) material damage; (3) cost of cleaning implement; (4) damage caused by acid rain; (5) urban degradation and (6) damage to buildings and surroundings. Following Guenno and Tiezzi [105], it was decided to focus on the external costs per ton of emissions from different pollutants. The cost per pollutant was taken from the ExternE project [20].
- *Item Q.* Costs of Noise Pollution: It was not computed.
- *Item R.* Loss of Wetlands: It was not computed.
- *Item S.* Loss of agricultural land: Assigning a monetary value to the consequences of urban expansion and inappropriate land management is a controversial task. An estimation of lost agricultural lands in the Costa del Sol was done according to data from the "Observatorio de Sostenibilidad en España" (OSE) report [133]. Besides, a cost of € 12,900 per hectare of lost agricultural land was chosen based on [225].
- *Item T.* Depletion of non-renewable resources: Including the cost of non-renewable resources depletion into the ISEW calculation has been a controversial issue since the very proposal presented by Daly and Cobb in 1989. Two different methods have been used in the literature. The first one was the *resource rents* method, which aims to separate the sustainable from the non-sustainable income parts. The second one is *the replacement cost* method, which stems from the idea that the total amount of non-renewable resources must be replaced by renewable resources. Although the former method was used by Daly and Cobb in 1988, the latter was the chosen one for the revision they presented in 1994. In this study, we have opted for the second methodology. Backstop technologies have been chosen to substitute CCGT in electricity generation

and fuels in transport: solar pv plus storage [68] is the backstop for electricity generation and biofuels the one for transport.

- *Item U*. Long-term environmental damage: Including this item, Daly and Cobb took a bias towards ecological economics positions. Valuing the long-term cost of environment degradation in a macroeconomic index is a clear indication of it. Nevertheless, applying an accurate annual value to this issue is extremely difficult and controversial [86]. As Neumayer and Stockhammer point out, the main question regarding this subject is whether this value should be accumulated over time or not [271]. According to Neumayer, to let this value accumulate over time is contradictory as it leads to multiple counting of the total future damage. Hence, he suggested applying a marginal social cost to long-term environmental damage per ton of carbon, and to calculate the total amount in the region under study. Several values of this marginal social cost have been proposed in the literature. An exhaustive research regarding different values assigned to a ton of carbon emitted was developed by Tol in 2005 [287][3] and revised in the recent IPCC report on climate change [87]. He presented several statistical marginal damages costs for carbon emissions and suggested a value not higher than 50 $/ton. In the present research an equivalent cost of € 93.95 per barrel of oil equivalent was used, based on Costanza's [60].

- *Item V*. Net capital growth: In order to sustain long-term economic welfare, there should be an increasing or constant supply of capital per worker. Daly and Cobb proposed that the ISEW took into account this net capital growth, which is calculated by, on the one hand, adding the stock of new capital and, on the other hand, by subtracting the capital requirement. Nevertheless, since the relative contribution of this value to the ISEW in a local urban area was found to be negligible, it was decided not to include it in the final results.

- *Item W-X-Y-Z*. ISEW and local GDP: Finally, these four items include: the ISEW calculation; the ISEW per capita; the GDP and the GDP per capita, respectively.

4.2.2 eMergy analysis

eMergy was presented in the state-of-the-art review in Chapter 3 within the proposals for exergy-based analysis. There, the basic methodology was described and the main references

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[3] The author is aware that these values are under constant review. It is pending for future developments to update these data in accordance with the most recent literature.

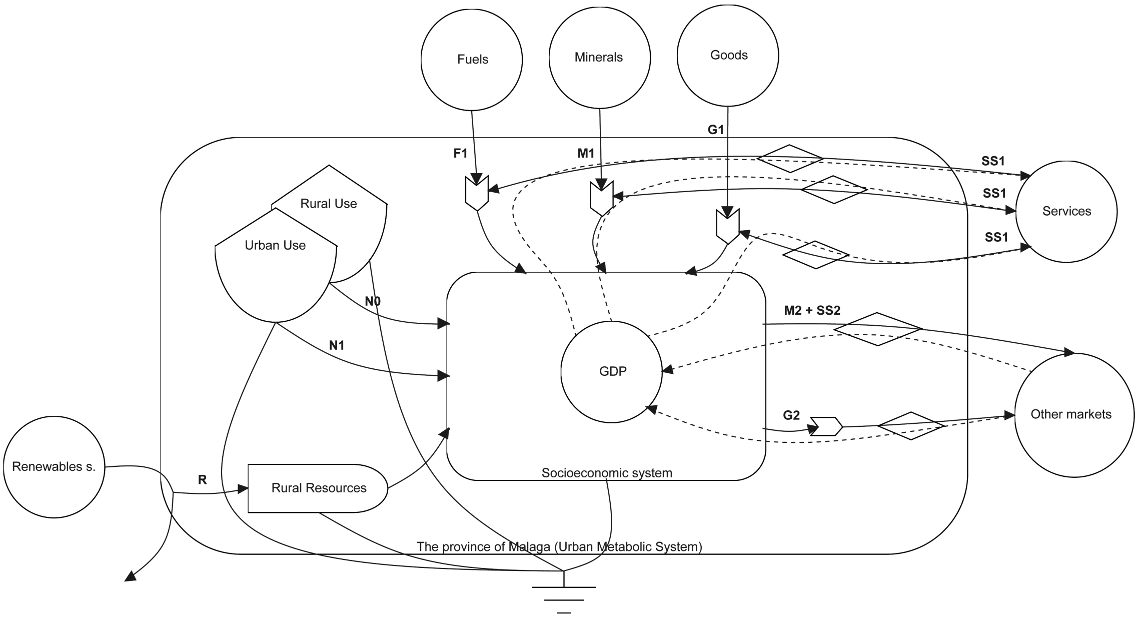

Fig. 4.2 eMergy model of the Costa del Sol (Own ellaboration based on [204])

were introduced. Therefore, this section will specifically focus on describing the concrete application of this methodology to the Costa del Sol study developed.

An eMergetic analysis is traditionally divided in four steps. Firstly the limits of the area under study are to be established. In this case, it was the conurbation of the Costa del Sol comprising the three physical divisions: east, center and west (see Fig. 4.1). Secondly, the emergy model including the different flows is to be drawn (see Fig. 4.2). Thirdly, the eMergetic tables are to be built. In Appendix C[4], these tables are included. And fourthly the eMergy indicators are to be calculated. Table 4.3 collects these results.

In this research, Lomas eMergy analysis for Spain was used as a guide [159]. The concrete methodology for obtaining these indicators can be consulted there.

Among the different indicators calculated, two are the most relevant, namely, Renewability and Carrying Capacity. More details on them are provided in the next section.

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[4] An eMergy baseline (GEB) was used to scale the transformities: 15.2E+24 sej/y [38]. A new GEB of 12.1E+24 was proposed by Brown in 2016 [39]. Un update of the results obtained using this new GEB is a pending task for the future. Nevertheless, since it is applied to every single transformity, it will not change the relative comparison among WS and SS indicators but only the absolute eMergy results.

4.2.3 eMergy footprint

Together with the conventional eMergy indicators presented above, an additional one was calculated here namely, the eMergy footprint.

"The Ecological Footprint (EF) is a measure of the load imposed by a given population on nature. It represents the land area necessary to sustain current leves of resource consumption and waste discharge by that population" [317].

20 years after its definition, the EF has become a consolidated indicator at national level. It is commonly used to measure the ecological performance of nations and to compare each other.

An eMergy footprint indicator derived from the eMergy assessment was calculated and hence presented in order to compare it with the carrying capacity results obtained previously thus providing more robustness to the results. Although a concrete proposal for the calculation of eMergy footprint was proposed by Chen in 2009 [50], in this case, the methodology used is specific. The indicator was calculated according to Eq. 4.2

$$EF = Sa(r)/Area \tag{4.2}$$

where $Sa(r)$ stands for the renewable support area of the Costa del Sol.

Two different areas were used, consequently two indicators were calculated. The first one considers only the area of the Costa del sol whereas the second one considers the total area of Málaga province as its support area.

4.2.4 EEA

Extended Exergy Accounting, as already mentioned in Section 3.2.4.3, is a method developed by Sciubba [255]. It is a standard exergy analysis in which Szargut's CEC [278] is enriched by additional exergy flows that represent the exergetic equivalents of the production factors of the economy.

A simplified application of the EEA methodology to the analysis of the exergetic behavior of the Costa del Sol has been developed for this analysis.

Consequently, Eq. 3.12 was applied to the energy and material inputs and outputs to and from the Costa del Sol. The seven fluxes proposed by Sciubba for an EEA analysis of a nation were obtained whereas a single sector approach was chosen (see Fig. 4.3). Exergy factors needed for CEC calculation were obtained from Wall [323], Ertesvåg [75] and Khattak [140].

On the one hand, $E_{Capital}$ was obtained as:

$$E_{Capital} = C(E_{in}/C_{ref}) \tag{4.3}$$

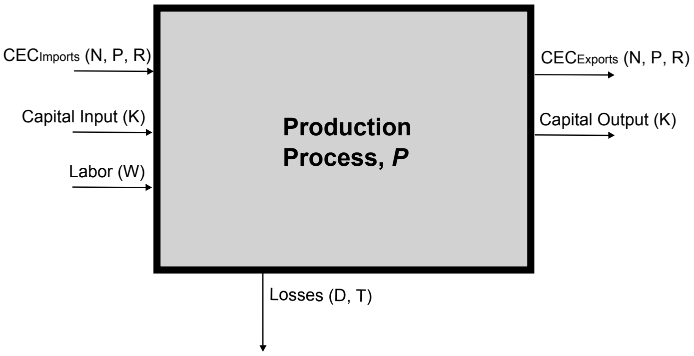

Fig. 4.3 Simplified EEA model applied to the Costa del Sol (based on [255])

where C is the monetary flow to be converted in exergy units (in our case, monetary services including tourism in the Costa del Sol); E_{in} is the reference exergy input to the system and C_{ref} is a reference amount of money. The total CEC plus E_{labor} inputs for E_{in} and the M2[5] of the province of Málaga in each year for C_{ref} where the references used. It is noteworthy that the K_C factor (E_{in}/C_{ref}) obtained for the Costa del Sol in 2001 was 37% lower than that calculated by Ertesvåg for the whole Norwegian society in 2000. On the other hand, E_{Labor} was calculated as:

$$E_{Labor} = nK_W \tag{4.4}$$

where n is the flux of work-hours in the Costa del Sol in each year and K_W is the conversion factor. Sciubba's value calculated for Italy in 2000 (199 MJ/man-hour) was used.

Eventually, E_R comprises two fluxes: T (trash) and D (discharge). T was obtained applying the fixed exergy factor of 2 PJ/Mton proposed by Ertesvåg to the wet-organic waste produced by the Costa del sol in each year. D was calculated using the exergy abatement cost methodology proposed by Valero [304].

Finally, the EE renewability, an specific indicator calculated in this analysis for comparative purposes, was obtained as:

$$EE_{renewability} = EnE_{Renewable}/EnE_{in} \tag{4.5}$$

where $EnE_{Renewable}$ stands for the renewable exergy input to the system and EnE_{in} is the total exergy input to the system.

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[5] M2 is a money supply economic indicator. While M1 is defined as the sum of currency held by consumers as well as deposits held at depository institutions, M2 is defined as M1 plus savings deposits plus low denomination time deposits plus money held in retail money market accounts.

Table 4.2 ISEW comparison. Costa del Sol. 2001 - 2015

A	**Year**	**2001**	**2004**	**2007**	**2010**	**2012**	**2015**
B	Personal_consumption_expenditure	8,608,531,299 €	10,234,908,945 €	13,385,394,671 €	13,626,922,088 €	13,925,704,390 €	14,096,167,565 €
C	Index_of_distribution_inequality	0.347	0.347	0.347	0.347	0.347	0.347
D	Weighted_personal_consumption_expenditure	6,390,891,833 €	7,598,299,142 €	9,937,189,808 €	10,116,497,467 €	10,338,310,609 €	10,464,860,850 €
E+	Services_of_household_labour	1,778,101,203 €	2,010,669,614 €	2,811,799,655 €	3,227,289,406 €	3,331,511,860 €	3,347,221,740 €
F+	Consumer_durables_services	329,073,386 €	414,586,123 €	543,288,387 €	675,110,303 €	684,151,791 €	673,813,121 €
G+	Services_from_public_infrastructure	187,751,772 €	241,095,408 €	319,615,841 €	367,017,248 €	166,172,991 €	258,331,786 €
H+	Public_expenditure_on_health_and_education	1,353,363,330 €	1,694,142,612 €	2,285,074,116 €	2,694,551,846 €	2,541,177,850 €	2,414,545,500 €
I-	Expenditure_on_consumer_durables	488,040,506 €	542,982,371 €	677,641,403 €	667,410,038 €	676,549,857 €	573,459,090 €
J-	Defensive_private_expenditure_on_health_and_education	317,560,695 €	263,539,409 €	323,962,818 €	334,540,490 €	324,016,847 €	446,007,890 €
K-	Local_advertising_expenditure	Not available	Not available	Not available	Not available	Not available	Not available
L-	Cost_of_commuting	332,802,729 €	375,370,890 €	502,849,092 €	542,584,736 €	550,719,730 €	535,811,316 €
M-	Cost_of_urbanisation	Not computed €	Not computed €	Not computed €	Not computed €	Not computed €	Not computed
N-	Cost_of_car_accidents	207,823,664 €	203,532,743 €	151,165,697 €	83,799,370 €	58,926,953 €	62,162,939 €
O-	Cost_of_water_pollution	120,467,990 €	133,080,833 €	138,609,150 €	143,246,753 €	143,768,624 €	145,723,396 €
P-	Cost_of_air_pollution	636,180,677 €	735,028,839 €	767,163,404 €	825,081,674 €	645,508,990 €	687,305,354 €
Q-	Cost_of_noise_pollution	Not computed	Not computed	Not computed	Not computed	Not computed	Not computed
R-	Loss_of_wetlands	Not computed	Not computed	Not computed	Not computed	Not computed	Not computed
S-	Loss_of_agricultural_land	43,885,542 €	43,885,542 €	43,885,542 €	10,971,386 €	10,971,386 €	10,971,385 €
T-	Exhaustible_resources_depreciation	261,708,291 €	421,702,467 €	431,541,594 €	271,155,383 €	401,591,520 €	311,805,483 €
U-	Long-term_environmental_damage	130,192,130 €	211,947,969 €	218,235,752 €	196,064,522 €	178,372,517 €	73,955,820 €
V+	Net_capital_growth	Not computed	Not computed	Not computed	Not computed	Not computed	Not computed
W	ISEW=sum_of_all_positive_and_negative_items	7,500,519,300 €	9,027,721,836 €	12,641,913,354 €	14,005,611,918 €	14,070,898,677 €	14,311,570,321 €
X	ISEW_per_capita	7,605 €	8,480 €	10,921 €	11,360 €	11,157 €	11,294 €
Y	GDP	12,293,509,885 €	16,499,459,613 €	21,208,106,580 €	21,511,182,857 €	21,313,388,744 €	21,231,456,368 €
Z	GDP_per_capita	12,465 €	15,498 €	18,321 €	17,448 €	16,900 €	16,755 €

4.3 Results

In this section the results obtained in the study are presented, starting by the results for each approach, namely, WS and SS, and followed by a comparison between them.

4.3.1 ISEW Results

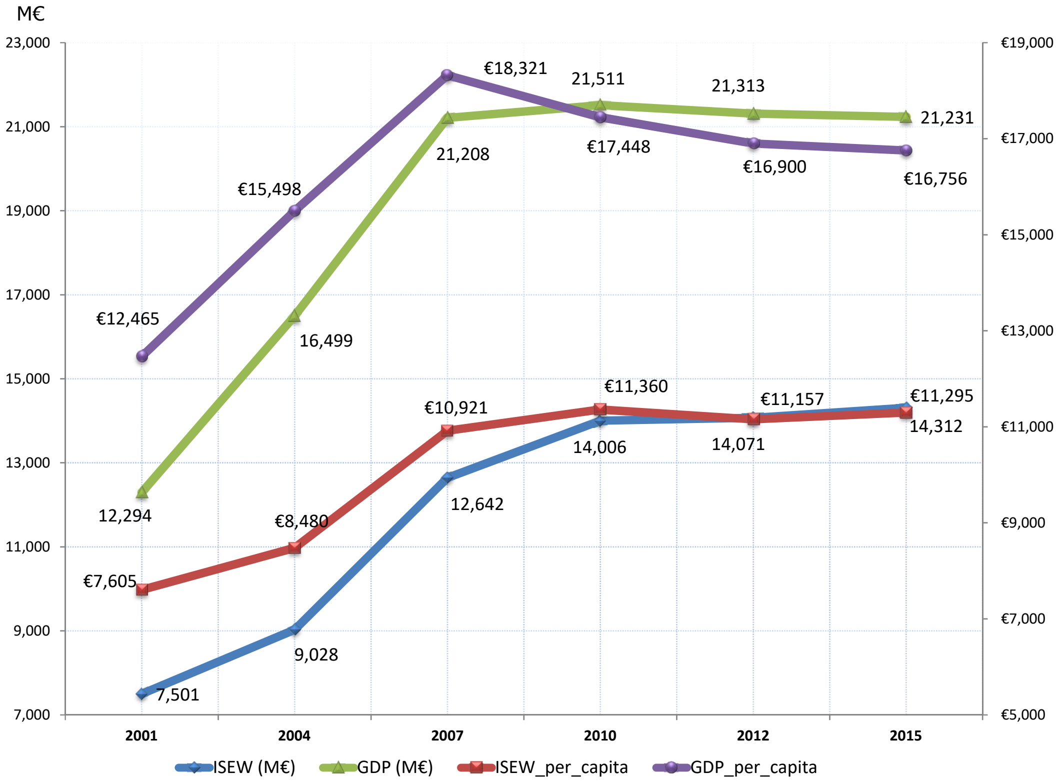

Fig. 4.4 ISEW and GDP evolution from 2001 to 2015

In Table 4.2 a summary of the results obtained in the ISEW calculation for the Costa del Sol in 2001, 2004, 2007, 2010, 2012 and 2015 is presented.

The table shows the results of each of the items that make up the indicator, as explained in the previous section.

The first element that may be highlighted from the table is that ISEW values are much smaller than GDP. This is mainly due to the adjustment of the PC using the GINI index. Applying the inequality factor reduces the value of personal consumption to a large extent.

Regarding the negative contributions, it may be observed that the cost of air pollution is the biggest negative contributor to the ISEW in 2001 and 2007, and the second in 2012.

Moreover, the sum of costs related to exhaustible resource depletion and to long-term environmental damage constitutes the third most negative contribution to welfare. It is worth highlighting that these items have been calculated using moderate instead of pessimistic assumptions. If Jackson's proposal would have been used [225], this contribution would have exceeded the 50% of total negative ones in ISEW. Hence, adding up these items, it can be stated that the main negative contributions to welfare in the Costa del Sol have to do with the use of non-renewable energy sources.

Having said all of the above, the most interesting result of the ISEW study for the Costa del Sol emerges when we analyze its evolution from 2001 to 2015. Figure 4.4 show this trend.

The evolution of ISEW and GDP in the period 2001-2015 looks very similar. ISEW shows a positive trend until 2007, after which its growth rate is reduced and becomes fairly stable. The main difference can be found in the more attenuated behavior of ISEW compared to GDP: whereas the GDP decreases in the period 2010-2015, the ISEW stagnates.

4.3.2 eMergy results

Table 4.3 contains the conventional eMergy indicators obtained by the present research for Costa del Sol in 2001, 2004, 2007, 2010, 2012 and 2015.

This table summarizes not only the eMergetic indices calculated, but also the main eMergetic inputs, outputs and some compound indices of our case example in the Costa del Sol. As mentioned above, Lomas' eMergetic analysis of Spain during the last two decades has been the main reference for the present research [159].

Additionally, in Appendix C, the complete tables of flows, imports and exports for the six years are collected. It can be seen that there is only one flow chart, the reason being that it was decided to use a natural base year as a reference for the whole study in order to reduce the variables involved in the analysis. Specifically, the year chosen was 2007.

In the table, each row is assigned one number, except for rows 2, 3 and 4 which condense several eMergetic components. Thus, rows 1 to 4 contain the eMergetic inputs and outputs of the system. In rows 5 to 7 the first order eMergetic indicators are presented, that is, those that stand for the eMergetic behavior of the system in general terms. Finally, rows from 8 to 11 include second order eMergetic indicators [35][6].

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[6] In [315, 44] a deep review and an interpretation of these indicators can be found. Additionally, the reader is also encouraged to revise Lomas' research about the decoupling process between local economic activities and natural capital in Andalusia [160]

Table 4.3 Emergy indicators. Costa del Sol. 2001-2015

No	Flow/Index	Expression	2001	2004	2007	2010	2012	2015	Units
1	Renewable inputs	R	1.57E+21	1.57E+21	1.57E+21	1.57E+21	1.57E+21	1.57E+21	Sej/year
2	Non-renewable indigenous sources	N	5.40E+17	5.40E+17	5.40E+17	5.40E+17	5.40E+17	5.40E+17	Sej/year
	Rural Use	N0	5.40E+17	5.40E+17	5.40E+17	5.40E+17	5.40E+17	5.40E+17	Sej/year
	Urban Use	N1	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	Sej/year
3	Imported emergy	IMP	8.89E+21	8.73E+21	1.10E+22	9.66E+21	9.24E+21	1.30E+22	Sej/year
	Fuels and electricity	F1	4.74E+21	5.97E+21	6.84E+21	5.84E+21	5.28E+21	4.43E+21	Sej/year
	Minerals	M1	7.08E+20	1.88E+20	2.61E+20	5.18E+19	1.77E+19	8.98E+19	Sej/year
	Goods	G1	1.74E+21	4.85E+20	5.33E+20	6.25E+20	5.40E+20	3.96E+21	Sej/year
	Services	SS1	1.69E+21	2.09E+21	3.41E+21	3.15E+21	3.40E+21	4.52E+21	Sej/year
4	Exported emergy	EXP	5.81E+21	6.35E+21	8.33E+21	8.54E+21	1.01E+22	1.41E+22	Sej/year
	Minerals	M2	3.71E+20	7.02E+19	8.15E+19	8.82E+19	8.51E+19	1.66E+21	Sej/year
	Goods	G2	1.26E+21	3.07E+20	2.62E+20	3.39E+20	4.71E+20	2.62E+21	Sej/year
	Services	SS2	4.17E+21	5.97E+21	7.99E+21	8.12E+21	9.59E+21	9.79E+21	Sej/year
5	Total emergy available	U=R+N+IMP	1.05E+22	1.03E+22	1.26E+22	1.12E+22	1.08E+22	1.46E+22	Sej/year
6	Renewability	R/U	1.77E-01	1.80E-01	1.42E-01	1.63E-01	1.70E-01	1.21E-01	***
7	Emergy use per capita	U/population	1.06E+16	9.68E+15	1.05E+16	9.11E+15	8.57E+15	1.12E+16	Sej/people/year
8	Empower density	U/Area	6.15E+12	6.06E+12	7.42E+12	6.60E+12	6.36E+12	8.57E+12	Sej/m2/year
9	Renewable carrying capacity	(R/U) x population	1.48E+05	1.62E+05	1.50E+05	1.73E+05	1.83E+05	1.40E+05	People
10	Developed carrying capacity at European standard of living (ESL)	ESL x (R/U) x population	3.56E+06	3.90E+06	3.61E+06	4.14E+06	4.41E+06	3.37E+06	People
11	Developed carrying capacity at Mediterranean standard of living (MSL)	MSL x (R/U) x population	1.99E+06	2.18E+06	2.02E+06	2.32E+06	2.46E+06	1.88E+06	People

It is important to stress that column 1, which includes the renewable inputs, does not refer to the renewable energies used in the system. That energy, if any, would be computed directly or indirectly by the imported energy flow (either because it has actually been imported in the form of electricity, for example, or because it is an energy saving for the system if local sources are being used). Thus this input has to do with the potential of renewable sources present in the territory. Following Odum's methodology [204], in order to avoid duplication of flows, the renewable source in the area with the greatest potential is to be chosen. In the case of the Costa del Sol in 2007, it turned out to be the potential energy of waves.

Among all the second order indicators calculated, eMergy Renewability in column 6 is the first in which we will focus our attention. It stands for the relation between the potential renewable eMergy to the total eMergy in the system. A value of less than 100 percent for this indicator indicates that the system is dependent on imported eMergy. So, the closer you get to 0%, the more dependent you become. The Costa del Sol is observed to be between 18% and 12%, indicating a very high dependency.

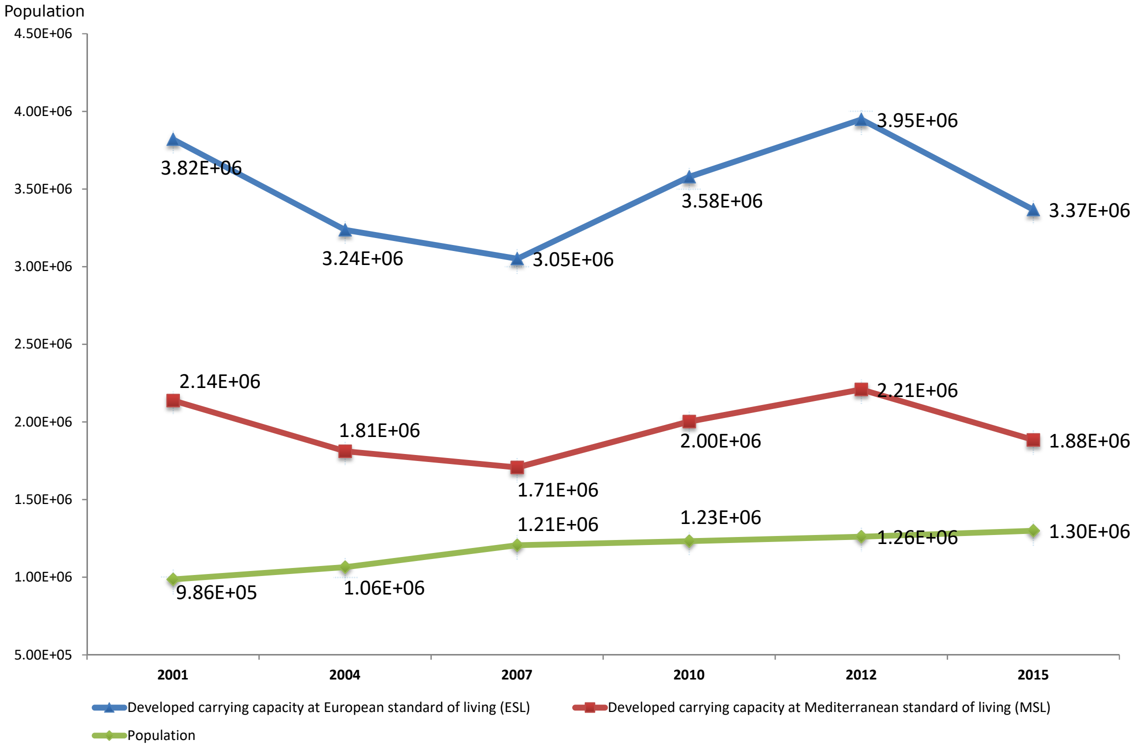

Fig. 4.5 Renewable Carrying Capacity in Costa del Sol. 2001 to 2015

The second family of eMergy indicators worth highlighting on this analysis are the carrying capacity ones, since they represented the main contribution expected from strong sustainability indicators. Following Lomas [159], in the present research it was decided to focus on a people-based renewable carrying capacity approach instead of an area-based one, since the former is better aligned with the most important event in the area during the period under study, that is, a significant increase in the population. This approach stands for the amount of people who could live in the region if only renewable inputs were accessible. This figure for the Costa del Sol can be found in row 9 of Table 4.3. In 2001, 159,000 people, that is, 16.13% of the total population, could have been supported by renewable resources whereas in 2015 just 140,000 (10.78% of the total population) were.

The people-based renewable carrying capacity is an extreme lower limit to environmental carrying capacity given that it only takes into account the gross renewable sources, neglecting the capacity of human development to meet their needs with optimized consumption patterns. In order to fix this drawback, Lomas [159], following Campbell [44], proposed an alternative methodology, which compares the population of the region under study with two reference regions and their respective "eMergy-standard of living". In the case of Spain, two regions were chosen: Europe (ESL) and Mediterranean basin (MSL). Rows 10 and 11 in Table 4.3 show these values.

Fig. 4.5 compares the evolution of both indicators, i.e. ESL and MSL carrying capacities, together with the actual population of the Costa del Sol. Although both indicators are above the limit, it is worth highlighting the fact that they worsen in a period of high economic growth (2004-2007), improve during the economic crisis (2007-2012) and worsen again significantly from 2012 to 2015.

After the calculation of the carrying capacity indicators, an eMergy Footprint value was also obtained. As mentioned above, even though eMergy Footprint is not a conventional eMergy indicator, it was decided to calculate it in this research in order to improve the robustness of the results.

Table 4.4 eMergy Footprint. Costa del Sol. 2001-2015

No	**Flow/Index**	**Expression**	**2001**	**2004**	**2007**	**2010**	**2012**	**2015**	**Units**
31	Renewable Empower Density (RempDr)	R/Area	1,77E-01	1,80E-01	1,42E-01	1,63E-01	1,70E-01	1,21E-01	Sej/m^2/year
38	Renewable support area (SA(r))	(IMP+N)/RempDr	1,06E+16	9,68E+15	1,05E+16	9,11E+15	8,57E+15	1,12E+16	m^2
	eMergy Footprint Costa del Sol	(SA(r)/Area Costa del Sol)	5.20	6.90	8.50	7.28	6.68	8.28	***
	eMergy Footprint Malaga Province	(SA(r)/Area Malaga Province)	1.21	1.61	1.98	1.70	1.55	1.93	***

Table 4.4 shows the results obtained. It can be observed that the load imposed by human activities in the Costa del Sol exceeds its available area in every year analyzed, specially in 2007 and 2015. This is clearly shown by the observation that, while any value above 1 means overload, the indicator reaches a value of 8.5 in 2007 and 8.28 in 2015.

If we compare it with the eMergetic indicators obtained previously, it can be seen that the evolution of both indicators is highly correlated with the eMergy renewability presented above. It is therefore shown that the first comparison between strong indicators provides a robust result.

4.3.3 EEA results

Table 4.5 EEA flows. 2001-2015

EE flows	**2001**	**2004**	**2007**	**2010**	**2012**	**2015**	**Units**
CEC (imports)	7.11E+15	1.11E+16	7.73E+15	1.30E+16	7.10E+15	1.24E+16	J/year
$E_{Capital}(inputs)$	1.83E+16	3.20E+16	4.95E+16	4.18E+16	4.29E+16	6.15E+16	J/year
$E_{Labor}(inputs)$	1.50E+17	1.75E+17	2.09E+17	1.78E+17	1.66E+17	1.92E+17	J/year
Total inputs	1.75E+17	2.19E+17	2.66E+17	2.33E+17	2.16E+17	2.66E+17	J/year
CEC (exports)	4.40E+15	6.32E+15	5.00E+15	6.22E+15	7.15E+15	1.07E+16	J/year
$E_{Capital}(outputs)$	1.14E+16	1.59E+16	3.08E+16	2.74E+16	2.87E+16	3.69E+16	J/year
$E_{Labor}(outputs)$	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	J/year
Total outputs	1.58E+16	2.22E+16	3.58E+16	3.37E+16	3.59E+16	4.75E+16	J/year
$E_{Discharge}$	3.21E+17	4.03E+17	4.52E+17	3.74E+17	3.31E+17	3.44E+17	J/year
E_{Trash}	9.89E+14	1.07E+15	1.21E+15	1.81E+15	2.22E+15	2.29E+15	J/year
Total losses	3,22E+17	4,04E+17	4,53E+17	3,76E+17	3,33E+17	3,47E+17	J/year

Table 4.6 EEA indicators

EE indicators	**2001**	**2004**	**2007**	**2010**	**2012**	**2015**
EE Renewability	1.60%	1.61%	1.40%	3.51%	4.18%	3.60%

In the same way as with the eMergetic footprint indicator, this new calculation of alternative exergetic indicators seeks to compare the results obtained with the eMergetic indicators, thus making them more robust.

Table 4.5 presents the summarized results of the EEA analysis. It is divided in three sections, i.e. inputs, outputs and losses flows, following the simplified EEA framework presented in the previous section (see Fig. 4.3).

Additionaly, Table 4.6 presents the EEA renewability indicator obtained from the EEA analysis. It is not the usual indicator obtained in other EEA analyses applied to nations like [256], [75] or [50]. As mentioned above, a simplified application of the EEA methodology has been developed for this analysis which can be better compared with the eMergy analysis also developed. Consequently, an exergy renewability indicator was calculated.

Fig. 4.6 compares the eMergy renewability and the EE renewability. Before analyzing this comparison it should be taken into account that both approaches are different. While the eMergy indicator is calculated using the *potential* renewable eMergy available, the EE indicator represents the *actual* renewable exergy used in the Costa del Sol.

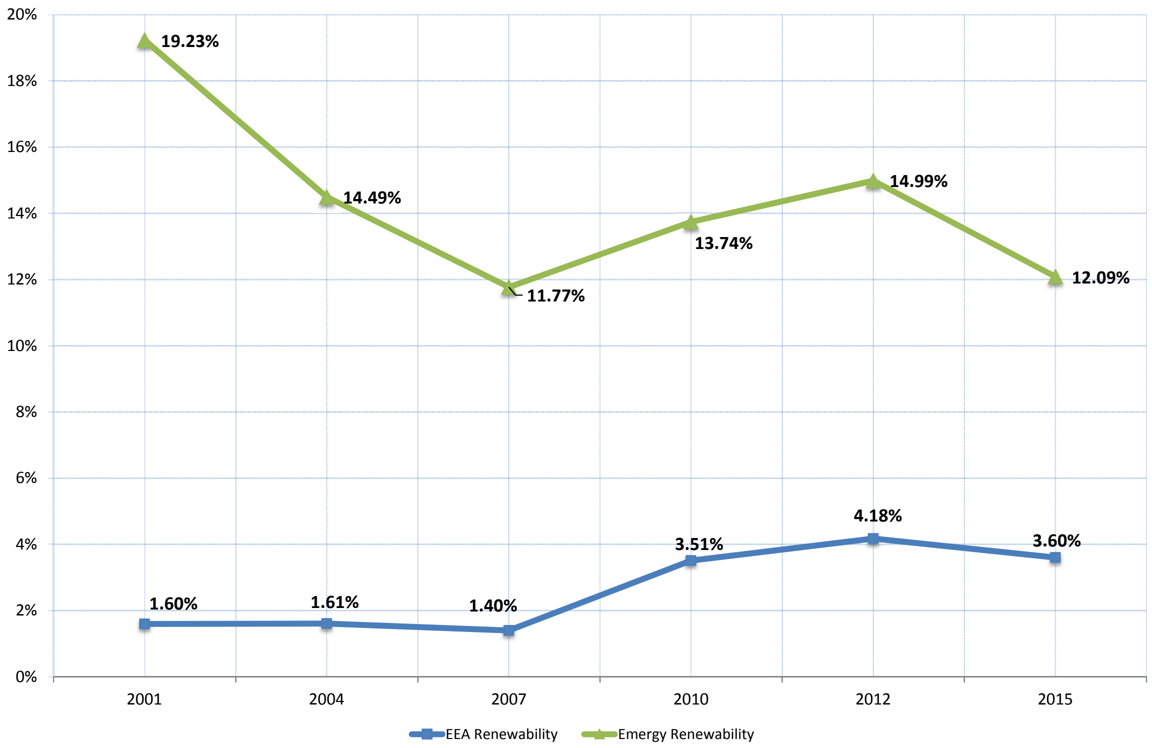

Fig. 4.6 eMergy and EEA renewability

Nevertheless, it can be seen that from 2007 to 2015, the correlation between both indicators is high. In contrast, from 2001 to 2007, the EE renewability is much more stable than the eMergy renewability.

In summary, although some differences can be found in EEA and eMergy analyses presented above, the most relevant results show a high degree of coincidence. Thus, the second comparison between families of strong indicators gives a positive result again: both provide very aligned information.

4.3.4 Weak and strong approaches comparison

Once the indicators from both proposals, i.e. weak and strong, have been obtained, it is time to compare them. By analyzing this comparison we will be able to infer what kind of relationship, if any, exists between them.

Eventually, Fig. 4.7 compares the evolution of both approaches, represented by ISEW and eMergy. For this comparison, the eMergy renewability indicator was chosen, as it is probably the closest eMergetic indicator to an extreme measure of environmental resilience, which represents a purer approach to strong sustainability, a higher R/U indicator means

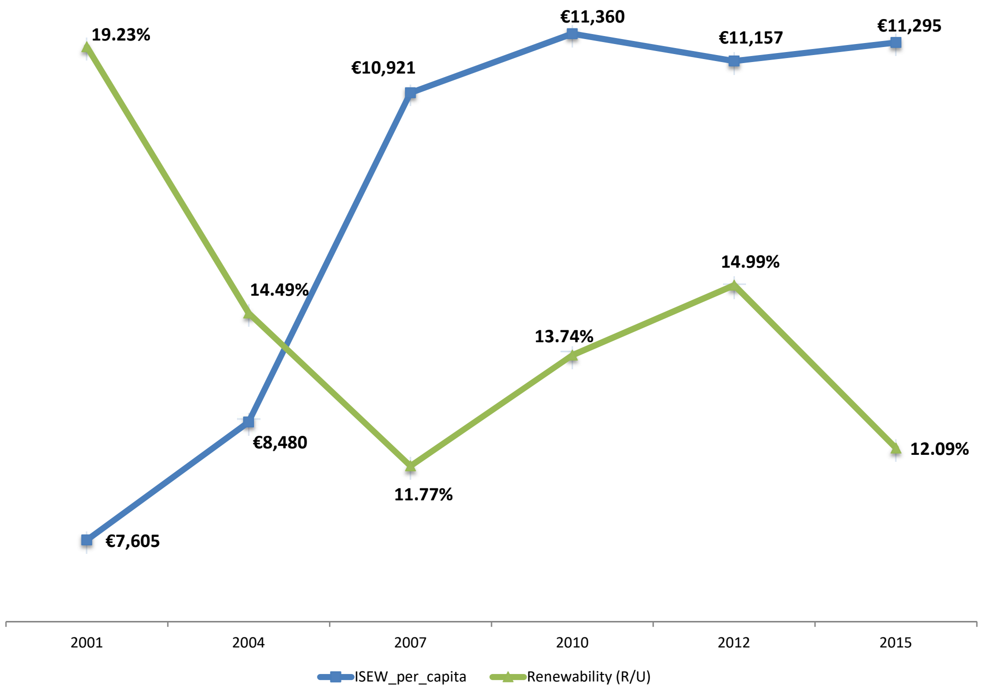

Fig. 4.7 ISEW-eMergy comparison

a lower dependency on non-renewable eMergy sources, thus a better sustainability of the region[7].

From 2001 to 2007, a period of great economic growth in the Costa del Sol, the ISEW improves, but the eMergy indicator worsens. It can be interpretes as basically non-renewable energy was boosting this economic growth.

From 2007 to 2010, during the economic crisis, both indicators improve. While a change of trend occurs in the eMergetic indicator, the ISEW experiences a very appreciable slowdown of its growth. With respect to eMergy, what drives the change of trend is the reduction in economic activity in general, which means a reduction in the pressure on the environment.

From 2010 to 2012, ISEW slightly worsens and eMergy continues to improve. The explanation follows on from the above. From ISEW's point of view, the economic crisis is draining the welfare reserves which are beginning to shrink, while eMergy is continuing its positive trend due to the even more marked reduction in economic activity, which, as mentioned above, was boosted by non-renewable energy sources.

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[7] Similar results are obtained if the comparison is made with the inverse of the people-based carrying capacity indicator in Table 4.3.

Finally, from 2012 to 2015, ISEW slightly improves and eMergy worsens significantly. Economic activity is recovering, which has a positive effect on the ISEW, whose positive trend returns, but, unfortunately it has a particularly negative effect on eMergy, since this growth means increasing the pressure on the environment.

In summary, the Costa del Sol during the period from 2001 to 2007 presented a sustainable development in socio-economic terms, in which the welfare of the population improved significantly. However, this development was based on an excessive dependence on non-renewable resources. This unsustainable energy behavior was imposing an increasing pressure on the ecosystem. Conversely, from 2007 to 2012, the economic crisis that stalled the ISEW indicator, meant a slight improvement of sustainability in eMergy and EEA terms. Eventually, from 2012 to 2015, a clear decay was revealed.

At a first glance, it might be inferred that both approaches have produced partially contradictory results. On the one hand, the ISEW for the Costa del Sol from 2001 to 2015 shows the same evolution as GDP but in a more attenuated way. Thus, from a weak sustainability point of view, the sustainability of the Costa del Sol improved from 2001 to 2007 and stagnated from 2007 to 2015. On the other hand, according to the eMergetic indicators obtained, an unsustainable trend is revealed. Although its carrying capacity is essentially above the upper limits defined by the development standards in Europe and the Mediterranean Basin (see Fig. 4.5), it worsens significantly in periods of high economic activity as from 2001 to 2007 or from 2012 to 2015.

However, it cannot be inferred from these results that improvements in welfare always come at the expense of ecological limits: from 2007 to 2012, the evolution is reversed and the eMergy indicator improves, following the ISEW. This points out that there is no strict inverse correlation.

Thus ISEW and eMergy, i.e. weak and strong sustainability approaches, provide different and possibly complementary insights to the same reality. As mentioned above, ISEW is basically providing a WS approach to SD (although it incorporates environmental concerns by including them in the neoclassical economic paradigm), and also addresses equity concerns; whereas exergetic approaches provide a SS insight. In other words, both approaches together are able to cover the requirements of sustainability presented in this thesis, namely, that a fairly allocated aggregated levels of capitals are non decreasing in time and the resilient limits of the environment are not surpassed. If they are analyzed, as usual, in a separate mode, only one partial and insufficient insight regarding the sustainability of the system is being taken into account. On the contrary, by using them together, we will get a better understanding of the changes in the sustainability in this area, what will allow us to build a more solid narrative and to take better decisions with regard to transiting towards more sustainable societies.

It is essential to make it clear that our experiment is limited by several factors. The first limitation is related to the availability of data. Table 4.1 included the information about the scope in which the data were collected. It may be noticed that many items were directly obtained using local data of the Costa del Sol, yet other were interpolated from regional (Andalusia) or National (Spain) statistics. The eMergy and EEA calculation partially suffer from the same problem. Nevertheless, although the lack of local data is a serious limitation, it might be accepted that the results obtained for the Costa del Sol still present a simplified picture of the social, economic and ecological sustainability of the urban area, which could be reinforced by other kind of studies focused on specific areas.

A second limitation is related to the risk of reductionism. Trying to convey the sustainability of an urban area in two, three of four indicators, whatever weak or strong, may not be enough. Nevertheless, it does not mean that the integrated weak-strong approach presented is not valid. We should take into account that the main purpose of this research was to illustrate the appropriateness or not of using a combined weak-strong approach when dealing with sustainability issues, as has already been commented on numerous occasions throughout this document. In any particular real application, a proper set of indicators (working within a proper framework) is to be chosen.

Besides, although comparing six years has offered interesting information, wide temporal and spatial series analyses are still needed in order to obtain, for instance, a comparative idea of the relative sustainability of the Costa del Sol to other Spanish regions.

Eventually, a fourth limitation of the present study is that, if we are concerned about actual ecological thresholds, we need to find the absolute carrying capacity limits of the Costa del Sol. The present research has calculated two approaches to this carrying capacity using eMergy indicators, but neither of them represents an absolute limit to the socio-economic activity in the region, but two relative ones. They show the negative or positive evolution, but they do not calculate an absolute value representing a real limit for the ecosystem of the Costa del Sol. Unfortunately, neither this kind of *static* strong sustainability studies, nor the weak ones are the most suitable to get these results. *Dynamic* studies could provide valuable insights into this issue[8].

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[8] Dynamic eMergy Analysis could be an interesting tool for this purpose [311].

4.4 Conclusions

In the introduction, the goal expected from this exercise was presented: to show the extent to which both weak and strong sustainability paradigms can cooperate within the proposed framework. In order to discern that, several indices (weak and strong) were chosen which might help to investigate the possibility for weak and strong sustainable paradigms to offer a consistent vision of the sustainable condition of a system, and they were applied to a real case: the Costa del Sol conurbation in southern of Spain.

The results show that the weak and strong indicators, when applied together and consistently to the Costa del Sol conurbation, provide not correlated views, but rather help us understand better the implications for the economic, social, ecological and equity aspects of sustainability.

The eMergy and the EEA methodologies incorporate the economic activity in their ecological paradigm, but social aspects of sustainability are not properly taken into account [236]. Nevertheless, that drawback of these approaches is, at the same time, the best asset of ISEW studies which are centered on analysing the welfare dimension of sustainability.

Therefore, and despite the limitations of both approaches, the possibility of cooperation between weak and strong paradigms has proven not only real but also very useful. On the one hand, the ISEW has offered a more accurate measure of welfare and the fairness in distribution of resources than classic GDP approaches. On the other hand, eMergy and EEA have contributed with its renewability and carrying capacity indicators to the knowledge about the environmental load that socio-economic activity is imposing on the ecosystems and to set limits to this activity according to them.

The conclusions of this (albeit limited) research is that, in the complex context of sustainability, strong and weak sustainability paradigms can and should be used together. The former should be responsible for finding critical limits of resilience or carrying capacity which can ensure that our socio-economic activity is within the biophysical limits of planet earth [319]. Once this fact is guaranteed, weak sustainability methodologies would be responsible for a relatively fair and sustainable allocation of welfare.

Nevertheless, some important limitations have also been highlighted during the present study that are worth mentioning. Both indices suffer from the two common ills of all these analyses. The first one is the difficulty to find accurate data for urban studies since most statistics are compiled at regional or national level. The second one is related to the risk to reduce the sustainability analysis to the simple calculation of certain set of indicators. Even assuming that, on the one hand, ISEW is really measuring welfare, and, on the other hand, eMergy or EEA are measuring resilience, a framework in which both approaches are adequately integrated and interpreted is still needed.

This is precisely the gap that the framework proposal presented in the next chapter seeks to fill.

Chapter 5

Framework to integrate weak and strong sustainability

Once the gap to be filled by this thesis has been presented, namely, to propose a particular operational framework for sustainability analysis based on a combined WS-SS approach which is applicable to energy systems, and after having tested in the previous chapter that this combined proposal is really effective, this one describes the framework itself.

In previous chapters, what characteristics would be asked of that framework applicable to energy sustainability studies were presented. There were three main features required, namely (1) that it should be operational; (2) that it should be compatible with the capital-based definition of sustainability; and (3) that it should be scalable.

These requirements guided the state of the art, which was divided into multi-criteria and systemic frameworks. From that exercise it was concluded that the former approach, while versatile and consolidated, was the most interesting, without this precluding from appreciating all that complex systems-based approaches inspire.

Thus, the strategy to be followed regarding the actual implementation of the framework in a real energy-related case study was clear, but it was still necessary to propose its generic formulation, which would basically consist of formalizing the requirements established previously.

To do this, Linares' proposal [157] was the inspirational reference, which is in turn based on the work of Neumayer [199] and Pearce [212, 213] on a capital-based approach to sustainability. In it, the four capitals to be sustained over time, namely economic, social, human and natural, are complemented by the equity aspect. All of this is subject to critical limits in those criteria where the precautionary principle persuades us to remain within the safety zone. This framework is summarized in the following formulation:

$$\begin{aligned} \dot{K} = \frac{\partial k_e}{\partial t} \oplus \frac{\partial k_n}{\partial t} \oplus \frac{\partial k_s}{\partial t} \oplus \frac{\partial k_h}{\partial t} &\geq 0 \\ s.t. \\ k_i \leq CL_i, \forall i \end{aligned} \tag{5.1}$$

where $\dot{K}$ represents the variation of the aggregated capitals over time, k_i stands for each type of capital, namely, economic, natural, social and human; and CL_i stands for critical limits.

It may be observed that the proposal brings together the two sustainability schools, WS and SS, in a very specific way. On the one hand, the function to be optimized is a version of the Hartwick's rule already mentioned above, where it is simply demanded as a condition of sustainability that the aggregate of capital is not decreasing in time. Hartwick would stay there, but this framework takes a step forward. It incorporates critical limits for all capitals, which is what actually sets the minimum conditions for sustainability.

Now, measuring capital themselves is a complex task. Therefore, it was decided to represent them using indicators that may measure the evolution of these capitals, and that can still give us an estimation of the changes in welfare of society. Also, since building a dynamic model would be excessively complex if we still want to keep the level of detail required for the energy system, it has been proposed to substitute it with a static model, that measures welfare in specific points in time, although still trying to optimize it for each of the time periods considered. This may of course generate some level of dynamic inconsistency, that should be addressed.

Therefore, Eq. 5.1 becomes:

$$\begin{aligned} OptK = f(k_e, k_n, k_s, k_h) \\ s.t. \\ k_i \leq CL_i, \forall i \end{aligned} \tag{5.2}$$

This optimization is not directly a maximization or a minimization. It will depend on the indicators chosen to represent each capital. For example, it will be clear that from an economic capital point of view, cost minimization will be a desirable objective. But equally desirable will be the maximization of jobs.

A framework is therefore being proposed that defines sustainability in the form of an operational optimization problem where the objective function to be optimized is dependent on capitals, that are represented by several criteria, subject to a set of critical limits that can be applied not only to natural capital, but to any type of capital. This framework is totally compatible with that capital-based approach to sustainability that defines being sustainable as being able to create value while not exceeding the resilient limits of the eco-social environment.

It is also important to note that the objective function in Eq. 5.2 is defined neither as a sum of capitals nor as an aggregation of capitals. It merely highlights the dependency of this function to be optimized on the capitals. This way, special care is being taken with this crucial issue of aggregation as discussed above.

This objective function can take different forms. In this thesis, in coherence with the previous chapters, it was decided to develop it based on multi-criteria techniques, specifically Compromise Programming (see Section 3.1.1). Thus, Eq. 5.2 would be formulated as follows:

$$
\begin{aligned}
\min L_p = \Big[\sum_{i=1}^{n}[w_i \frac{k_i - k_i^*}{k_{i*} - k_i^*}]^p\Big]^{1/p} \\
s.t. \\
k_i \leq CL_i, \forall i
\end{aligned}
\tag{5.3}
$$

where w_i represents the weight assigned to each capital k_i, p stands for the distance to be minimized (from 0 to ∞), and k_i^* and k_{i*} represent the ideal and anti-ideal (nadir) values for each capital, respectively.

Another possible derivation of the general framework is that put forward by Hediger [118]. He developed an approach that seeks to reconcile the two approaches to sustainability: WS and SS, by interpreting the K function in Eq. 5.2 as a corrected social utility function, which he defined as "sustainability-based social value function".

It is interesting to note that the WS side of the proposed framework presented here is in line with that proposed by Hediger. Not surprisingly, the multi-criteria framework based on Compromise Programming has a direct interpretation as a function of social utility [156].

Therefore, it has already been developed in its algorithmic form the proposed framework for sustainability analyses, but there is still to cover one of the fundamental elements that were identified as essential, namely to incorporate the issue of equity in the distribution of capitals. This requirement will have to be specified in each of the partial analyses to which the framework is applied. For example, in the case of the energy sector, equity concerns may be introduced by ensuring that an affordable and quality energy service is provided to the entire population.

The formalization of this requirement within the proposed optimization problem could be as follows:

$$\min L_p = \Big[\sum_{j=1}^{m}\sum_{i=1}^{n}[w_{ij}\frac{k_{ij} - k_{ij}^*}{k_{ij*} - k_{ij}^*}]^p\Big]^{1/p}$$

$$s.t.$$

$$k_{ij} \leq CL_{ij}, \forall i, j \tag{5.4}$$

It can be observed that a disaggregation of the capitals according to the sub-index j has been added. This sub-index might represent different population subgroups and how they participate in the different capitals. For example, for economic capital these would translate into income deciles. Thus, when imposing critical limits, this approach would make it possible to consider certain vulnerable groups that should be subject to specific boundaries appropriate to their specific situation. An example of a partial application of this proposal can be found in the case study in Chapter 7, where households in Spain have been disaggregated into two groups: vulnerable and non-vulnerable, thus making it possible to meet the energy demand of the former in a particular way.

This new formulation is consistent with what has been described above. That is to say, the minimum conditions of sustainability are fulfilled respecting the critical limits, which are no longer applied only to an aggregation of capitals, but also to a disaggregation of them that incorporates equity concerns. Once it is guaranteed that this condition is met, the optimization of the use of the different socio-environmental capitals can be considered.

Additionally, it is also important to stress that the framework proposed responds to Martínez-Alier and Munda's suggestion of using frameworks in which the compensability[1] is not rejected, but simply limited: "Of course, the possibility of limiting the compensability among indicators and to put lower bounds of acceptability (e.g. by the notion of a veto threshold) is of a fundamental importance to operationalize the strong sustainability concept." [170]. That is exactly what is at stake here. There is partial compensability on the side of capital and welfare, while this is suspended at critical limits.

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[1] By compensability we mean the possibility of one capital assuming the role of another. That is to say, it is a similar concept to the substitutability already mentioned above.

Therefore, the first two requirements of the framework mentioned at the beginning of this chapter, i.e. it is operational and it is capital-based, are met, but the extent to which it is scalable remains to be shown. This is a point at which the framework draws directly from the complex inspiration present in proposals such as VSM or SOHO. If we understand the eco-social environment in which human activity takes place as a viable system in Ashby's sense (see section 3.1.2.3.3), we should define this system using a framework that is self-replicating at various scales. So is the proposed optimisation framework.

Where this question of scaling up a particular system, such as the energy system, to the global socio-environmental system becomes especially important is when we define the critical limits. The particular limits that are defined and applied to a particular case study will have to be fully consistent with the global limits. This will mean that, in some cases, a certain a priori distribution of efforts between sectors will have to be assumed. A good example of this is CO_2 emissions. If we want to define an emissions limit for the energy sector compatible with the global effort to decarbonise the economy, we will have to make an assumption of distribution of CO_2 reduction efforts in the other sectors. This is precisely what has been done in the case study in Chapter 7, based on the roadmaps to 2030 and 2050 of the European Union.

Since it is defined as an optimization of well-being subject to critical limits, this framework is applicable from the highest possible level, i.e. the challenge of SD on a global scale, to the contribution of a particular sector, such as energy, to this challenge. Of course, in each case the indicators and constraints will have to be carefully selected, but the formal structure of the framework would be identical.

Once the formalized proposal for the framework has been presented, some reflections on the indicators are necessary. It can be seen from the formulation itself that, as described in previous sections, two types of approaches are needed. The first has to do with capital, and more specifically with how that capital adds up to well-being. The second has to do with the critical limits of the eco-social environment.

Thus, depending on the case study, indicators of both types will have to be chosen and each of the two sustainability schools (WS and SS) is better suited to one of them, i.e. WS for well-being and SS for biophysical limits, respectively. This way both paradigms have their range of application within the proposed framework, that is to say, no one dominates the other[2].

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[2] It may be also observed that this proposal is compatible with the Doughnut Economics proposed by Raworth [230].

At this point we are in a position to apply the proposed framework to a specific case study. This will be done in the Chapter 7. But, before that, it is still necessary to analyze one of the key elements needed in order to provide a comprehensive framework for energy sustainability. I am referring to equity, or in other words, to what we mean by equity when we talk about energy. Chapter 6 will attempt to answer this question.

Chapter 6

Integrating equity concerns: energy poverty

Throughout the previous chapters, it has become clear how important it is to incorporate the equity aspect into a comprehensive framework that addresses the sustainability analysis of energy systems. Within these equity aspects, I have explicitly referred to the issue of energy poverty. Nevertheless, the question of energy equity and, therefore, that of the energy poverty contained in the previous one, are in turn part of an even broader concept that in recent times has been conceptualized as energy justice. Sovacool [268] states that an energy justice framework must respond to the following challenges: (1) equity, (2) due process, (3) transparency, (4) accountability, (5) sustainability, (6) responsibility, (7) availability and (8) affordability.

It can be observed that this purpose of Sovacool is shared by the author and is reflected in the approach presented in this thesis. A re-reading of the framework proposed in the previous chapter from the keys that Sovacool's framework provides shows that all of them are contained directly or indirectly in it:

In the first place, it should be noted that the concept of justice proposed by Sovacool is very close to the proposal of equity presented in this thesis. In other words, the equity to which I refer in this document is distributive justice, not equality, which is what Sovacool probably means when he uses the concept of (1) equity. That is the first key of comparison.

Then, (2) due process means that countries should respect human rights in their production and use of energy. This is an aspect that is not explicit in the model but that is reflected in some way in its anthropocentric starting point, which seeks to leave options open so that both present and future generations can satisfy their demands according to chosen (not imposed) preferences.

(3) Transparency and (4) accountability have more to do with the theoretical proposal than with the way to implement it. In this sense, the multi-criteria methodology that serves as a foundation for the framework proposed in the thesis includes within its many associated techniques the consultation process seeking to obtain the preferences of the stakeholders. These preferences will ultimately define the weights associated with the different criteria. An example of the application of this methodology can be found in the case study in the following chapter. The use of this methodology gives the decision-making process an open and much more transparent character.

The aspects of (5) sustainability and (6) responsibility in Sovacool's framework refer fundamentally to the respect of the resilient limits of the environment, which in this thesis have been mainly associated with a partial strong approach to sustainability. It is important to emphasize, however, that the concept of sustainability that I manage in this document is broader than that proposed by Sovacool. In fact, sustainability incorporates justice, not the other way around.

Finally, let us analyze two very related aspects: (7) availability and (8) affordability. Both point to the same challenge: to guarantee that the entire population is capable of covering its basic energy needs. The difference between the two is that availability emphasizes the need to guarantee the access to modern forms of energy, while affordability focuses on the fact that the provision of energy services do not become a financial burden for consumers, especially the poorest. They are in fact the two sides of the same coin, as the author understands it. It is not enough to guarantee access to energy; it is also necessary to ensure that this access actually translates into consumption. Sovacool expresses it very graphically with a metaphor: "the proof in the pudding lies not in its making, but in its eating" [268].

However, the geographical incidence of both issues is very unequal. The question of availability is mainly concentrated in developing countries, while affordability is presented mainly in those developed countries where the former is already guaranteed.

From the above, it is concluded that the inclusion of the justice/equity issue will depend on the specific analysis in which we are focusing. If the study refers to developing countries, the main aspect to take into account will be (7) availability. If, on the other hand, the analysis deals with the energy system in a developed country, the study will have to analyze the issue of (8) affordability[1].

It is in this second case where the present chapter of the thesis is focused on. This is done in coherence with the case study carried out, which consists of the analysis of the

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[1] Of course, the remaining justice-related factors that Sovacool raised are also important and, as highlighted above, are in fact already being addressed by the framework proposed.

sustainable energy transition in Spain. In order to integrate the equity aspect into this case, it was necessary to understand the reality of affordability in the country. The question of availability is a very prolific branch of study [178, 94] which will not be explicitly addressed in this thesis.

Thus, this chapter[2] presents an introduction to the state of the art on the issue of affordability, and then it focuses on the Spanish case. For reasons of clarity and compatibility with most of the existing literature, the term energy poverty will be used to name this affordability challenge.

6.1 Introduction

25 years after the publication of Brenda Boardman's book about fuel poverty[3] [21], the debate in Europe regarding this important issue is probably more alive than ever. Although the most relevant contributions come from the UK [22, 125, 180, 106, 117, 127, 66] some other assessments can be found in the literature coming from other European countries as well [28, 81, 42, 84, 103, 144, 248, 251, 285, 286]. In addition, projects like EPEE, INSIGHT-E, the EU Fuel Poverty Network, the EU Energy Poverty Observatory (EPOV) and the recent report by Trinomics [226], have also contributed significantly to the understanding of this complex issue.

In 2012, an special issue of Energy Policy introduced by Liddell's editorial [150], helped summarize some of the most relevant achievements to date, together with the pending issues. Five years later, some of them are still open, in special those regarding the proper definition of energy poverty and the right methodology to obtain a comprehensive indicator.

The methodologies proposed in the literature are quite diverse. Some are subjective approaches based on personal or third parties perceptions of affordable warmth at home; whereas others calculate objective indicators. Although these different proposals have already been theoretically criticized [85], [119] or [252], an empirical comparative analysis that measures in a real case study the practical impact of the theoretical limitations and their policy implications detected for the different indicators was still pending.

Thus the goal of this chapter is to deepen into the roots of this crucial dimension of energy sustainability by comparing critically the different approaches used to measure energy

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[2] This chapter is based on the paper:"The policy implications of energy poverty indicators", developed by the author, Pedro Linares and Xiral López and published in Energy Policy [237].

[3] In this survey, the term energy poverty instead of fuel poverty has been used. A discussion about the difference between them can be found in [149].

poverty on an objetive basis, and to propose a new methodology that might be able to overcome some of the major problems that affect current proposals, i.e. (1) excessive sensitivity to energy prices and housing costs, (2) arbitrariness in the election of the thresholds and (3) relative approaches that measure inequality rather than poverty. This third drawback will be further elaborated in Section 6.2.

However, defining a more accurate indicator that is able to show the extent of the energy poverty incidence in a country is not enough. If the energy poverty issue is to be correctly addressed, we must be able to identify the characteristics of those households most affected by it. Again, although some proposals have been done regarding the identification of vulnerable households [176], [147], there is still room from improvement. Therefore, in the present chapter, the major factors that determine the vulnerability of households to energy poverty are also analyzed. Then, the main policy implications of the results are presented.

The methods are applied to Spain, a country that, although features a rather benign climate (and would therefore be assumed to suffer little from this problem), has also been severely affected by the economic crisis, and in which energy prices have also increased very much recently (placing it among the most expensive countries for energy in households). As a result, Spain presents energy poverty rates comparable to other European countries and is therefore a good reference to test the different indicators.

Eventually, this analysis outlined in this introduction will clarify the role of equity within the concrete context of energy sustainability and how to measure it, so that it can be integrated into the framework of analysis that this thesis presents, and its practical application in the case study in Chapter 7.

The structure of the chapter is as follows: Section 6.2 presents a brief state of the art of energy poverty indicators. Section 6.3 applies the methodology proposed to the Spanish case and calculates the indicators, focusing on the search for their limitations and strengths. Additionally, the econometric study of vulnerable households is also introduced. Finally, Section 6.4 includes the conclusions and some policy recommendations in the light of the empirical results.

6.2 Measuring energy poverty

The first studies about energy poverty were elaborated in the early 80s in the UK. They were conducted by Bradshaw and Hutton [29], and are the prelude to Boardman's study [21], also in the UK, where the first formal definition of energy poverty was presented: a home would be energy poor if its expenditures on energy services were higher than the 10% of its total income.

In 1991, the English Housing Condition Survey (EHCS), that became the English Housing Survey (EHS) in 2008, used this threshold proposed by Boardman to measure the "affordable warmth", i.e. the ability of households to ensure a comfortable temperature in winter. Since then some other definitions to energy poverty have been proposed [85], [224]. Among them, Heindl's [119] classification of energy poverty indicators is particularly interesting:

1. Subjective and qualitative developed by the individuals themselves.
2. Subjective and qualitative developed by third parties.
3. Objective and quantitative indicators not income-expenditure based (eg, humidity, incidence of mold in the household or epidemiological data).
4. Objective, quantitative and income-based indicators.

Ideally, as Heindl points out, all these indicators should be taken into account when addressing the study of energy poverty in a country. Although the fourth group should provide the final figures, their empirical calibration must be based on the information that the other three groups of indicators provide. Additionally, the Trinomics report on energy poverty [226] provides an interesting critical analysis of the different approaches and proposes a tool to monitor energy poverty at an European level. Although recognizing the need to include subjective (consensual) and objective (income-based) approaches, the present research focuses on the latter.

Of the objective income-based indicators, some have focused on the share of energy costs in relation to the total household income, similarly to the already described 10%. The most common ones are those based on the double average or median expenditure on energy, a group of indicators that Schussler [252] summarizes as 2M indicators.

Alternatively, others are based on the Minimum Income Standard (MIS) approach[4]. According to this paradigm, a household is energy poor if, when we subtract the MIS and housing costs from the total household income, the remaining income is not enough to cover its energy needs [180].

Finally, a third approach, the Low Income High Cost (LIHC) indicator [125], combines both aspects, i.e. energy costs and household income. According to this proposal, only the households located in the worst quadrant (that is, experiencing low income and high energy costs) would fall within the category of energy poverty.

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[4] According to Bradshaw et al. [30], a minimum income standard (MIS) has to do with having what you need in order to have the opportunities and choices necessary to participate in society.

In Table 6.1 a selection of energy poverty analyses in Europe in recent years is presented. It is noteworthy that there is a great deal of variability in it, even within the same study, depending on the type of energy poverty indicator used.

Table 6.1 Energy Poverty indicators in Europe

Reference	Country	Year	Indicator	Value
[124]	England	2009	LIHC	9%
[180]	England	2008	MIS	25.5%
[286]	Hungary	2005-2008	Double Median Expend.	4-8%
			Energy Expend > Food Expend.	17-25%
[25]	Austria	2013	LIHC	2.5%
[300]	Italy	2011	MIS	8.4%
[119]	Germany	2011	10%	27.6-29.5%
			MIS	9.9-10.6%
			LIHC	11.1-15.6%
[147]	France	2013	10%	16.6%
			AFCP	20.9%
			LIHC	9.2%
[232]	UK	1997-2008	10%	18-18.2%
[67]	England	2014	LIHC	10.6%
			10%	11.6%
[129]	France	2006	10%	11-13%
			LIHC	10%
[211]	Greece	2015	10%	58%
[72]	Spain	2013	10%	18.24%
			LIHC	8.71%
			MIS	9.88%

Let us present now, according to the literature, the main advantages and drawbacks of each of these three groups of objective income-based indicators.

6.2.1 10% indicator

According to this indicator, a household is energy poor if it has to spend more than 10% of their income to pay for adequate energy services. This definition by Boardman [21] became the official energy poverty indicator in the UK from 2001 to 2013, when the whole strategy was revised and a new indicator: the LIHC, was chosen [125].

It cannot be denied that the the 10% indicator has several advantages. It is a simple, easy to communicate and relatively versatile indicator from a pragmatic point of view. However, it also suffers from significant limitations which have been clearly highlighted in the literature [252] and [119].

Criticism is mainly due (1) to the excessive sensitivity to energy prices; (2) to the arbitrary selection of the threshold at 10%, which is justified on the socio-economic situation in the UK in the early 90s, but cannot be directly extrapolated to other spatial and temporal situations; and finally, (3) to the lack of any reference to the household income.

In fact, it has been shown that this threshold of 10% calculated over different countries may include a significant number of households that are not energy poor, e.g. high-income households with inefficient homes or with an otherwise excessive energy consumption. In Heindl's analysis [119] the 10% indicator is considered an outlier, as it places the phenomenon of energy poverty above 25%, much higher than what you get using other indicators.

In order to better understand these criticisms we should analyze the initial justifications that led to the election of 10% as the threshold for the UK. In the pioneering work of Boardman [21], which used data from 1988, the 10% indicator represented, on the one hand, the average energy expenditure of 30% of the poorest households in Britain, and on the other hand, approximately twice the median percentage of energy expenditure of all households. At first, as Schuessler points out [252], this second interpretation was considered the most relevant and it served to consolidate the indicator. Nevertheless, if we highlight this capability of the 10% indicator to approximate the average cost of a specific percentage of the poorest households in the country distinctly from the entire population, as the second interpretation did, the indicator takes on a new dimension, although with problems also. It is worth noticing that the first justification is referred to an absolute limit of poor households, whereas the second relies on a relative level of consumption.

This reflection by Schuessler opens the debate between the convenience of using relative or absolute indicators when dealing with poverty issues. From the author's point of view, the problem of energy poverty, as a social justice issue, is essentially normative, or in other words, it is a problem of absolute limits. The fact that the whole society improves or worsen their aggregate behavior in this matter does not bring a concrete home in or out of energy poverty. Hence, from my understanding, a relative measure of poverty reflects inequality rather than poverty as such.

That said, the author is aware that there is a broad consensus about the appropriateness of using relative rather than absolute methodologies to analyze poverty issues [290]. The soundest arguments to defend that position are rooted on the ability of relative measures to be extrapolated to different geographical and temporal situations and, at the same time, to reflect inequality, a social illness so closely related to poverty that should be considered jointly. I acknowledge that this argument is important, however, since we are specifically trying to measure energy poverty, defined as a problem of social justice (and not as an indicator of welfare, in which case relative comparisons may be pertinent) I still defend that absolute measures are more appropriate. Needless to say that these measures will be very much enriched with an specific analysis of energy inequality. In that case, using relative measures will become a necessity.

6.2.2 Low Income/High Cost indicator

The LIHC was proposed by Hills [125] and constitutes the basis of the new strategy in the UK in the fight against energy poverty.

According to the LIHC indicator, a household is defined as energy poor when income is below a certain (relative) poverty threshold and when its energy costs are higher than an energy expenditure threshold. Obviously, the use of this indicator requires the definition of both thresholds, which is not an easy task. Regarding the first, the approach used by Hills is the 60% of the median equivalent income after subtracting housing and modeled energy costs. For the second threshold, Hills used the median equivalent energy expenditure calculated over the total households.

This proposal is not exempt of criticism either. Moore [180] criticized the LIHC for different reasons: (1) because, in his opinion, it is an overly complex and not transparent indicator, mainly by the problems of modeling the energy equivalent indicator; and (2) because setting the threshold of energy expenditure does not take into consideration the effect of energy efficiency of homes, and makes it difficult at the same time to find out those households that can come out of energy poverty by way of reducing their energy costs.

In addition to these two points highlighted by Moore, another problematic aspect of this indicator is its double-relative character (being the quotient of two relative measures), what makes very difficult to isolate causes and effects in the analysis of their results, especially when analyzing time series, and provokes some odd dynamic behaviour [120].

6.2.3 MIS based indicator

Applying this approach to the case of energy poverty, a household would be energy poor if it does not have enough income to pay for its basic energy costs, after covering housing and other needs. This indicator specifically identifies households which would be above the poverty threshold but fall below it because of its energy expenditures.

To find a study of energy poverty indicator based on the MIS, we must go once again to the UK, and specifically to the work of Moore [180]. According to this researcher, the MIS provides a consistent and accurate measure of energy poverty, and at the same time it is easily adaptable to different standards of living in Europe. He also suggests that a scale of energy poverty based on MIS would help measure the level of vulnerability of different households.

The indicator of energy poverty based on the MIS is undoubtedly one of the most robust when measuring objective income-based energy poverty, because it addresses the problem from its very economic root: the income available for energy needs after the basic needs have been met. Unfortunately, it also presents a technical difficulty: the determination of the minimum income on an objective basis.

After the mayor theoretical drawbacks of the three different groups of objective and income-based energy poverty indicators have been presented, the following section summarizes the results of an empirical analysis based on a real case, i.e Spain, in which these limitations are put at stake.

Let us not forget that our ultimate objective is to deepen our understanding of energy poverty as a key equity variable to be incorporated into a comprehensive energy sustainability analysis framework. In this sense, this analysis of indicators will be very useful to clarify which indicator is the most appropriate for the framework proposal made in this thesis.

6.3 Energy Poverty indicators for Spain

6.3.1 Indicators

In the previous section the pros and cons of the three families of objective and income-based energy poverty indicators consolidated in the literature have been presented. Now they are estimated in a real case: Spain in 2015. This analysis will allow us to detect the practical problems behind the implementation of these indicators, and in particular, the amount of false positives and negatives that they can generate, and their sensitivity to the assumptions.

The data source used for this study was the Spanish Household Budget Survey (EPF) in 2015.

The methodology to calculate the 10% indicator is exactly the same of that proposed by Boardman [21]. Nevertheless, the methods to calculate the LIHC and MIS-based were slightly different to those proposed by Hills [125] and Moore [180] respectively.

The LIHC has been calculated so that energy poor households are those that verify Eq. 6.1 and Eq. 6.2.

$$[Household\ expenditure\ on\ energy] > [Median\ expenditure\ on\ energy] \quad (6.1)$$

$$[Household\ income] - [Household\ expenditure\ on\ energy] < 60\%[Mean\ Household\ income - Mean\ expenditure\ on\ energy] \quad (6.2)$$

The difference with Hills' approach [125] is located in the latter equation. Hills proposed using Eq. 6.3 instead of Eq.6.2

$$[Household\ income] - [Household\ expenditure\ on\ energy] < 60\%[Mean\ Household\ income] \quad (6.3)$$

In our case, Eq.6.2 was preferred to Eq.6.3 because in it the mean expenditure on energy was subtracted from the mean household income in Spain in order to be consistent with the first term of the equation in which the income of the household after energy costs is considered.

Regarding the MIS-based indicator, Moore proposed that a house is energy poor when Eq. 6.4 was verified.

$$[Fuel\ Costs] > [Net\ household\ income] - [Housing\ costs] - [MIS] \quad (6.4)$$

In Moore's calculations the three first elements were taken from the English Housing Survey (EHS) whereas the MIS was taken from Bradshaw et al. [30]. This MIS covers all needs, other than council taxes, rent/mortgage payments and fuel.

Unfortunately, in Spain there is neither a similar study to Bradshaw's that calculates a MIS in different regions by a participatory process, nor a similar survey to EHS, which includes not only data of actual energy expenditure but also theoretical energy needs depending on the characteristics of the household. In Spain, neither the Household Budget Survey (EPF), nor the Survey on Living Conditions (ECV) collect information about the physical characteristics of houses. For this reason, a different strategy was chosen to estimate a MIS-based indicator for Spain. Since in some Spanish regions a minimum income allowance is available (RMI), the MIS was assimilated to the average RMIs in the territory, weighted by population. From these data a MIS of € 415.2 for the whole country was obtained. It should be noted that, by proposing this MIS, it is being assumed that this amount is enough to cover all the household needs, something that, as will be seen later, is not necessarily true.

Subsequently, given that the RMI is received only by the household main breadwinner, a person-based MIS was transformed into a household-based MIS by using the equivalence rules recommended by the OECD. Hence, the equivalent MIS-based energy poverty indicator for Spain was calculated using the following Eq. 6.5.

$$
\begin{aligned}
&[Actual\ Household\ expenditure\ on\ energy] > \\
&\qquad [Net\ household\ income] - [Housing\ costs] - \\
&\qquad - [MISeq. - Average\ energy\ expenditure - Average\ housing\ costs] \qquad (6.5)
\end{aligned}
$$

where the average energy expenditure and the average housing costs in Spain in 2015 were € 1,045 and € 2,584 respectively, as taken from the EPF.

6.3.2 Results

Table 6.2 includes the three energy poverty indicators calculated for Spain in 2015.

Table 6.2 Energy Poverty Indicators. Spain. 2015

Indicator	**2015**
10%	14.96%
Minimum Income Standard (MIS)	8.70%
Low income/ High cost (LIHC)	8.10%

It is worth noticing the divergence between these indicators, which makes it difficult to obtain a clear picture of the actual situation of energy poverty in Spanish households.

According to the 10% indicator, 14.96% of Spanish households would be energy poor, whereas just 8.10% of Spanish households are considered energy poor according to the LIHC indicator and 8.70% according to the MIS based indicator.

To try to shed some light on this issue, a comparative study looking for the intersections between them was carried out (see Fig. 6.1). As can be seen, 67% and 59% of households considered energy poor according to 10% are not so according to the MIS-based and LIHC indicator respectively. Besides, 58% of the households that the LIHC classifies as energy poor are not considered as such according to the MIS based indicator.

Two main findings may be highlighted from this exercise. First, 3% of Spanish households are energy poor regardless the indicator chosen. This would set the indisputable minimum of energy poor households in Spain in 2015. Second, the three indicators are clearly identifying different households, i.e. they do not measure the same problem.

The 10% indicator, which does not account for income levels, is probably measuring an excessive energy expenditure rather than energy poverty. This fact is clearly highlighted when we disaggregate the indicators by household income deciles. Table 6.3 summarizes the percentage of energy poor households (according to each indicator) that belong to each income decile.

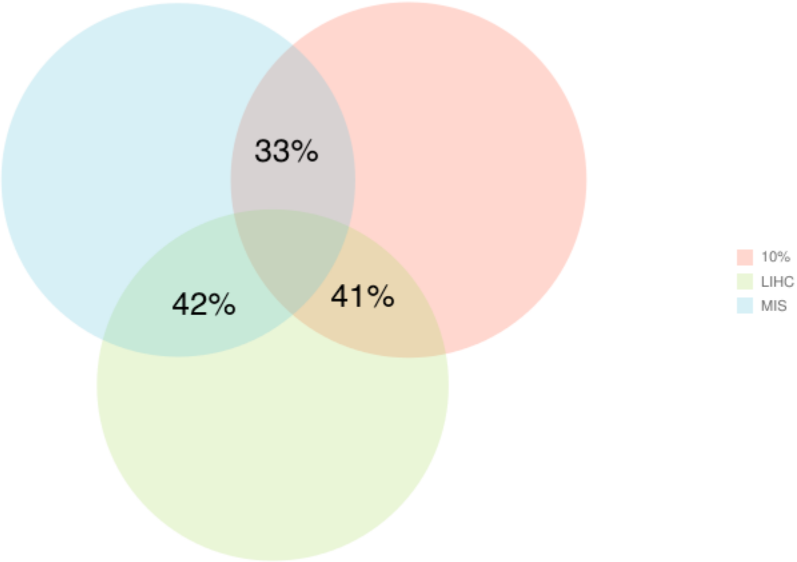

Fig. 6.1 Indicators Overlap

Table 6.3 Energy-poor households per income decile

Decile	**10%**	**LIHC**	**MIS**
1st	37.06%	41.59%	74.73%
2nd	18.34%	51.71%	20.41%
3rd	13.33%	6.39%	2.89%
4th	10.96%	0.29%	1.06%
5th	7.80%	0.02%	0.43%
6th	4.39%	0%	0.25%
7th	4.27%	0%	0.10%
8th	1.93%	0%	0.02%
9th	1.31%	0%	0.12%
10th	0.62%	0%	0%

This analysis shows very clearly the weakness of the 10% indicator. By not accounting for income levels, it identifies as energy poor households in all income deciles, what is clearly inconsistent. It seems sensible to say that all households considered to be energy poor above the 4th or 5th decile of income are probably false positives, since their income is clearly sufficient to pay for reasonable energy expenses, even if they exceed 10%. The other two indicators, which do account for income levels, do not present this behavior, thus pointing out to the relevance of incorporating income levels to any reliable energy poverty indicator[5].

However, that does not mean, as mentioned earlier, that the three indicators are measuring the same issue. By definition, 10% will still measure high energy expenditures, but not energy poverty. And as such, it will always feature a large degree of false positives. The LIHC does eliminate many of these, but its evolution is more difficult to interpret because of its doubly-relative nature, which makes it more suitable to measure energy inequality than energy poverty. Eventually, and in spite of its limitations, the MIS-based indicator seems to be the best available alternative for measuring energy poverty. In addition, it is the only one that provides an absolute measure of poverty, what is clearly another advantage. Nevertheless, it is not without criticism either.

As anticipated in the previous section, the main difficulty faced by MIS-based energy poverty indicators is how to determine the minimum income standard. A change in this value would mean a significant change in the indicators obtained. In order to analyze to what extent this factor influences the indicator, a sensitivity analysis was carried out.

As can be seen in Figure 6.2, the dependence on the MIS of the MIS-based indicator is very strong. For example, if instead of choosing the MIS from the average RMIs in the regions weighted by population, the MIS proposed by Caritas were chosen, (85% of the inter-professional minimum wage, that is, €550), the MIS-based indicator would have reached 15%, i.e. 72% higher than the original one.

This strong relationship led us to develop a more in-depth analysis to illustrate the possible deficiencies of the indicator and, at the same time, to propose strategies that would help to mitigate them. Ultimately, the question is whether the strong assumption that the MIS chosen covers the essential minimum expenses of any household is true.

Firstly, an analysis of the influence of housing expenditures was done. Given that this is the main expenditure in aggregate terms for households, the first step was to disaggregate the energy poverty indicator into two groups according to the tenure status of the household. On

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[5] It should be noted that the range of 8-10% of energy poverty in Spain highlighted by the LIHC and the MIS indicators is well aligned with other subjective measurements like the inability to keep home adequately warm. This indicator is included in the EU-SILC statistics on income and living conditions, which affected 8.0% of Spanish households.

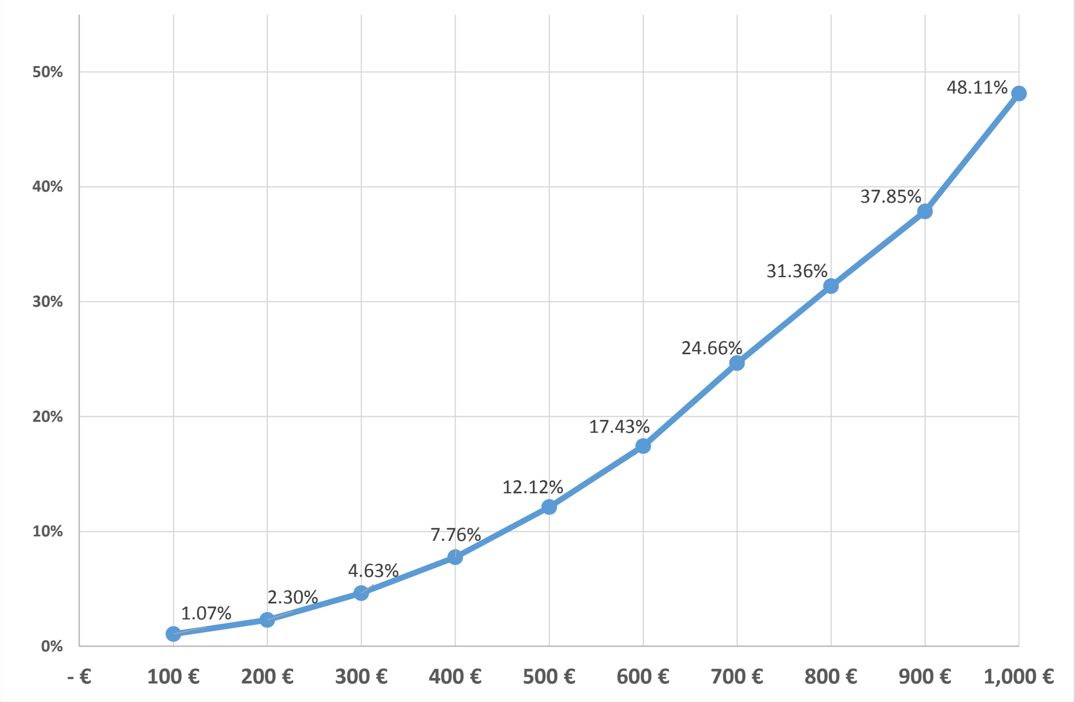

Fig. 6.2 Sensibility analysis to MIS

the one hand, the owners without mortgage and on the other hand those owners who were facing a mortgage and rented households. In this way it was sought to isolate the influence that housing expenditures were having on the calculation of the indicator.

The first group is characterized by having zero housing expenditures, € 1,075 average expenditure on energy and a 7.24% MIS-based energy poverty indicator. The average household expenditure of the second group is € 5,518, their average expenditure on energy is € 1,010 and their energy poverty indicator is 7.84%.

The results for the first group were coherent: their MIS-based energy poverty indicator is lower than the global indicator. Nevertheless, the results obtained for the second group were not. It did not seem coherent to us that the MIS-based energy poverty indicator of this group, whose expenditure on household is not zero, is lower than the MIS-based indicator of the complete set of households (7.84% versus 8.7%). The answer of this paradox was found analyzing the last component of Eq. 6.5.

After subtracting the average household expenditures from the MIS in order to eliminate the influence of this factor in the calculation of the energy poverty indicator, the MIS equivalent obtained became zero or even negative for some households, specifically those constituted by only one person. This fact made them to be considered not energy poor when some of them actually could be. In other words, a problem of false negatives associated to the MIS-based indicator was found, and the reason for that is the MIS selected, which did not cover the total needs of the household in some cases.

In order to detect those false negatives, a particular analysis of households constituted by only one member was developed. Eq. 6.5 was applied to this group and 52,000 households were revealed to be energy poor, i.e. 0.29% of total households in Spain. Thus a corrected MIS-based energy poverty figure for Spain in 2015 would be 8.99%.

The conclusion of this analysis is that, if a MIS-based indicator is to be used to measure energy poverty, this MIS has to be calculated in a manner in which its ability to cover the total needs of the household is absolutely guaranteed.

This would require defining a set of basic standard needs according to certain geographical and social characteristics of the household. For instance, regarding the basic energy needs, that component of the objective MIS would be calculated as the cost of the minimum energy needs of the household attending to the climate condition of its geographical area, to its energy efficiency and to the average cost of energy in the area. Similarly, the other components of the MIS (namely, food, clothes, shoes, health, education, etc) should be calculated attending to the typology of the household. It should be noted that one of this components is the housing expenditures, the most controversial and problematic component, as shown above, that will have to be managed carefully.

According to this methodology, there would be *indications* of energy poverty in a household when:

$$[Net\ household\ income] - [Actual\ Household\ expenditure\ on\ energy] < [non\ energy\ MIS]_{Type\ T} \tag{6.6}$$

where the $[non\ energy\ MIS]_{Type\ T}$ stands for the MIS of a household classified as type 'T' excluding its energy needs. In order to further analyze those indications of energy poverty the following two issues are to be checked:

1. If the income of the household is higher than the equivalent MIS of type 'T' households. If that is the case, the household can be considered specifically energy poor. Otherwise, that household is income poor, being energy only one of the factors contributing to this situation.

2. For those energy poor households, it should be verified if their energy expenditures are higher than the energy component of the MIS of the type 'T' household to which they belong. If so, the nature of the energy poverty of those households would be related

to their energy bills, which is too high because of the inefficiency of the household or because of sumptuous expenditures. Otherwise, the nature of their energy poverty would be related to structural high costs of energy in the area.

Of course, this methodology based on the calculation of an absolute MIS requires a complex previous process in which the different components of the MIS for the different typologies of households are properly designed and calculated. In addition, this methodology requires a data source that compiles household income and the actual and theoretical energy expenditures. Both the EHS (in the UK) and Phoebus (in France) surveys already do so. Unfortunately, although the Spanish Institute for Energy Diversification and Saving (IDAE) provides statistics about theoretical energy expenditures in households, since neither the EPF nor the ECV in Spain currently collect this information, both sources cannot be related.

However, all this discussion about the right aggregate indicator is not enough to design energy poverty policies, since they do not allow us to identify vulnerable households, nor those elements that characterize them. Identifying vulnerable consumers also will help us to assess whether the indicator is correct or not, and its implications for policy-making. It will also provide additional insights to better understand how to integrate equity concerns in the energy sustainability framework of the thesis.

6.3.3 Vulnerable households in Spain

Once the global energy poverty indicator has been calculated, the second step in the way to define effective policies that are able to cope with this issue is to identify the characteristics of those households more vulnerable to energy poverty. This way, specific policies targeting specifc criteria can be implemented.

The methodology proposed in this study is an econometric analysis based on Legendre's proposal [147][6]. A logit model was estimated in which the dependent variable is equal to one if the household is energy poor according to the MIS indicator and equal to zero otherwise. The logit model presents the advantage of highlighting the direct relation between the estimated coefficients and the probability ratios [43], so that by calculating the exponential coefficients we can determine the effect of each variable attending to the probability ratio, that is, the quotient between the probability that the household is energy poor and the opposite. Thus, if the ratio is greater than one, it means a greater probability of energy poverty and viceversa.

Attending to the results in Table 6.4, the configuration of the household significantly increases the likelihood of a household to be energy poor, although it is always linked to the income, so that families with children and especially those with low-incomes, are more likely to be energy poor than households headed by a single person, a couple without children or large families with high incomes. Besides, the greater the number of children in the home, the greatest the likelihood that the household is energy poor; whereas the number of members over 65 years influences negatively reducing the likelihood of households to be energy poor.

All the above suggests that any measure taken to reduce energy poverty will have to take into account not only the income but also the configuration of the household.

The tenure status of the housing has also a big influence on the probability of a household to be energy poor. Households with home ownership without a mortgage show a lower probability to be energy poor than households settled in rented flats or those with a mortgage. In fact, the former doubles the probability of being energy poor of the latter. One possible explanation for this phenomenon is that living on a lease is an indication of lower income. Nevertheless, given the limitation of the MIS-based indicator highlighted above, i.e. the strong influence of the mortage and the rent in the MIS, we should be cautious with these reults.

A third element worth analyzing is the occupation of the main breadwinner of the household. There is a greater probability of the household being energy poor if the main breadwinner is unemployed, has an elementary occupation or is and administrative or service worker (though it is not the most important factor in relative terms). In addition, the educational level of the main breadwinner has an influence as well, so that a household whose main breadwinner has only primary studies or no education at all is more likely to be energy poor.

It is striking the little significance of the energy consumption indicator (contrary e.g. to the indicators used in the Spanish social tariff); what tell us that simple measures such as those that try to identify vulnerable consumers based only on their level of consumption do not make much sense. Instead, the age of the dwelling does indicate a greater vulnerability, but its effect is not very relevant.

In summary, low-income households (and low energy consumption), with children and with labor instability of their breadwinners, are the most vulnerable to energy poverty.

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[6] Although this entire chapter is based on the paper developed by the author et al. mentioned at the beginning, specifically this study was mainly carried out by Dr. Xiral López.

Table 6.4 Vulnerability to Energy Poverty. Spain. 2015

	Coefficients	**Probability ratios**
Type of household		
Single	0.2325*	1.2618*
large family High income	-1.553	0.2116
Large family Low income	2.3852***	10.8608***
Normal family	1.0008***	2.7205***
Tenure status of households		
Mortage	-0.898***	0.4074***
Without mortage	0.9636***	2.621***
Rent	1.2661***	3.5468***
Type of house		
Detached house	-0.2885	0.7494
Terraced house	-0.496	0.6090
Condo less than10 apartments	-0.6464	0.5239
Condo more than 10 apartments	-0.7003	0.4965
Age of the property		
Older than 25 yrs	0.2254**	1.2529***
Heating		
None	-0.3282	0.7202
Electricity	-0.7226	0.4855
Natural gas	-0.8685	0.4196
GLP	-0.8465	0.4289
Liquified fuel	0.748	0.4733
Solid fuel	-0.6065	0.5452
Type of employment of the main breadwinner		
Manager	-0.100	0.9048
Professional	-0.3714*	0.6898*
Administrative employee	0.3390*	1.4036*
Craftman	0.1811	1.1985
Elementary jobs	0.8996***	2.4586***
Employment of the main breadwinner		
Employed	-1.9742***	0.1389***
Leave	-1.8607***	0.1556***
Unemployed	0.7416***	2.0992***
Retired	-1.4700***	0.2299***
Student	0.5341	1.7059
Household tasks	-0.7227**	0.4854**
Permanent disability	-0.8991***	0.4069***
Education level of the main breadwinner		
Primary	0.8554***	2.3523***
Secondary	0.4566***	1.5787***
Area of residence		
Urban	0.2043**	1.2267**
Members of the family under 14 yrs	0.1642***	1.1785***
Members of the family over 65 yrs	-0.7623***	0.4666***
Dummy low energy consumption	0.1717**	1.1873**

$R^2 = 0.3634$ Wald $c^2(53) = 4612.90(p - valor = 0.0000)$

Note: Asterisks indicate the level of significance of the parameters, so that
*** indicates significance at 1%, ** at 5% and * at 10%

Therefore, policies designed to deal with energy poverty issues should be primarily focused on them.

Eventually, a sensitivity analysis of the previous results was developed by restricting the consideration of households in a situation of energy poverty to those that, in addition to being considered energy poor according to the MIS, have an equivalent level of income below the median. Therefore, possible false positives were excluded and the consistency of the previous results could be highlighted. The results of this new estimation, which are included in Appendix D, are similar to the previous ones and also, they have the same significant variables and with the same sign, which demonstrates robustness.

6.4 Conclusion and Policy Implications

The results of the empirical analysis highlight that the most common objective income-based energy poverty indicators used so far, i.e. the 10% threshold, includes a high number of false positives. This fact, together with the relative nature of the LIHC indicator that makes it more suitable for energy inequality than for energy poverty analyses, make me recommend the use of a MIS-based energy poverty indicator, calculated on an objective and absolute basis.

Moreover, since as mentioned above, indicators only provide aggregate figures which do not allow us to clearly identify households at risk in order to propose adequate policies, the profile of those households most vulnerable to energy poverty in Spain were identified as well, i.e. those households that would need to benefit from some kind of support. These are households with low incomes, with children and with labor instability of their breadwinners. Interestingly, the only policy against energy poverty in Spain until 2017 (the social tariff or social check) does not identify these households as vulnerable.

In light of the results, the following policy recommendations are proposed:

1. To select a sound and robust global energy poverty indicator together with the right methodology for its calculation.

   After the analysis presented in Section 6.2, a suitable objective and income-expenditure based energy poverty indicator would be one that (1) takes into account both incomes and expenditures of the household (thus avoiding a big number of false positives) and (2) can be calculated using an absolute strategy so that it measures actual energy poverty instead of energy inequality.

   Thus a MIS-based energy poverty indicator is probably the most suitable alternative. Nevertheless, a new approach able to overcome the current flaws is still needed. A possible alternative has been presented in section 6.3.2.

2. To provide a definition of the vulnerable consumer which is aligned with the profile discovered.

   Providing this definition is also mandatory according to the European Commission Directives 2009/72 and 2009/73 on the Electricity Market and the Gas Market, in which member states are urged to establish a clear definition of the "vulnerable consumer" as a preliminary step in drafting legislation to protect them.

   Energy poverty and the concept of vulnerable consumers have only recently been recognized explicitly in European legislation. The so-called Clean Energy Package [79] sets out a new approach to protect vulnerable consumers, including provisions such as (1) the requirement that a proportion of energy efficiency measures be applied primarily to households living in energy poverty, (2) the obligation on Member States to monitor and report on the situation of energy poverty or (3) the creation of an energy poverty observatory to obtain better data on the problem and its solutions and to assist Member States in combating it. In addition, the proposal for the revision of the directive on the internal market for electricity [80] makes a distinction between vulnerable consumers and energy poverty, requiring Member States to define both concepts. The results of the vulnerabilty analysis of this report can help to establish that vulnerable consumer profile. As shown in Table 6.4, low-income households with children, in lease and with an unstable employment situation are clearly those that are most vulnerable to situations of energy poverty.

3. To design an appropriate support system. A support system aligned with the results of the previous analysis could be a social tariff[7] that (1) covered the costs of all energy sources [27], not just electricity and (2) were available to vulnerable consumers and only them: i.e. low-income families with children under their care, and with unstable employment status.

Eventually, other measures that could be implemented are those energy efficiency measures which have, in theory, great potential to alleviate energy poverty by reducing the energy expenditure required to achieve basic energy services. However, as in the case of the social tariff, for these measures to actually have the right effects, the target should be only the vulnerable households. In all cases, as with any other policy measures, they should be based in strong evidence.

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[7] At the moment in which this thesis is being concluded, the debate in Spain on the new social tariff is very lively. Coverage has been extended to the thermal demand (natural gas) and an income criterion has been included when it comes to identifying vulnerable households, in line with the proposals outlined here.

This analysis of energy poverty, including the main indicators used to measure it and its calculation for Spain, has provided useful information to better understand this issue of equity linked to energy.

The first conclusion is perhaps the need for a multi-faceted approach to the issue. In the same way that was commented on in the state of the art of indicators in Chapter 3, trying to condense a complex problem into a single figure is often misleading to say the least.

However, that being said, of all the methodologies for measuring objective energy poverty indicators based on income and expenditure, the MIS-based one has revealed as the most robust, as long as the MIS is correctly obtained.

From all of the above, it is concluded that in order to address the issue of energy equity into the integrated framework for the study of energy sustainability presented in this thesis, a first step might be dividing the population under study into two groups, namely, vulnerable and non-vulnerable, and to meet their energy demand in a particularized manner. The way to identify the vulnerable group will vary according to the scale of the case study. If we are in a local environment, this can be done following a bottom-up methodology that verifies the vulnerable condition of the households taking into account the profile obtained in the econometric analysis (see Section 6.3.3). If, on the other hand, the scope of the case study is a country, the most appropriate methodology would be a top-down approach in which the population is divided according to an aggregate energy poverty indicator. In that case using a MIS-based approach is suggested.

Given that the case study to be analyzed in the next chapter is included in this second group, it will be possible to observe in more detail how this analysis would look like in a real implementation.

Chapter 7

Case study. Energy transition in Spain towards 2030 and 2050

This chapter[1] develops the case study already anticipated in previous sections. It consists of applying the sustainability analysis framework to the planning of the energy transition in Spain towards 2030 and 2050.

The MASTER.MC, a computer model based on the MASTER.SO [162] model, was developed for this purpose.

As a result of this practical exercise, different energy system scenarios were obtained for Spain in 2030 and 2050, as well as different sensitivities that help to calibrate their robustness.

7.1 Introduction

The energy transition is generally linked mainly to the decarbonization of the energy sector. Nevertheless, other elements must also be considered to achieve a truly sustainable energy roadmap. And, sometimes, these may be conflicting goals.

As has been emphasized throughout the thesis, an analysis of the role that energy is playing in the global challenge of SD requires that all aspects involved be included. From an environmental point of view alone, the challenge goes far beyond the CO_2 emissions. Local pollutants, namely NO_x, $PM_{2.5}$ and $SO_{2.5}$, are a serious public health problem, and their emissions are almost entirely linked to energy uses, especially in transport. Also, economic

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[1] This chapter is based on a working paper entitled “Illustrating the conflicts in the Spanish sustainable energy roadmap towards 2050”, in development by the author and Dr. Pedro Linares.

and social capitals together with equity concerns must also be taken into account. All these elements, and certainly some others, will have to be integrated within the framework of the energy system analysis if we want to effectively study the contribution of the sector to the global SD goal.

The sustainability framework chosen for this exercise is based on the integrated weak-strong paradigm described in Chapter 5[2], where the four capitals to be sustained over time, namely economic, social, human and natural, represented by several indicators, are complemented by the equity aspect, that has to do with ensuring that an affordable energy service is provided to the entire population[3].

All of this is subject to critical limits in those criteria where the precautionary principle persuades us to remain within the safety zone [157]. Again, as discussed above, these critical limits will have to be defined according to the specific application of the model. If we were focusing on a planetary scale, they would formalize Rockstrom's planetary boundaries [233] along with other economic and social limits that the international community had determined. In the present case, the environmental limits have been limited to local pollutant emissions and energy dependence. That been said, although the limits must be adapted to the specific case study, they must be at the same time aligned with the critical limits on a planetary scale. This scale perspective is of central importance for the achievement of global SD.

These critical limits ultimately act as strong constraints to the problem. Within the debate on the possibility or not of capital substitution that gave rise to the distinction between SS and WS, these limits represent the first one. There is no possible substitution for them. They advocate for critical capital that under no circumstances can be put at risk.

By including these critical capitals, the proposed framework completes this aim to integrate the two approaches to sustainability into a single conceptual map. In this case it does so by providing a workspace for each of them, without looking for a synthesis that is probably impossible, but from a dialogical approach (see Section 3.1.2) where both WS and SS (thesis and antithesis) are not subsumed in a unified theory (synthesis), but remain active in a permanent creative tension.

Thus, the framework proposed is summarized in the following formulation:

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[2] Part of that description is reproduced here again for clarity purposes.

[3] An energy poverty indicator is used to measure it (see Chapter 6).

$$\min L_p = \Big[\sum_{j=1}^{m}\sum_{i=1}^{n}[w_{ij}\frac{k_{ij}-k_{ij}^{*}}{k_{ij*}-k_{ij}^{*}}]^p\Big]^{1/p}$$

$$s.t.$$

$$k_{ij} \leq CL_{ij}, \forall i, j \tag{7.1}$$

where L_p represents the distance to be minimized using MCDM compromise programming techniques, w_{ij} the weights to be applied to each criteria, k_{ij} stands for each type of capital (i), namely, economic, natural, social and human at any disaggregation level (j), k_{ij}^{*} and k_{ij*} represent the ideal and anti-ideal (nadir) values for each capital, respectively, and CL_{ij} stands for critical limits.

A framework is therefore being proposed that defines sustainability in the form of an operational optimization problem where the objective to be optimized deals with capitals represented by several criteria, subject to a set of critical limits that can be applied not only to natural capital, but to any type of capital; and with an additional disaggregation that seeks to reflect equity concerns. This framework is totally compatible with that capital-based approach to sustainability on which this thesis is based, that defines being sustainable as being able to create value while not exceeding the resilient limits of the eco-social environment.

Once the framework has been presented, an application to the case study of the transition of the Spanish energy system towards 2030 and 2050 is developed next. To this end, a multi-criteria model has been developed, following some of the techniques introduced in the Section 3.1.1. This model will allow, among other things, to illustrate the conflict between decarbonization and other energy transition objectives for the Spanish energy roadmap towards 2030 and 2050. The model includes not only generation technologies, but also energy service technologies, hence allowing for a large participation of energy efficiency.

Some other multi-criteria based proposals can be found in the literature, in fact this proposal continues the path already begun by one of them, i.e. Volkart's [316], by providing a full integration of multi-criteria decision making and partial equilibrium energy system modelling.

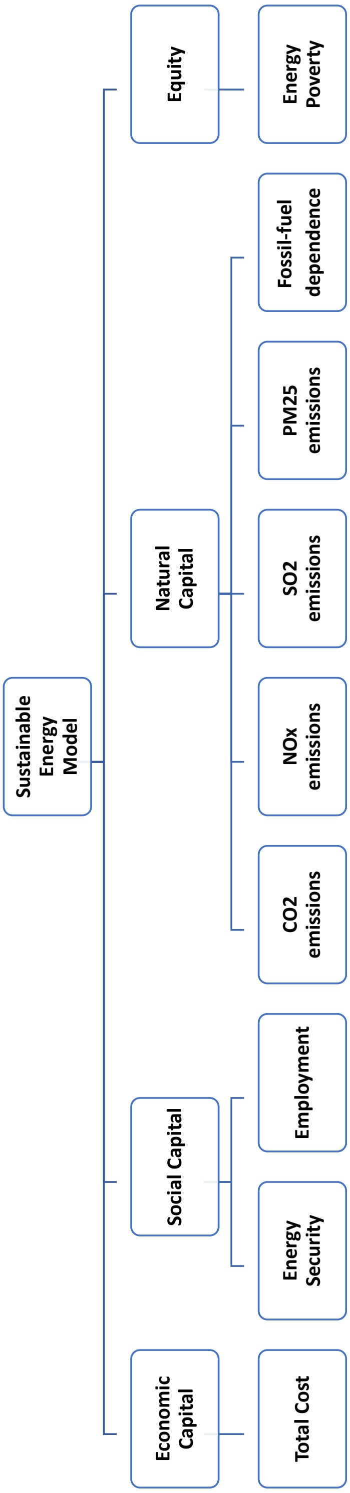

Fig. 7.1 Multi-criteria tree

In the application of this framework to the study of the Spanish energy system in 2030 and 2050, indicators representing the different capitals involved together with equity were chosen. Additionally, a survey involving different stakeholders was carried out in order to define the aggregated social weight of each indicator in the multi-criteria analysis (see Fig.7.1). This way, social preferences have also been incorporated into the analysis.

The figure shows that equity has been incorporated into the level of capital as one of them. This has been done in order to emphasize that in this particular case equity will have its own indicator (energy poverty). It is an indicator that comes from the breakdown of economic capital into two: vulnerable and non-vulnerable households, and seeks to optimize the latter in a particularized way, in coherence with what was proposed in the general framework of Eq. 7.1. However, it should not be forgotten that in a complete development of the framework, equity should be considered in each capital.

I conclude this introduction by highlighting the most novel aspects of this proposal (beyond the computational tool itself): (1) the above mentioned inclusion within the criteria to be considered of the issue of energy poverty representing equity concerns in the energy sector; and the (2) integration of the strong and weak combined perspective within an operational framework for sustainability analyses.

Thus, the chapter is structured as follows: after this introduction, the next section is devoted to presenting the methodology (Section 7.2). Next, Section 7.3 describes the results, which is structured to present those for 2030, 2050 and some sensitivities. The chapter concludes presenting the main conclusions (Section 7.4).

7.2 Methods and data

This section is divided into two parts. The first will deal with the definition of the problem, that is, the specification of the framework, and the second will focus on the technical proposal, which includes the description of the model developed as well as the multi-criteria techniques used.

7.2.1 Problem definition

The aim here is to justify the different criteria chosen, as well as the critical limits and scenarios. Finally, the decisions taken with regard to the obtention of the preferences of the decision-makers are explained.

7.2.1.1 Criteria selection

Fig.7.1 shows the multi-criteria criteria tree designed for this analysis. Inspired by an AHP methodology (see Section 3.1.1), three levels have been established: the upper one corresponds to the ultimate objective to be achieved, namely, a sustainable energy system; the middle one corresponds to the different capitals involved in the task together with equity; finally, the lower one includes the different indicators identified as proper representatives of the different capitals.

Thus, it can be observed that in the third level of indicators, one has been chosen for economic capital, i.e. the total cost of the system; two for social and human capital, i.e. energy security and employment; five for natural capital, i.e. emissions of CO_2, $PM_{2.5}$, SO_2, NO_x and fossil-fuel dependence; and finally, one indicator of energy poverty has been chosen to represent equity concerns.

The choice of these indicators has been a process in itself. Since this analysis was meant to be based on the capital-based definition of sustainability, the objective was to identify indicators that could represent each of these capitals.

Of all the literature on energy sustainability indicators, Vera et al.'s work was the main guide for this study [314, 313].

They proposed a set of energy indicators representing a consensus reached on this subject by five international agencies, namely, the Department of Economic and Social Affairs, the International Atomic Energy Agency, Eurostat, the European Environment Agency and the International Energy Agency. They identified 30 energy indicators for SD which were classified into the three classic dimensions of SD, that is, social, economic and environmental.

In the case of economic capital, the choice was immediate: the total cost of the system was the indicator par excellence and to some extent included a large part of the indicators proposed by Vera et al. In the case of natural capital, the emissions of CO_2 came naturally, but I also decided to incorporate the rest of the atmospheric pollutants, as Vera et al.'s also did, persuaded by their importance in terms of its impact in human health. In addition, and in order to incorporate a more clearly SS indicator, I decided to include the fossil-fuel dependence indicator as a proxy for those exergetic indicators of carrying capacity described in the Section 3.2.4.3.

With regard to the indicators of social and human capital, although I am aware of the impossibility of condensing into a couple of values all the variety inherent in the concept, I decided to incorporate two indicators, namely, energy security and employment[4]. Finally, with regard to equity, the choice was clearer. By focusing the case study on a developed country like Spain, the goal of affordable and accesible energy for all (both indicators are included in Vera et al.'s proposal) was well represented by the energy poverty concept. Therefore, an energy poverty indicator was to be included. In order to get a better understanding of this issue, a full description of the problem of energy poverty in Spain was presented in the Chapter 6.

Clearly, the choice of these indicators is subject to debate. It is important to emphasize that this is merely an illustrative exercise of application of the sustainability analysis framework. Further research should either help to consolidate or rule out some or all of these criteria. In the latter case, additional variables could be suggested and incorporated into the analysis.

In addition to this substantive criticism of the criteria used, it would seem highly advisable to extend the consultation exercise with experts (which at present includes only consultation on their preferences among the proposed weights) to the very choice of these criteria in the future. This will make it possible to transform this analysis exercise into an assessment in the sense proposed by Giampietro et al. [99]. In fact, a first phase of this process has already been carried out internally. The author presented a first version of the criteria tree to his colleagues at the research institute. As a result of the subsequent discussion, the criterion of jobs that had not been considered from the beginning was actually included.

Additionally, given the complexity of the problem we are facing, this process must necessarily be open, that is to say, it must be in a permanent revision state.

7.2.1.2 Critical limits

Once the different criteria have been integrated within the multi-criteria optimization strategy, critical limits representing those absolute limits that cannot be exceeded in any circumstance are to be included as well.

As noted above, these limits will have to be determined on a case-by-case basis to which the study framework applies. In this case, and as an illustration, I have limited to incorporating critical limits only to environmental criteria, and not to all, but only to emissions of CO_2 and atmospheric pollutants. These are the most consolidated data, which is why they have been incorporated.

For CO_2, the adjusted roadmaps proposed by the European Union in 2030 (30% reduction compared to 2015) and 2050 (95% reduction compared to 2015) were the values used. Table 7.1 includes these data.

An interesting future investigation would be to define the remaining limits using tentative values and analyze their impact on the results of the optimization. For example, a very direct

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[4] The former was included in the Vera et al. indicators, while the latter is an original contribution.

Table 7.1 Critical limits

Year	CO_2 **[Mton]**	SO_2 **[kton]**	NO_x **[Mton]**	$PM_{2.5}$ **[kton]**
2030	230	421.41	0.87733	130.05
2050	12.84	153.24	0.56506	76.5

one to investigate would be that of fossil-fuel dependence, whose calculation can be obtained from an eMergetic analysis of the Spanish energy system. This calculation of eMergetic dependence in Spain will shed light on the national impact of energy activity in terms of natural capital. Along these lines, it would also be desirable to extend the calculation of this eMergetic dependence to the global level, since it is on this scale where one of the great environmental challenges is at stake, such as the limitation of global warming.

7.2.1.3 Scenarios description

The present work has focused on two specific years: 2030 and 2050. For each one, various simulations have been carried out to analyze possible future alternatives for the Spanish energy transition.

The choice of these two years and not others is due to the fact that there are two roadmaps at European level for 2030 and 2050 with which the national energy transition agenda will have to be compatible. In addition, at the international level, 2050 is a key year on the decarbonization agenda. The scenarios used by the IEA and the IPCC mark the middle of the century as the key moment to have achieved a very significant reduction in emissions if we want to remain below the limit of 1.5 degrees increase in the mean temperature by the end of the 21st century.

Table E.1 in Appendix D collects the most relevant input data for these scenarios.

7.2.1.4 Preferences of the stakeholders

As discussed in the state-of-the-art section devoted to multi-criteria techniques (see Section 3.1.1), obtaining the preferences of decision-makers is a key step in some of these proposals. The case of compromise programming, the concrete technique on which this case study is built, is one of them. The preferences of the decision-makers will make it possible to obtain the relative weights assigned to each criterion.

Following [155], a survey involving the nine objectives considered in this research was conducted and presented to a group of four regulators; four academics; four environmentalists and four representative of private companies of the energy sector, for a pairwise comparison. It is important to clarify again that this is an illustrative exercise. A real survey should include a larger group of decision-makers.

Thus, an AHP method (see Section 3.1.1) was developed in order to obtain the preferences. Based on these preferences, and following a goal programming methodology [156], the preferential weights of the decision-makers for each of the criteria were obtained, as well as the inconsistency of their value judgments.

A description on how this different methodologies were applied to the case study is presented in the description section below.

7.2.2 Technical tools

This section explains the specific tools used during the development of the case study. The main one is a multi-criteria computational model of partial equilibrium on the energy sector. Its input data have been collected for the Spanish case, but it could be applied in principle to any other national energy system.

Additionally, some multi-criteria techniques were used to obtain the aggregated preferences of the stakeholders that are also introduced below.

7.2.2.1 MASTER.MC model

MASTER.SO is a bottom-up partial equilibrium static model of energy systems that was conceived for sustainable energy policy analysis. It is a linear programming model that satisfies demands for energy services while minimizing the total costs of energy supply (investment costs, operating costs, imports costs, etc) as well as externalities (CO_2 emissions). While supplying demand, the model respects the main technical constraints of energy systems, such as energy balances, capacity limitations, and technical reliability conditions, among others [162].

For this research, a evolution of this MASTER.SO model called MASTER.MC has been developed. It uses the basis of the previous model and transforms it into a multi-objective compromise programming model based on Linares' multi-criteria model for the electricity sector in Spain [154].

The equations of the model as well as its indices, parameters and variables are listed in the Annex E.3.

Both MASTER.SO and MASTER.MC are optimization models that represent the energy system of a country as a whole and that seek to cover a given demand in an optimal way, taking into account the different additional constraints that are considered.

In addition to the demand, both models use a large amount of data that characterize the energy system. The most relevant are included in Annex D.

Compromise programming is a technique for reducing the set of efficient solutions consisting of selecting the area of the efficient set that is closest to the ideal point (the one where all the attributes reach their optimum value), while taking into account the preferences of the decision-makers. Thus this technique seeks to minimize the distance (using an specific metric) to that ideal point. This theory was initially developed by Yu and Zeleny in 1973. A detailed description of the methodology can be found in the Section 3.1.1.

The MASTER.MC model developed for this research uses this technique to switch the MASTER.SO linear optimization model based on the minimization of a single criterion, i.e. the total cost of the national energy system in a year, for a multi-criteria optimization model involving the criteria included in Fig. 7.1.

$$\begin{aligned} \min(\lambda L_1 + (1-\lambda)L_\infty) \\ s.t. \\ f(x) \in F \\ \left| w_i \frac{\left| f_i^* - f_i^* \right|}{\left| f_{i*} - f_i^* \right|} \right| \leq D, \forall j \end{aligned} \tag{7.2}$$

The optimization problem described in Eq. 7.2 was modelled and solved in various model runs in which either the distance L_1 ($\lambda = 1$), or the distance L_∞ ($\lambda = 0$), or the distance corresponding to a value of $\lambda = 0.5$, was optimized, both in 2030 and 2050. The first represents a solution of maximum efficiency while the second represents one of maximum equity [156].

7.2.2.2 Criteria implementation

A brief description of how the different criteria have been included into MASTER.MC is presented below.

7.2.2.2.1 Total cost (COST)

This is the only optimization criterion that the original MASTER.SO incorporated.

As mentioned above, this is the classic criterion used in many optimization models applied to the sector [162].

These costs include (1) the costs of domestic primary energy production (including investment, operation and maintenance); (2) the net balance between the costs of importing and the revenues of exporting energy; (3) the costs of energy conversion, mainly electricity, refining and regasification; (4) the costs of energy transport and (5) investment in energy equipment in the final transport, service and household sectors.

In addition to the above, additional factors specific to the electricity system were added, i.e. the cost of reserves and the cost of investing in new capacity.

For more information on this criterion, the reader is invited to refer to the documentation of the MASTER.SO model [162].

7.2.2.2.2 Energy poverty (PE)

Following the study of energy poverty presented in Chapter 6, the indicator based on the MIS was chosen as the benchmark for the incidence of energy poverty in Spain. According to this indicator, 8.7% of the total population in Spain in 2015 were energy poor. This 8.7% of households consumed 7% of the total household energy according to the EPF, so it was this 7% that was chosen to disaggregate the demand for household energy services between the vulnerable and the non-vulnerable. Of course, this assumption is a subject of discussion and will need to be updated in the light of new available data.

The energy poverty criterion consists of calculating the total cost for vulnerable households of their energy services in one year, to which the annual depreciation of the investment in equipment is added.

The way to integrate this criterion into the model is to divide the residential sector into two groups: on the one hand, non-vulnerable households and, on the other, vulnerable households. Thus, the initial formulation of the MASTER.SO model in terms of residential demand was split.

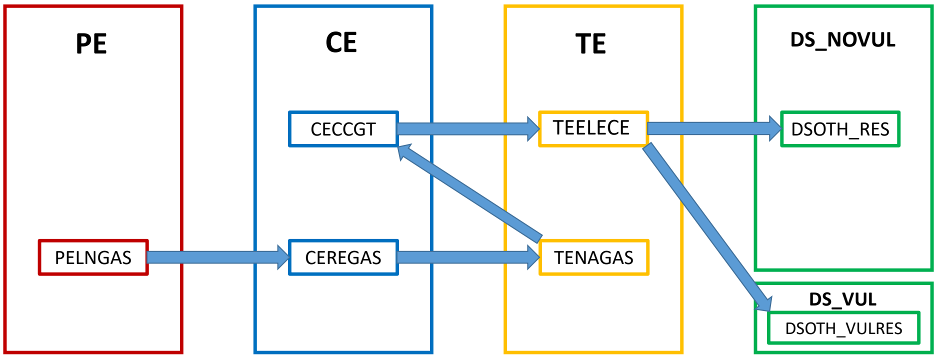

Fig. 7.2 MASTER.MC flow description

Fig. 7.2 describes how the MASTER.MC works. Similarly to MARKAL/TIMES proposals [164], each rectangle represents a column of the model, namely, primary sources (PE), conversion (CE), transport (TE) and demand services (DS)[5]. As an example, a specific flow has been added, that of the natural gas that enters in liquefied form to the system, is regasified, then redirected to a CCGT plant where electricity is generated and finally distributed to the differentiated final demand: non-vulnerable residential and vulnerable residential, respectively. Additionally, within the fourth column there is a fifth one that includes the different end-use technologies that allow to cover the different demands not in energy units but on energy services unit, like pkm (passenger-kilometer) or tkm (tonne-kilometer) for transport. They are called in the MASTER model jargon “Energy Service Supply Technologies” (ESSTs). This functionality is very useful because it allows the different technological options to be easily updated in the future.

Two elements are considered when calculating the total cost of energy supply for vulnerable households, namely, (1) the consumption of energy in vulnerable households and (2) the depreciation of the investment in equipment in these households.

7.2.2.2.3 CO2 emissions (CO2)

The CO_2 emissions criterion has been reformulated in MASTER.MC compared to MASTER.SO. In the original formulation, emissions of CO_2 were incorporated either into the objective function by adding an emission cost to the total cost of the system or in a constraint limiting the maximum amount of emissions allowed. On this occasion, emissions enter the model in two ways as well: one as an optimization criterion within the multicriterion framework of compromise programming described above, and the other as an absolute limit, similarly to the previous version, but representing this time a SS-based critical natural limit.

Emissions are calculated in every column of the model (see Fig. 7.2 and then added up to a single figure.

The model calculates all CO_2 emissions associated with energy consumption. Other GHG emissions, like methane leakages, can also be determined, but have not been included because of their low relevance.

7.2.2.2.4 Fossil-fuel dependence (DEP)

This criterion of fossil-fuel dependence tells us to what extent the Spanish energy system depends on non-native sources. Given that in the case of Spain, indigenous sources are

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[5] A detailed description of how these columns are modeled and how flows circulate between them can be found in [162].

essentially renewable, the dependency indicator is transformed in practice into a strong sustainability indicator that shows the non-renewable dependency of the Spanish energy system.

It is calculated by dividing imported energy by total primary energy.

An alternative to this criterion, to be explored in future research, would be to obtain an indicator of eMergetic dependence instead of fossil-fuel dependence. To do this, the ratio R/U would have to be obtained, where R represents the renewable eMergy flow and U the total eMergy embedded in the system. For more details on this point, the reader is invited to return to two sections of the thesis: the State of The Art of exergetic indicators, Section 3.2.4.3 and the partial application of the framework to the Costa del Sol, Section 4.3.

7.2.2.2.5 SO_2, NO_x and $PM_{2.5}$ emissions (SO2), (NOX), (PM25)

These three environmental indicators are also very important criteria at local, regional and national scale. Their impact at this scale is even greater than CO_2 emissions since they affect public health in the short and medium term.

For instance, close links between exposure to $PM_{2.5}$ and premature death from heart and lung disease have been found [223]: a long-term exposure to $PM_{2.5}$ may lead to plaque deposits in arteries, causing vascular inflammation and a hardening of the arteries which can eventually lead to heart attack and stroke.

The emissions of these particles are mainly linked to the burning of fossil fuels, especially in transport, but also come from the burning of other types of fuels considered clean, such as biofuels and biomass. This point is very important to bear in mind when designing sustainable transition strategies, since reducing CO_2 emissions is not always aligned with reducing the emission of other pollutants.

These emissions are calculated in the model in a similar way to those of CO_2, i.e. they are calculated for each block (see Fig. 7.2) and finally added together in a single value.

On this occasion, the calculation of emissions has been limited to the conversion (CE) and end-use (DS) columns.

7.2.2.2.6 Energy security (SEC)

While the inclusion of this criterion was clear from the beginning, it was not clear whether it should be included within the economic criteria (after all, it was ultimately counted as a cost) or within the social criteria. Finally, it was decided to include it in the second group. A more detailed critique of this dichotomy remains for future research.

Energy security has two components, namely (1) price and (2) quantity. Thus two aspects of the cost of energy (in)security are to be taken into account when assessing energy security from an economic point of view. The price aspect consist of measuring the vulnerability of the economy to movements in energy prices, changes that may be abrupt (price shock) or continuous over time (volatility). Quantity, on the other hand, consist of measuring the economic cost of an energy supply disruption by calculating the welfare loss resulting from a change in energy availability.

Taking as a reference the work of Peersman and Van Robays [217], where a comparison of the macroeconomic consequences of different types of oil shocks in a series of industrialized countries (including Spain) is made, in the present investigation an extra cost for crude oil of 4.3 €/MWh has been assigned. Additionally, this value served as a reference to scale up the rest of the prices of energy raw materials, including natural gas.

Thus, the energy security criterion is calculated as a monetary surcharge for the system. It is important to clarify that this extra cost is not added to the total cost of the system (the fact that it is expressed in the same monetary unit does not mean that it can be directly added up to) and therefore does not affect its optimisation. Their incorporation into the analysis is through the multi-criteria approach within the compromise programming described above.

In future research this reference value of 4.3 €/MWh for crude oil used to scale up the other imported primary sources including natural gas could be revised, so that other effects associated with energy security beyond the price shock, like volatility (from the perspective of price analysis), or loss of welfare resulting from a change in energy availability (quantity component), can be incorporated.

7.2.2.2.7 Total jobs (JOB)

This criterion is intended to incorporate another key social variable in the analysis: the contribution of the energy sector to the labour market. Of course, I acknowledge that including this criterion presents several problems:

First, it is already included in the cost of the energy produced. However, here we do not want to account for the economic aspect of labour, but for its social aspect, as something desirable because of the social inclusion, recognition and dignity it provides. Second, estimating the change in the number of jobs with a partial equilibrium model like the one presented in this thesis has several limitations. Although we can estimate the amount of direct jobs created, and even compare them among the different energy technologies, indirect or induced jobs are much more difficult to estimate correctly, since they will depend on the behavior of the economy. Indirect jobs are typically estimated with the help of input-output tables, but this requires assuming that the structure of the economy remains stable under different configurations of the energy system. Moreover, since different energy scenarios will imply different costs and hence income, this will be translated into different patterns of job creation or destruction across the economy, which cannot be traced without using a macroeconomic model that accounts for these changes. Finally, if public funds are involved, net job creation should always be calculated comparing against a counterfactual in which these public funds are used in an optimal way.

In spite of these limitations, it was opted to estimate direct and indirect jobs as a first approximation to this very relevant social aspect. For the former, I focused on the conversion sector, including both the costs of new construction and operation and maintenance. In this case, data from the Institute for Sustainable Futures in 2015 were used [245]. For the latter I focused in the services sector, specifically in technologies that cover energy demand for end use. In this case a new parameter was calculated in the model which acts as an employment factor associated with each ESSTs. These factors were calculated dividing the number of jobs by the NPV of the corresponding sector, according to INE statistics.

7.2.2.3 Methodology for obtaining preferences

As discussed above, the participatory process for obtaining decision-makers' preferences is a key step in many of the multi-criteria techniques. In the case of this application, two of these techniques have been used to obtain the weights assigned to the different criteria, namely, GP and AHP. Both techniques were introduced in Section 3.1.1.1.

Firstly, following AHP, decision-makers were asked to express the relative importance they give to each criterion by comparing them in pairs. This was done through ad-hoc online questionnaires in which decision-makers could express themselves in terms such as: criterion A is moderately more important than criterion B or criterion B is extremely more important than criterion C. The results obtained in these questionnaires are included in Annex D.

These expressions were then translated into numbers, using a scale designed by Saaty [156]. From these values, matrices were constructed in which the relationship between all the elements contained in the same hierarchical level was expressed.

Then the relative preferences of each hierarchical level (see Fig. 7.1) were obtained from this matrix by solving the system of equations:

$$W_i - a_{ij} W_j = 0, \forall i \neq j \tag{7.3}$$

where W_i and W_j are the relative weights of the criteria i and j that was to be determined, and a_{ij} is the term of the criteria comparison matrix for the corresponding hierarchical level.

This system of equations has the trivial solution ($W_i = 0$, for all i), unless the value judgments expressed in the comparison matrix are perfectly consistent, which happens in very few cases. Therefore, it is necessary to find the set of W_i weights that is closest to those expressed indirectly by the decision-makers.

To this end, a GP method was used [155].

Thus, an optimization problem arose as follows:

$$\begin{aligned} \min \sum_{k=1}^{n} (n_k + p_k) \\ s.t. \\ W_i - a_{ij} W_j + n_k - p_k = 0, \forall i \neq j \\ W_i \geq 0, \forall i \end{aligned} \tag{7.4}$$

In this problem, the aim is to minimize the deviations, so that the weights are as close as possible to the optimum solution. This deviation measures the level of inconsistency of the decision-maker for that hierarchical level and that group of criteria.

This inconsistency, while preventing the achievement of "ideal" weights, is not a defect in itself, but something inherent in human behaviour, as it reflects doubts, hesitations and contradictory feelings. Therefore, the set of weights that would be obtained if the inconsistency were removed cannot be said to be closer to the actual preferences [153].

However, a high inconsistency may lead to undetermined solution, so preferences expressed with a high inconsistency are not considered tolerable. To establish what this tolerance threshold is, the inconsistency is measured as a ratio to its maximum value.

In this case, in order to rule out those decision-makers whose inconsistency were too high, the maximum inconsistency was first calculated by solving the optimization problem described in Eq. 7.4 not as minimization, but as maximization.

Of all the hierarchical levels, I focused only on the criteria associated with natural capital, because that is where the possibility of inconsistency of decision-makers was found greatest, given that five criteria competed with each other. This hierarchical level is represented by a 5x5 matrix whose maximum deviation was found to be 4.

Finally, once the maximum possible deviation was calculated, those decision-makers whose inconsistency ratio exceeded 20% of that maximum were eliminated. Two regulators, one academic and two environmentalists were discarded.

Then, once the relative weights of the criteria at each hierarchical level were obtained, they should be aggregated up to the top level in order to obtain the absolute preferences of the criteria. This was done by multiplying the weights by the relative preference of the hierarchically superior level. For instance, the absolute preference for the reduction of CO_2

emissions was obtained by multiplying its relative preference within its hierarchical level of natural capital by the relative preference of natural capital over the other capitals and equity.

In addition to all of the above, it was necessary to calculate the relative importance between decision-makers. That is, the percentage of the decision that each group considered the others should have.

The method used to obtain these weights was that of the eigenvector [156]. The first step of the method was to obtain the comparison matrices of each group with respect to the others, for each of the agents involved. Through GP, a set of weights of the different groups was obtained for each agent. These individual preferences were aggregated for each of the groups by a simple arithmetic mean, resulting in a preference vector for each group. These vectors grouped in columns form a square matrix, of equal dimension to the number of groups. Then, following Ramanathan and Ganesh cited in [156], the real weights corresponding to the relative importance of each group were obtained by calculating the eigenvector of that matrix.

Finally, multiplying the aggregate weights according to the different hierarchical levels by those relative weights representing the relative importance of each group, the definitive weights for each criterion as a result of the AHP process were obtained.

7.3 Results

The results of the different scenarios, starting with those of 2030, followed by those of 2050 and ending with the sensitivity analyses performed are presented below. Yet, before that, the results of the weighting preferences obtained are introduced first.

7.3.1 Preferences

Table 7.2 Second level preferences

Group	Economic Capital	Natural Capital	Social Capital	Equity
Utility	0.294	0.224	0.304	0.179
Academia	0.316	0.106	0.229	0.349
Environmentalists	0.023	0.627	0.186	0.164
Regulator	0.324	0.348	0.246	0.082

Table 7.2 shows the preferences of each group assigned in the second level in Fig. 7.1, i.e. capitals and equity.

Table 7.3 shows the weights representing the relative importance of each group expressed by the different stakeholders with respect to each other.

Table 7.3 Preferences among stakeholders

Group	**Utility**	**Academia**	**NGO**	**Regulator**
Utility	0.360	0.308	0.249	0.444
Academia	0.247	0.115	0.317	0.080
Environmentalists	0.179	0.389	0.222	0.256
Regulator	0.213	0.188	0.213	0.221

Table 7.4 Preferences of the stakeholders

	COST	**PE**	**CO2**	**DEP**	**NOX**	**SO2**	**PM25**	**SEC**	**JOB**
Utility	0.294	0.179	0.049	0.036	0.04	0.049	0.045	0.154	0.150
Academia	0.316	0.349	0.013	0.026	0.02	0.010	0.037	0.188	0.041
Environmentalist	0.023	0.164	0.202	0.202	0.07	0.068	0.087	0.071	0.114
Regulator	0.324	0.082	0.046	0.042	0.05	0.054	0.153	0.197	0.049
Aggregated	0.227	0.203	0.083	0.085	0.05	0.043	0.085	0.152	0.076

Finally, Table 7.4 shows the weights assigned by each group to each criterion once the individual preferences of the third and second levels have been aggregated and corrected using the relative importance between the different stakeholders[6].

7.3.2 2030 results

7.3.2.1 Payoff matrix

Table 7.5 Payoff matrix. 2030

Criteria	**COST [G€]**	**PE [G€]**	**CO2 [Mton]**	**DEP [p.u.]**	**NOX [Mton]**	**SO2 [kton]**	**PM25 [kton]**	**SEC [G€]**	**JOB [Mjobs]**
COST	**120.76**	2.07	163.82	0.73	**0.88**	9.314	**130.050**	2.62	**1.20**
PE	177.44	**1.62**	137.10	0.81	0.44	**53.45**	80.07	**3.23**	1.52
CO2	222.91	2.98	**5.39**	0.38	0.11	4.54	**130.050**	2.01	2.33
DEP	184.61	3.41	38.83	**0.22**	0.19	2.41	**130.050**	1.64	1.83
NOX	235.56	3.15	**230**	**0.93**	**0.01**	2.74	1.13	3.23	2.25
SO2	223.10	3.18	71.28	0.52	0.30	**0.020**	**130.050**	2.02	2.30
PM25	209.19	3.16	**230**	0.92	0.08	0.62	**0.017**	3.21	1.87
SEC	179.48	2.87	33.24	0.37	0.15	1.90	89.44	**0.84**	1.90
JOB	**329.42**	**4.89**	157.79	0.75	0.31	49.06	**130.050**	3.42	**4.41**

As introduced in Section 3.1.1, the payoff matrix is obtained by optimizing each objective individually, obtaining at the same time the respective values for the other criteria even though they do not play any role in the optimization process. In this way, a square matrix is obtained, which dimension coincides with the number of criteria.

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[6] In Section E.2 of the Appendix E, the individual responses of stakeholders in relation to the comparison between capitals, between criteria within natural capital and between the stakeholders themselves are included.

Thus, the payoff matrix provides the ideals of each objective, that can be found in those elements of its main diagonal that compose the so-called ideal point, i.e. the point at which all the criteria reach their optimum value. They are marked in blue in Table 7.5.

Anti-ideal (nadir) values for each attribute are also obtained from the payoff matrix by identifying the most unfavourable value for each attribute in each column. Although it has been shown by the literature that the anti-ideal obtained from the payoff matrix does not necessarily have to coincide with the nadir value of the efficient set, some authors consider that it can provide a good approximation [156]. These anti-ideal values are marked in red in Table 7.5. Eventually, a dominance study was performed which showed that there were no redundant criteria.

Thus Table 7.5 presents the payoff matrix in 2030. Although the payoff matrix is specifically used in the multi-criteria methodology of compromise programming to obtain the ideal and anti-ideal values that will allow the different criteria to be normalized, the matrix itself provides very relevant information about how the different criteria compete or collaborate with each other. Firstly, it is interesting to note how the maximization of the employment criterion is obtained at the expense of a system where almost all other criteria are significantly worse, particularly those reflecting costs (naturally so). Conversely, the system's total cost minimization criterion produces the minimum (anti-ideal) value of jobs. This was otherwise expected, as it is the most cost-efficient system. The explanation for this phenomenon can be found in the direct relationship between employment and investment, which is nevertheless a very reductionist approach to the matter. For this reason, complementing the results of the employment criterion by means of other analyses of the general equilibrium type or input-output tables that make it possible to understand the interactions between the energy sub-sector and the rest of the economy would be a very desirable future work. Thus, phenomena such as the possible creation of indirect employment in a scenario of reduction of energy consumption by improving the overall efficiency of the system could be detected.

Besides, the anti-ideal value of $PM_{2.5}$ emissions is noteworthy. It can be observed that this value has been reached in 5 different criteria. This highlights that in all these cases the system is bounded by the critical limit imposed (see Table 7.1), that is, that the result of the optimisation, if there were no such limit, would be a system with a higher rate of emissions of this atmospheric pollutant. This issue will be further analysed in the sensitivity analysis described in section 7.3.4, but it can be anticipated here that, in this case, the use of biomass is behind this phenomenon.

Another very interesting figure is the total cost of the system resulting from the execution that minimizes the emissions of CO_2. Reaching a minimum emissions value of 5 Mton CO_2 implies total costs almost twice as high as the optimal value: 223 G€ versus 121 G€ .

Finally, it is also worth noting the clear correlation between two criteria, namely fossil-fuel dependence and energy security. However, it can also be seen that there is no dominance of one over the other, what means that both criteria are to be taken into account separately. These examples highlight something of crucial importance in this analysis. The criteria present clear conflicts between them, some of them very evident. The extent to which it is possible to resolve satisfactorily these conflicts will limit the success of the decision taken regarding the energy transition in Spain.

7.3.2.2 Base scenario

Once the payoff matrix was obtained, the proper multi-criteria compromise programing was developed. Firstly, a base scenario execution was done that consisted of a minimization of the distance L_1 using the aggregate weights in Table 7.4 and the inputs described in Table E.1. Table 7.6 collects the values for the nine criteria obtained for this base scenario 2030, together with the value for L_1 distance.

Table 7.6 Base scenario 2030

Criteria	**Values**
COST [G€]	142.96
PE [G€]	1.85
CO2 [Mton]	52.57
DEP [p.u.]	0.50
NOX [kton]	0.16
SO2 [Mton]	1.79
PM25 [kton]	73.02
SEC [G€]	1.16
JOB [Mjobs]	1.92
L1	0.22

The first thing that stands out in these results is the value obtained for the CO_2. Although the adjusted critical limit imposed on the model for the CO_2, according to the EU Roadmap to 2030, is 230 Mton (see Table 7.1), the social optimum obtained from multi-criteria performance is well below (53 Mton[7]). This result has to be taken with caution as the model has been allowed to optimize the system without imposing additional calibration restrictions on end uses. This has a very significant impact especially in the transport sector, where the model is allowed an extreme modal shift towards zero-emission public and private transport. If calibration restrictions are included that force certain modal uses, emissions would increase very significantly.

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[7] CO_2 life cycle emissions were also obtained. It was found that to the 53 Mton of CO_2, 4.2 additional Mtons corresponding to the life cycle emissions should be added. Nevertheless, the system would remain significantly below the limit of 230 Mton proposed by the EC.

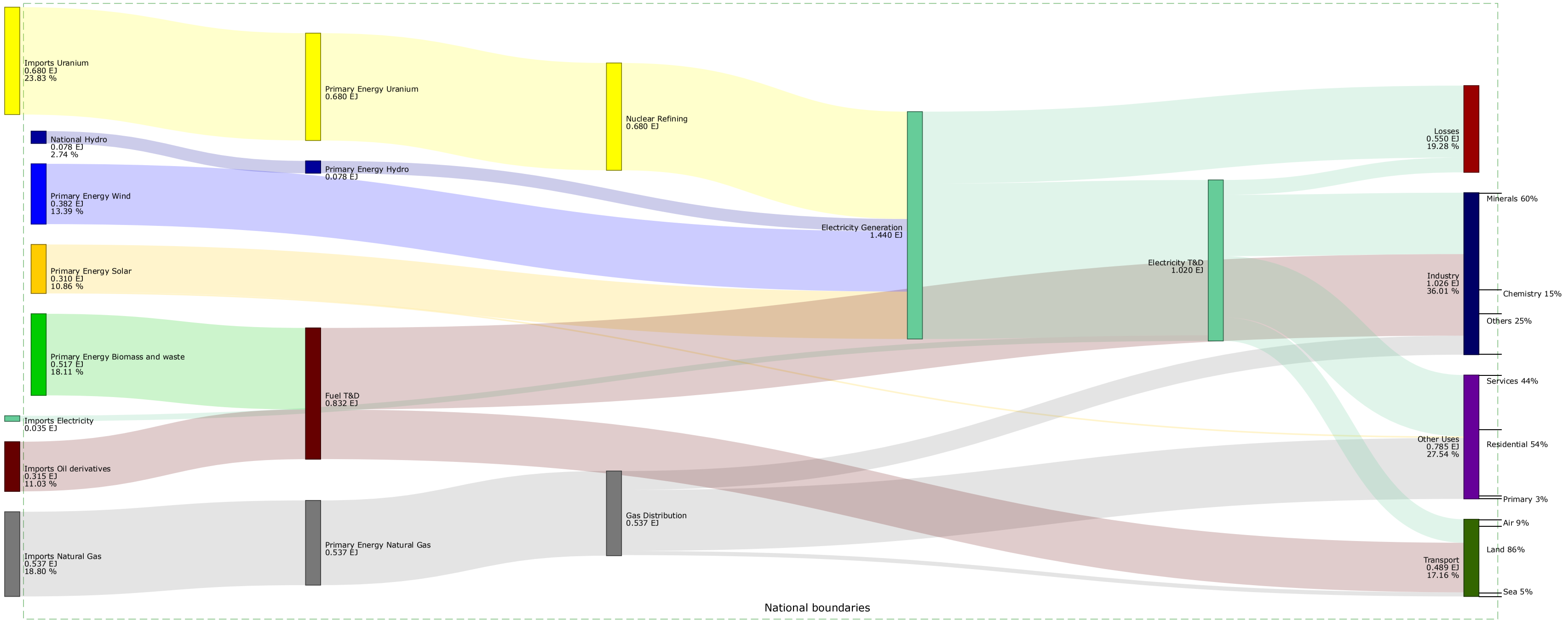

Fig. 7.3 Energy Sankey Spain 2030

However, even more interesting than the result obtained for each of the criteria is the energy mix behind it. Fig. 7.3 graphically displays all this information in the form of a Sankey Diagram.

It can be noticed that the role of renewables is becoming increasingly important. Solar copes 11 percent of the primary mix, while wind covers 13 percent.

On the other hand, it can be observed in Fig. 7.3 that the weight of natural gas in the mix is still very significant, however, its participation in the electric mix is negligible. Most of the imports of natural gas are directed to final uses, mainly to residential and services.

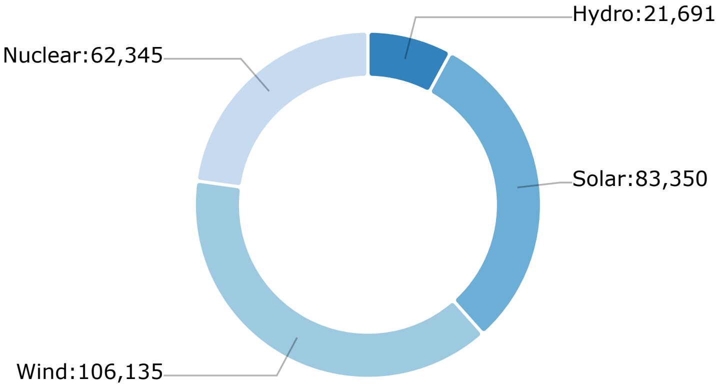

Fig. 7.4 Electricity produced in 2030 [GWh]

Additionally, Fig. 7.4 shows the electricity produced in 2030. It is observed that only four sources are producing this energy, namely, nuclear, hydro, solar (including pv, thermal and distributed pv) and wind (marginal contributions like those coming from from OCGT are not included). Regarding the new installed capacity, it is remarkable that OCGTs holds a relevant role as a back-up technology covering peak-demand. 27GW were installed for this purpose. This power is a response to the adequacy and reserves constraints in MASTER.SO model and thus inherited by MASTER.MC. These results, however, should be corroborated by another type of specific unit-commitment model for the electricity sector [48]. This model will also allow us to show how these power plants, together with storage technologies, operate effectively covering peak demand periods, something that the reduced level of demand blocks disaggregation of the MASTER.MC model does not allow us to observe.

7.3.2.3 Stakeholders comparison

Once the efficient solution represented by the L_1 execution described in the previous section had been analyzed, two comparative studies were carried out. The first one corresponds to

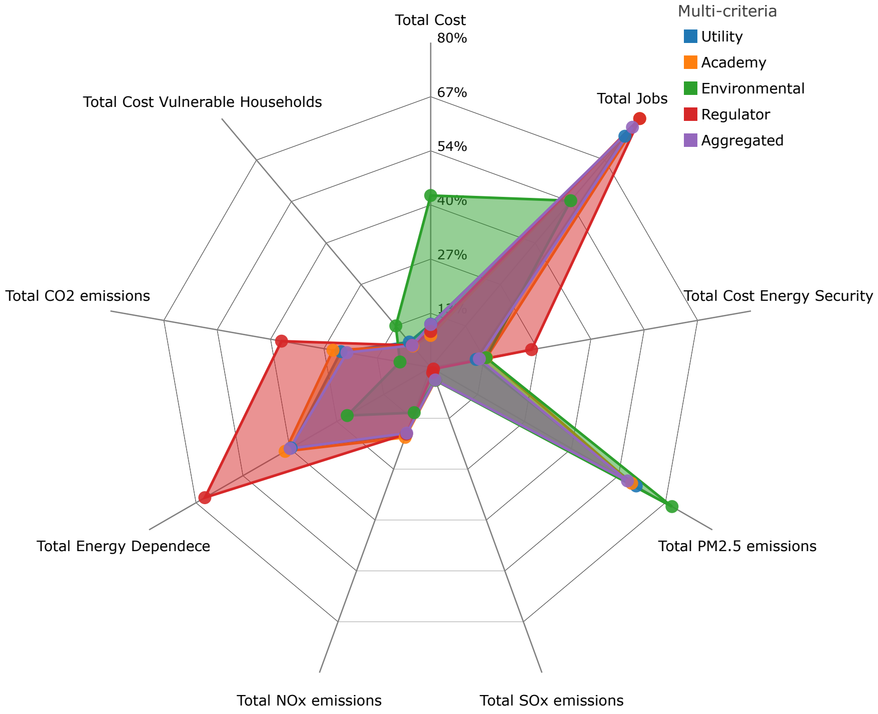

Fig. 7.5 Stakeholders comparison 2030

the preferences of the stakeholders whereas the second relates to the multi-criteria strategy chosen.

Focusing on the former, successive L_1 optimizations were carried out using the different weights assigned by each stakeholder group to each criterion (see Table 7.4). The aim was to analyse how the results of each optimization varied according to the preferences of each individual social group.

Fig. 7.5 shows this comparison using a webdiagram where the unweighted normalized results for each criterion are represented in the axis, whose center corresponds to the optimum value for all the criteria and the 100% in the scale corresponds to the nadir values. Thus, as we move away from the center, the value worsens.

It can be seen that the aggregate result is robust when compared among all stakeholders except the environmentalists. In this case, the weight of the decision is shifted towards minimizing fossil-fuel dependence and CO_2 emissions, which at the same time implies a significant increase in the total costs of the system and worsens the energy poverty and PM2.5 emissions criteria as well.

7.3.2.4 Multicriteria comparison

The second comparative study had to do with the multi-criteria execution itself.

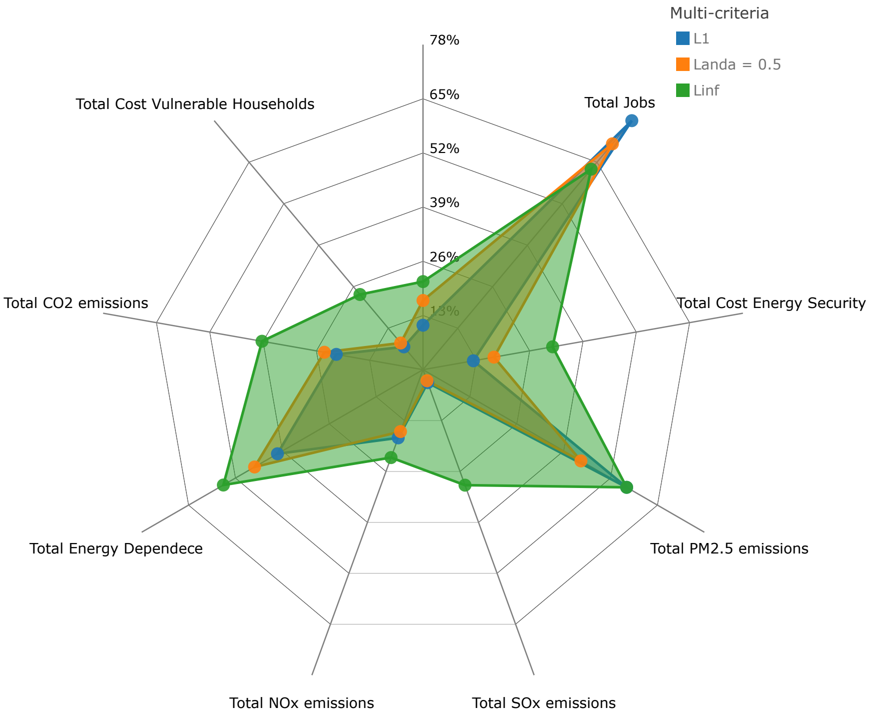

Fig. 7.6 Multicriteria comparison 2030

As described in Section 7.2, two are the most representative distances within the compromise programming methodology, namely the L_1 or Manhattan distance, and the L_∞ or Tchebyschef distance. The former represents a solution of maximum efficiency, while the latter prioritizes a solution of maximum equity among criteria. Both represent the two extremes of the segment that defines the efficient set containing all the intermediate solutions.

Thus, a comparative study was carried out by solving Eq. 7.2 using three different values for λ, i.e. 0 for L_∞, 1 for L_1 and 0,5 for an intermediate value.

Fig. 7.6 collects this comparison in the form of a webdiagram again.

As can be observed, there are no big differences in the results, although it is especially interesting the behavior of the criterion of jobs. The solution L_∞ is forced to improve this criterion at the cost of worsening in some others, especially those involving costs. This might seem strange in the first place, because by definition the L_∞ solution would have to be a perfect balance between criteria. What alters this balance in this case is the assignment of weights as well as, to a lesser extent, the limits imposed on optimization.

This comparison becomes particularly relevant when considering which priorities are assigned in the policy-making regarding energy transition. If efficiency is the priority, i.e. a "minimum area" result, the L_1 solution will be the most appropriate. If, on the other hand, a balanced solution is preferred, the L_∞ must be the chosen one.

7.3.2.5 Residential comparison

As explained in Section 7.2, the MASTER.SO model and, by extension, the MASTER.MC developed on the basis of the previous one for this study, calculates an energy system that covers a given energy demand in a given country and year, including also investment in new capacity if required. This exercise is carried out with a level of disaggregation that ranges from the import of the different energy sources, through conversion (electricity generation and oil refining) to the choice of the specific technologies that cover the different final energy services demanded in industry, transport, services and residential. The model chooses among more than 300 of these ESSTs.

Each of the executions that have been discussed in the previous sections contains all this level of detailed breakdown in the final services, which is not further elaborated here for clarity purposes. However, I did find it interesting to include at least a specific aspect of this analysis: that of the residential sector, and more specifically the difference between vulnerable and non-vulnerable households. This is an original contribution that aims to tentatively incorporate, for the time being, the phenomenon of energy poverty into strategic decision-making in the design of a sustainable energy transition in Spain. For this comparison, the base scenario described above was used.

Table 7.7 Residential 2030

Source	Vulnerable households	Non-vulnerable households
Centralized Electricity	20.34%	63.21%
Natural Gas	79.66%	36.79%

Table 7.7 presents these results in an aggregated form by energy carriers.

It can be clearly seen that the process of electrification of the demand in vulnerable households is smaller than in non-vulnerable households. The former are still 80% dependent on fossil fuels (natural gas) for heating, while the latter cover only 37% of their demand from these sources, the rest being covered by centralized electricity (63%). In other words, vulnerable households turn to the cheapest but most polluting sources, and this is something to be taken into account when defining policies and support schemes. These results highlight an important fact when dealing with long-term decision-making in energy transition: decarbonization goals must be accompanied by affordability concerns.

7.3.3 2050 results

7.3.3.1 Payoff matrix

Table 7.8 collects the 2050 payoff matrix. As in the case of 2030, the dominance study reflects that there are no redundant criteria.

Table 7.8 Payoff matrix. 2050

Criteria	COST [G€]	PE [G€]	CO2 [Mton]	DEP [p.u.]	NOX [Mton]	SO2 [kton]	PM25 [kton]	SEC [G€]	JOB [Mjobs]
COST	**206.58**	3.53	**12.84**	0.27	**0.13**	4.499	**76.500**	2.48	3.29
PE	257.75	**2.63**	**12.84**	**0.28**	0.12	4.513	**76.500**	**2.67**	3.94
CO2	309.06	5.24	**5.78**	0.12	0.10	4.467	**76.500**	1.77	3.54
DEP	299.42	**6.11**	**12.84**	**0.06**	0.13	4.506	**76.500**	1.11	3.31
NOX	307.64	5.40	**12.84**	0.13	**0.06**	3.856	61.476	1.94	3.38
SO2	277.32	5.15	**12.84**	0.17	0.09	**0.614**	**76.500**	2.63	**2.83**
PM25	286.55	5.18	**12.84**	0.17	0.09	3.705	**34.422**	2.52	2.97
SEC	304.52	5.18	**12.84**	0.07	0.11	4.546	**76.500**	**0.72**	3.47
JOB	**313.42**	4.69	**12.84**	0.24	0.11	**6.895**	**76.500**	1.96	**5.01**

Again, from the mere observation of the payoff matrix, very relevant information can already be obtained.

This time the behavior of the CO_2 criterion is the most noteworthy result in the matrix. Unlike in the case of 2030, this time the 12.8 Mton limit does represent a strong limit that binds the model in most executions. The fact that in the optimization of the other criteria the value obtained for the CO_2 criterion is precisely 12.8 Mton indicates that we are forcing the model to respect a limit that definitely constrains the optimum sought. The same happens for $PM_{2.5}$. This phenomenon was already observed in 2030, but this time it has been exacerbated.

7.3.3.2 Base scenario

As in the case of 2030, a base scenario was obtained as a L_1 optimization, using the aggregate weights of the stakeholders in Table 7.4 and inputs of Table E.1.

Table 7.9 Base scenario 2050

Criteria	**Values**
COST [G€]	253.20
PE [G€]	3.33
CO2 [Mton]	10.40
DEP [p.u.]	0.17
NOX [kton]	0.09
SO2 [Mton]	1.50
PM25 [kton]	75.92
SEC [G€]	1.01
JOB [Mjobs]	4.07
L1	0.40

Table 7.9 presents the results of this optimization. It may be observed that, in general, there is an increase in all the criteria, as expected given the increase in the demand in 2050. Besides, it should also be noted that CO_2 emissions are very close to the limit imposed of 12.8 Mton[8].

Additionally, Fig. 7.8 shows the Sankey Diagram resulting from the 2050 base scenario, and Fig. 7.7 the produced electricity mix.

It can be seen that in this case we have a very electrified mix, in which solar represents 26% of the total primary energy, wind 33% and natural gas accounts for only 2.4%. It is also interesting noticing that biomass has entered the energy mix coping a significant share: 19.6%.

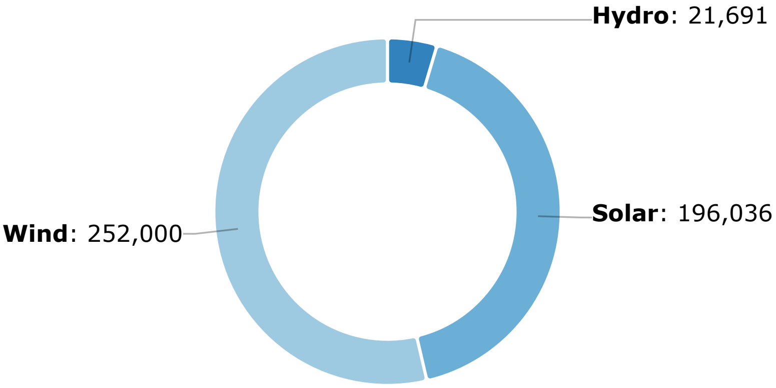

Fig. 7.7 Electricity produced in 2050 [GWh]

Besides, it is again remarkable the role of OCGT as back-up technology. 60GW were installed for this purpose. This is a very high figure, probably due to an overestimation of the need for backup by the model. It is necessary to contrast this value with the one obtained by running a unit-commitment model specific to the electricity sector.

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[8] This time 11.54 Mton LCA CO_2 emissions are to be added to the 10.4 Mton. Eventually, these extra emissions could bring infeasibilities to the system.

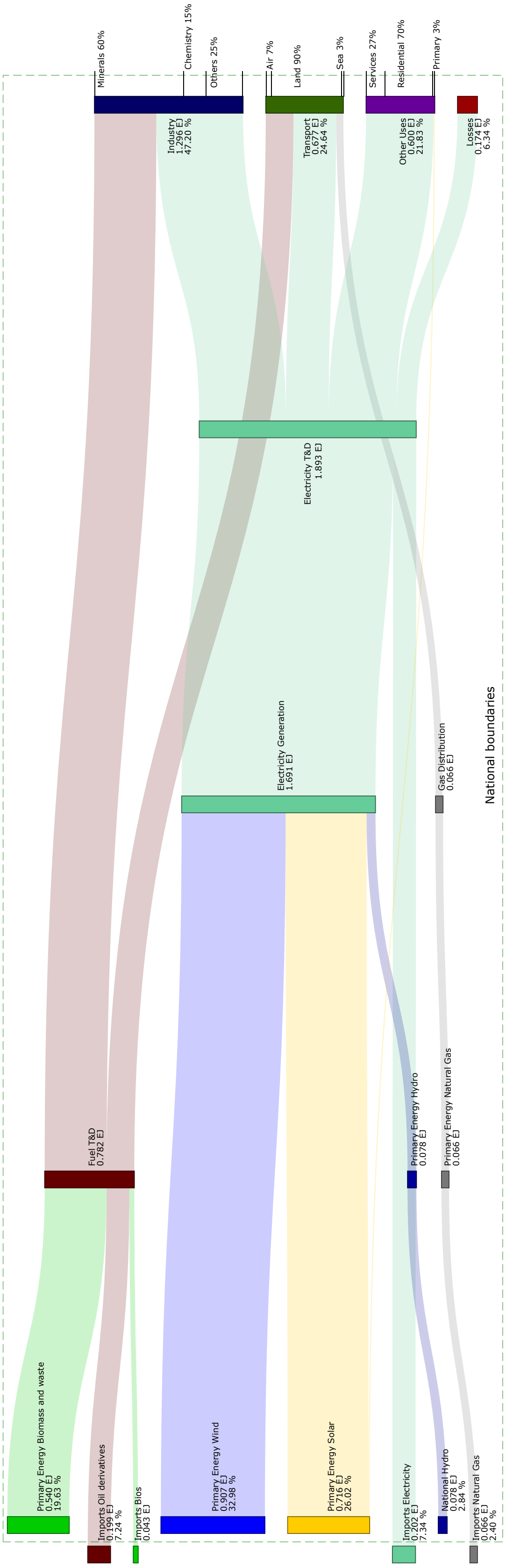

Fig. 7.8 Enery Sankey Spain 2050

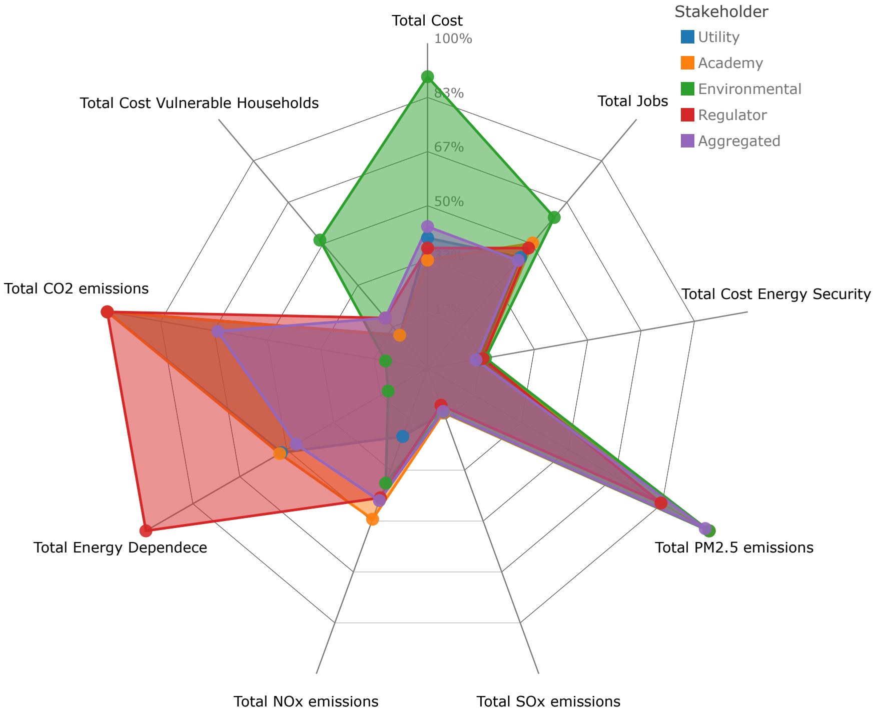

Fig. 7.9 Stakeholders comparison 2050

7.3.3.3 Stakeholders comparison

The first comparative analysis in 2050 was that of the different stakeholders preferences. Again, the model was run several times alternating the assigned weights in Table 7.4.

Fig. 7.9 shows the result of this analysis.

The first thing worth being stressed is that the same phenomenon continues to occur as in 2030, that is, the group representing the environmentalists has a remarkably different behaviour from the rest. For this stakeholders, the fossil-fuel dependence criterion is clearly prioritized, at the expense of the total costs of the system.

Additionally, the proximity of CO_2 to anti-ideal values is a constant for each group, given the tight limit imposed.

7.3.3.4 Multicriteria comparison

The next analysis developed for 2050 consisted of a comparison between the three compromise programming executions varying the target distances, i.e. L_1, L_∞ and an intermediate one ($\lambda = 0.5$), as previously done in 2030.

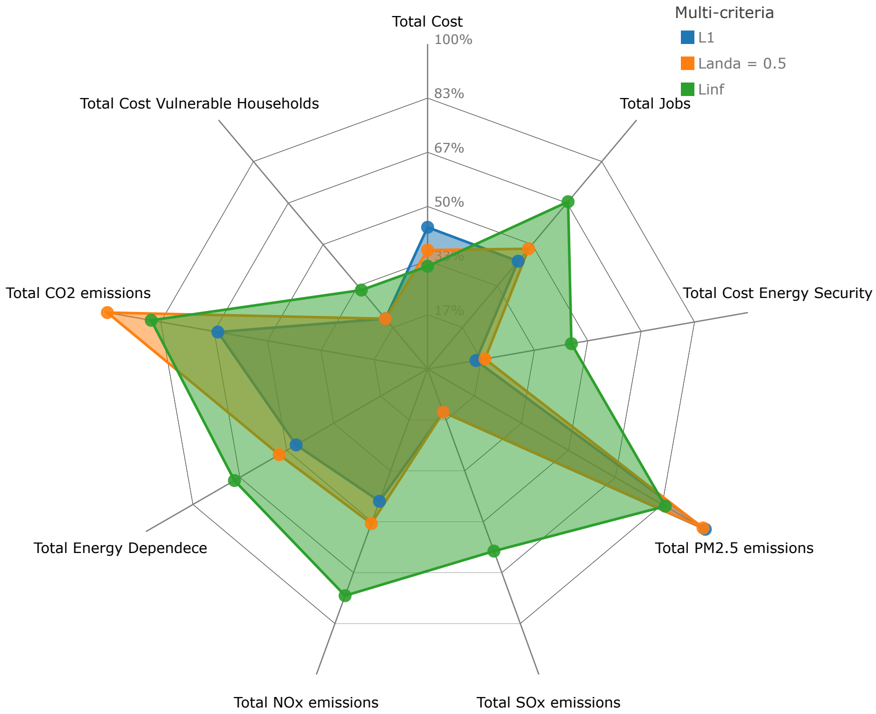

Fig. 7.10 Multicriteria comparison 2050

Fig. 7.10 displays this result again in the form of a webdiagram, where its center represents the optimum value for all the criteria and the 100% in the scale represents the anti-ideal value for the corresponding criteria.

The same phenomenon already detected in 2030 can be observed here, namely that the L_1 execution presents minimum-area solution while the L_∞ is slightly biased towards the most vulnerable criteria. This time, this criteria is $PM_{2.5}$.

Compared to the results obtained in 2030, two criteria have significantly worsened its performance in general terms, namely CO_2 emissions and $PM_{2.5}$. Both case are self explanatory: the limits imposed are restrictive enough to determine the optimization and modifies the social optimum.

7.3.3.5 Residential comparison

In relation to the comparative behaviour between the two groups of households, namely vulnerable and non-vulnerable, the same exercise already carried out in 2030 was repeated.

Table 7.10 shows the values obtained.

It is particularly interesting to note that the process of electrification of demand has been completed in non-vulnerable households. However, this has not yet happened in vulnerable

Table 7.10 Residential 2050

Source	Vulnerable households	Non vulnerable households
Centralized Electricity	87.26%	100%
Natural Gas	12.74%	0%

households that continue to demand natural gas to meet their thermal demands: 12.74%. This percentage would have been much higher if the CO_2 constraint had been relaxed.

7.3.4 Sensitivity and robustness

Given that this whole analysis is intended to address a decision problem, it is essential to ensure that the one offered is as robust as possible.

In order to analyze this robustness, several additional sensitivity exercises were proposed.

7.3.4.1 Sensitivity to fuel prices

The first sensitivity analysis consisted of executing the model modifying the import price of the different primary sources in 2030.

Two sensitivities were analyzed: one in which the price was 50 percent higher than the base price, and the other in which the price was 50 percent lower. In addition to checking the robustness of the model, this exercise would also make it possible to analyze the concrete effect of the change in the price of energy raw materials on all the criteria considered in the multi-criteria optimization.

Thus, forcing a 50% variation in the price of crude oil and the other energy imports, the sensitivity analysis was developed.

Fig. 7.11 shows the results in the form of a webdiagram.

It can be seen that the base scenario in 2030 is robust to price fluctuations. The changes in the different criteria are small. Only the emission criterion of $PM_{2.5}$ shows a significant reduction in the scenario of low energy commodity prices. This is due to the trade-off in this particular case between natural gas and biomass. When the price of natural gas decreases, the model chooses to increase its weight in the energy mix, at the cost of a reduction in the use of biomass, the main vector of PM2.5 emissions in the scenario.

This robustness is also shown when we analyze the variations in the electric mix. The electric mix in 2030 in the three scenarios remains basically stable. Nuclear covers just under 25 percent of the demand, solar just under 30 percent and wind just over 30 percent.

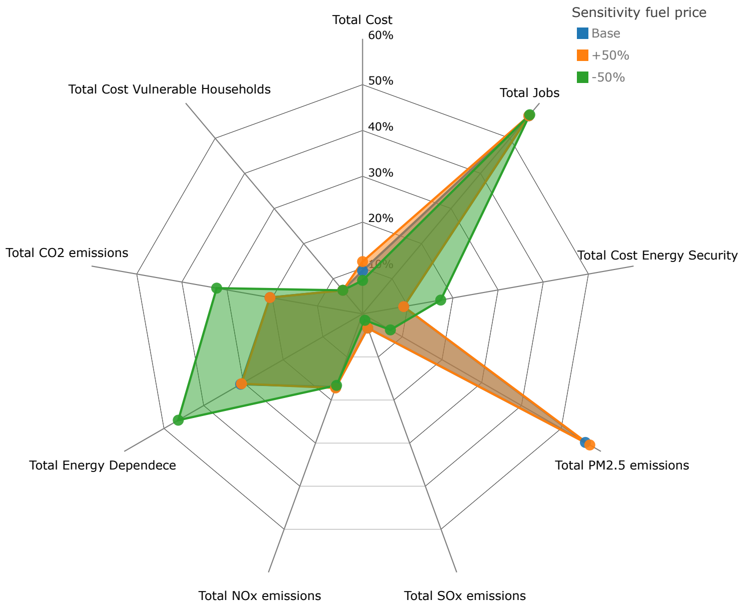

Fig. 7.11 Robustness to fuel price variations in 2030

7.3.4.2 Sensitivity to nuclear

This sensitivity developed over the 2030 base scenario, consisted in assessing the effect on the energy mix of the complete elimination of nuclear energy in that year. It should be highlighted that in 2050 it is assumed that no nuclear power will be operating, therefore no additional sensitivity was required for this year. In order to carry out this exercise, firstly a new payoff matrix was calculated, in which the nuclear technology was discarded. Then, an L_1 distance minimization execution was run that took into account the new ideals and anti-ideals. Table 7.11 collects the results obtained.

Table 7.11 No nuclear scenario 2030

Criteria	**No nuclear**	**Base scenario**
COST [G€]	150.78	142.96
PE [G€]	1.99	1.85
CO2 [Mton]	56.69	55.57
DEP [p.u.]	0.41	0.50
NOX [kton]	0.17	0.16
SO2 [Mton]	1.85	1.79
PM25 [kton]	76.24	73.02
SEC [G€]	1.45	1.16
JOB [Mjobs]	1.94	1.92
L1	0.17	0.23

Compared with the results of the base scenario, it is observed that there is a slight worsening in the COST and PE criteria. This is mainly due to the investment in new capacity needed to cover the electricity demand.

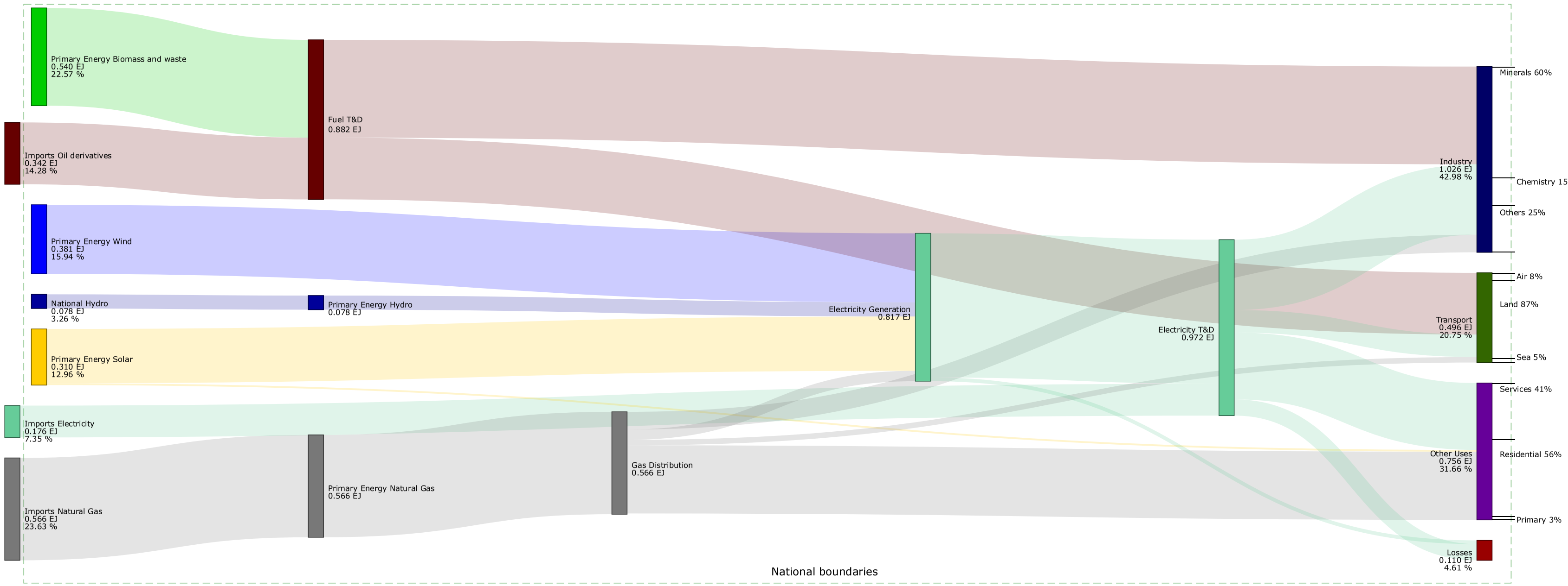

Fig. 7.12 Sankey diagram. No nuclear scenario 2030

The main change between the two scenarios is observed when analyzing the new Sankey diagram (see Fig. 7.12). It can be seen that natural gas, biomass, solar and wind have assumed the role that previously covered the nuclear within the energy mix.

7.3.4.3 Sensitivity to biomass

Sensitivity to the use of biomass in 2050 was also analyzed. It was intended to make a stress test of the system in case of limitations in the possibility of using this domestic fuel.

This test consisted of reducing the energy available from this national biomass to the 10 percent of its theoretical availability. The result was as expected: the system became infeasible. The CO_2 emission reduction target was not achieved in this scenario with reduced domestic biomass availability. The reason for this infeasibility lies in the inability of the system to meet its thermal energy demand. Some possible technical responses to this situation would be the use of other alternative fuels, such as hydrogen, or an even greater increase in the electrification of thermal demand, including industry.

This result has important consequences for the energy transition planning as it calls into question the viability of a biomass-dependent model which, although it has advantages in terms of reducing CO_2 emissions, suffers from other problems like indirect emissions due to biomass imports. or the increase in the emissions of other pollutants.

7.3.4.4 Sensitivity to efficiency in residential and services

This sensitivity takes advantage of MASTER.SO's functionality to estimate the impact of energy efficiency measures on buildings. More information on this particular functionality of the model can be found in [162].

By activating this possibility, a very interesting reduction in emissions of CO_2, fossil-fuel dependence and the cost of energy security is verified.

Table 7.12 collects these results.

Analyzing the micro results, the most effective measures are those related to improved insulation (including envelopes) in residential (townhouses and blocks) and commercial buildings, especially those that reduce the U of the building to values below 0.2 W/m^2 (standard for almost passive buildings). In these cases, the savings in heat and cold in commercial buildings are 83 and 75 per cent respectively.

The sensitivity analysis carried out shows the robustness of the model to changes in key parameters of the system, but at the same time shows the need to take these aspects very much into account when designing the optimal energy transition strategy in Spain.

Table 7.12 ESVM scenario 2050

Criteria	2050 ESVM	2050 base
COST [G€]	252.67	253.20
PE [G€]	3.33	3.32
CO2 [Mton]	8.01	10.4
DEP [p.u.]	0.14	0.17
NOX [kton]	0.09	0.09
SO2 [Mton]	1.40	1.50
PM25 [kton]	70.91	75.92
SEC [G€]	0.90	1.01
JOB [Mjobs]	4.15	4.07
L1	0.34	0.40

Of course, many other equally important sensitivity analyses could have been considered. It remains for future developments to delve deeper into them. Eventually, in those future developments, an uncertainty analysis might also be implemented. It could be carried out through the formulation and resolution of a game against nature procedure as in [156].

7.4 Conclusions

The analysis of the results has revealed some interesting conclusions:

Firstly, the exercise carried out has brought to light some very obvious conflicts between criteria. Regarding the employment criterion, it has been highlighted the significant inverse correlation with total cost and energy poverty criteria.

Speaking of the latter, it is noted that seeking greater attention to this objective results in a non-negligible increase in system costs, as well as the costs associated with energy security.

With regard to emissions, the main conflict lies between CO_2 and $PM_{2.5}$. A low CO_2 system has turned out to be a system that reaches the limit of particulate emissions imposed not only in 2050, but also in 2030. The use of biomass is behind this phenomenon.

Also in 2050, the 12.8 Mton limit does compromise the social optimum. Most of the different executions carried out by 2050 are not naturally within the emissions safety zone. They are forced by this limit.

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[8] It is important to clarify that this statement is made exclusively within the study parameters used in this study, mainly referred to the level of demand and investment costs of new technologies and the absence of additional policy restrictions in end-use technologies. With other assumptions, we would undoubtedly be confronted with different scenarios.

Regarding the other pollutants, i.e. $PM_{2.5}$, SO_2 and NO_x, the former represents a major challenge. According to the results, in both payoff matrices at 2030 and 2050 it is observed that the individualized optimization of each criterion clashes in many cases with the critical limit imposed for $PM_{2.5}$, mainly due to the presence of biomass in these partial scenarios that constitute the payoff matrix. Nevertheless, in multi-criteria executions the combination of objectives pushes these emissions downwards, resulting in very controlled scenarios as far as $PM_{2.5}$ is concerned.

The role of natural gas in both scenarios 2030 and 2050 is another interesting issue to be analyzed. Natural gas is progressively removed in order to reduce CO_2 emissions. Yet if the constraint is relaxed then it comes back in. Moreover, in 2050, the contribution of natural gas to the overall energy mix is almost negligible. In that case, without exception, its use is restricted to end-use heat demands.

Another aspect to highlight was the comparison between efficiency and equity among criteria, represented by the executions L_1 and L_∞. In both 2030 and 2050, an efficient solution (minimum area) was found between the different criteria using the former, while when using the latter, a balanced one with a bias towards the employment criterion in 2030 and to $PM_{2.5}$ in 2050 was found. This fact seems to be of particular interest. Both approaches provide relevant information: the first provides an efficient solution in a given preference scenario, while the second prioritizes the worst criteria in terms of its proximity to the optimum to be pursued. It is therefore a very relevant analysis when it comes to understand in more detail who wins and who loses in the energy transition, and with regard to the latter, how they could be compensated and at what price.

With regard to the preferences of decision-makers, it has become clear that the only group that is significantly far from consensus in 2030 and 2050 is environmentalists. Its bias towards the prioritization of the natural capital criteria is remarkable.

Eventually, a novel contribution of this study has been the incorporation of the criterion of energy poverty in the decision-making process for the design of the energy transition. This made it possible to compare the behaviour in terms of energy demand of two types of groups, namely vulnerable and non-vulnerable households. It can be seen that the process of electrification of demand in the former is much more advanced than in the latter, where it was 100% completed in 2050. In my opinion, this is a particularly relevant result, especially in terms of understanding how two fundamental objectives in the design of a sustainable energy system clash, i.e. limiting CO_2 emissions and assuring affordability for all.

In relation to future developments, some of them have already been anticipated throughout the text. With regard to the multi-criteria tree itself, it would be highly recommended to broaden the consultation of decision-makers on the convenience of adding, replacing or removing some criteria. In this regard, I would like to highlight the possibility of (1) setting new critical limits obtained in a substantive or perhaps in a participative way, always taking special care in distinguishing between strict critical limits and preferences; (2) transforming the energy dependency criterion into an eMergetic dependency criterion; or (3) assessing the convenience of moving the energy security criterion to economic capital and reviewing the overcosts assigned. Besides, another interesting future work would be to incorporate LCA emissions endogenously and not simply as ex-post analysis. Eventually, an uncertainty analysis using a game against nature methodology would also be a very interesting addendum.

Once the conclusions concerning the objective results of the exercise have been presented, some more general conclusions are set out below, which have to do with the entire journey made in this thesis.

As stated in the introduction to the chapter, this practical exercise did not seek exhaustiveness in the analysis of the energy transition in Spain to 2030, but rather to show an example of the application of the proposed energy sustainability analysis framework, which is the heart of this work. In this sense, the exercise has highlighted the potential of this analysis methodology. It has been possible to see how the different criteria that ultimately measure the evolution of capitals and the equity variable in an energy system present very disparate and conflicting evolutions among themselves. A clear example of this is the direct relationship between investment and employment, which means that an increase in employment in the sector almost always implies an increase in the total costs of the system. Another example is that of emissions, where it is found that the imposition of strong limits, especially on CO_2 and $PM_{2.5}$, radically determines the resulting energy system, especially in 2050. A third example is the relationship between emissions of CO_2 and vulnerable households. The fact that these households opt for cheap and polluting technological alternatives in order to reduce their costs highlights the conflict between two unavoidable objectives of the energy transition, namely, that it be clean and that it be fair.

If we remember, the main objective of the thesis was to offer an (1) operational framework for energy sustainability studies (2) compatible with the capital-based definition of sustainable development. It can be observed that this case study has shown that the proposed framework is in practice capable of responding to what was requested. It is an (1) operational framework capable of designing specific strategies; and is (2) compatible with the definition of capital-based sustainability, since it encompasses them in a multi-criteria exercise in which the equity dimension is also incorporated.

The interest in applying the proposed framework to a problem as concrete as the design of a sustainable energy transition is thus demonstrated. But it is still pending to continue escalating its performance to higher scales of the global eco-social system.

Chapter 8

Conclusions

The challenge of the SD, as we understand it today, is a roadmap for the success of humanity. It encompasses not only respect for the environment, the guarantor of our survival, but also the achievement of well-being both for our generation (without exclusion) and for those to come. This welfare is not to be a preconceived and imposed welfare, but a discerned and respectful of individual freedom one.

This major challenge has many dimensions: temporal, geographical, economic, ecological, social and sectoral. All of them, despite having their own identity, are part of a complex web we call global SD. Hence, in order to reach a definition of the challenge that will eventually help us to make the right decisions to move towards it, we need conceptual tools capable of gathering that unity in diversity.

This thesis tried to contribute to this immense goal. The focus was to set out a framework to help understand the extent to which our energy systems were adding to or subtracting from the global challenge of the SD. However, the journey started from the very beginning, that is, wondering what definition of SD was the most appropriate so that we would never lose sight of the global challenge. This led me to review the proper literature and to choose the perspective of capitals.

It can be said that this is the first conclusion of the thesis: the fruit of the revision of the academic literature about the conceptual approaches to SD led me to adopt the capital-based approach because of its robustness and its better capacity for operationalization. However, this approach was not without its problems. The main one had to do with a very strong implicit assumption: capitals are perfectly substitutable for each other. This is not obvious at all. Not in vain did the classic dispute in the 1970s between Georgescu-Roegen and Solow/Stiglitz in this respect result in the birth of the two classical sustainability schools: the weak and the strong. The first one defends that this aggregation of capitals is possible or, in other words, compensation between capitals is possible. On the other hand, the strong school totally rejects this assumption and raises the need to establish critical limits, especially for natural capital. Exploring this fruitful academic discussion led me to adopt a working hypothesis that served as a common thread for all the research. This hypothesis advocated the possibility of complementarity between the two schools, without denying their opposing positions.

After that preliminary analysis, we were already in a position to set out the conditions that would have to be required of an energy system in order for it to be called sustainable. Basically, there were three conditions, namely, (1) that it should be compatible with the global challenge of guaranteeing a human welfare that does not diminish in time; (2) that it should respect the critical limits where and when they exist and (3) that it should guarantee that these capitals are distributed in an equitable way. In this way, the framework to be presented would have to be able to identify to what extent an energy system was complying with these requirements.

Thus we reached the state of the art of the thesis, which would help me to choose the appropriate proposal of framework, as well as the indicators that would work within it measuring capitals and critical limits. For the former, there were two approaches that were identified as potentially suitable: multi-criteria and complexity-based approaches. With respect to the former, a review was made of the different methodologies available. In this process, their capacity to adapt to the objective of the thesis was verified. Not in vain, there were proposals in the literature that had been successfully applied to some case studies on the sustainability of energy systems.

With regard to the complex proposals, I wanted to tackle the root of the issue. Much of the strong sustainability literature advocated a complexity-based epistemological approach to sustainability studies. That is precisely why I wanted to understand what this epistemology consisted of, to what extent it differed from the classical scientific approach, and whether there were concrete operational proposals in the literature that could serve as the basis for our own framework proposal.

The result of this analysis helped me to identify two opposing realities. On the one hand, the remarkable capacity of complex thinking to conceptualize non-simple problems such as sustainability was identified. On the other hand, it was verified the practical impossibility of transforming these complex approaches into concrete operational instruments. I am not referring to a lack of studies and proposals in this sense that could be solved by future work, but to a factual impossibility. The complex paradigm is open, while all concrete proposals are necessarily closed, hence the impossibility. This limitation, however, preserves the inspiring capacity of complex thought to nuance the results coming from simplifying proposals, as well as to highlight the need to complement these partial perspectives with others that could help to travel the difficult path that leads from models to reality. In that sense, the present thesis, although it opted to set forth its contribution from the classical multi-criteria theory, was very enriched by the critical thought that complex epistemology incorporates. It did so concretely in two areas. The first had to do with the process of incorporating the choices made by decision-makers. Although a closed AHP process was chosen, the need to develop more open and inclusive methodologies in the future was emphasized. The second element of complex inspiration was the incorporation of the dialogical principle in the elaboration of the framework itself. According to this principle, apparently conflicting theories about reality can be compatible as long as they are integrated into a framework in which both maintain autonomy of action while limiting the application of their opposite. This is exactly the case for the proposed integration of the two classical schools of sustainability: strong and weak.

With regard to indicators, the starting point was the finding of another limit: any set of indicators chosen a priori to measure the sustainability of a system will always remain merely illustrative. Two decisions were made on this basis. On the one hand, we would have to face this process of choosing particular indicators at the time when the case study was being defined. On the other hand, it seemed to us very relevant to delve, even if for illustrative purposes, into those sustainability indices most used in the literature from both a weak and a strong perspective. This work could serve as a basis for empirically verifying the hypothesis mentioned above, namely that the two classical sustainability schools can in practice work in a complementary manner.

Thus, in the first place, it was analyzed the literature of sustainability indices proposing a classification of them according to their strong or weak inspiration. Subsequently, I proceeded to deepen the knowledge of two of them that were considered most representative of each school: the ISEW for weak sustainability and exergy and its derivatives for strong sustainability.

In this analysis, the initial intuition was confirmed: both approaches were, a priori, susceptible of complementing each other since they addressed different conditions of sustainability. While weak sustainability was more appropriate for measuring the evolution of equitable well-being, strong sustainability could be asked to define strong limits to activity, especially in terms of natural capital.

All this was corroborated in the Costa del Sol sustainability study. When comparing the behavior of two representative indicators for each school, it was found that there was no direct or inverse correlation between them. Both were measuring different but necessary elements of the sustainability of the region, and therefore had to be taken into account together.

At this point, we were already in a position to present the algebraic frame proposal, which was done in stages. At first, inspired by Linares' proposal, I started from a generalized Hartwick rule. In it, to the condition of a non-declining evolution of welfare, understood as function of capital, the condition that the critical limits for each capital were respected was added.

In a second moment, the previous approach was transformed into an static optimization of an specific welfare function based on capital. It was done using a compromise programming formulation, so that the framework was transformed into an optimization problem where the objective function to be minimized was the distance to an ideal multidimensional point, where each dimension represented a capital.

Finally, the equity dimension had yet to be integrated into the framework, which was done by disaggregating the variables that represented each capital according to a new level that would represent the diverse distribution of capital. This was applied not only to the objective function, but also to the critical limits. In this way, the framework would eventually allow forcing a particular distribution of some particular capital that was identified as critical.

We already had the framework so what was left was to apply it to a specific case that illustrated its real usefulness for analyzing the sustainability situation of a specific energy system. For this, the case of the Spanish energy system in its transition to 2030 and 2050 was chosen.

Before that, however, it was necessary to define, on the one hand, how different capitals were to be measured and, on the other, how energy equity could be integrated. A full chapter of the thesis was devoted to analysing this last point, in which the issue of energy equity was explored, arriving at the concept of energy poverty. Then an analysis about the main indicators used to measure it and their calculation for the Spanish case was accomplished. The main conclusions obtained from this study are the identification of false positives in some indicators, which led me to discard them as possible metrics for our framework, and the choice of a particular indicator as the most appropriate, i.e. the MIS-based, as well as the proposal of a new methodology that would facilitate its calculation in a more robust way in the future.

With all the above background, we entered into the case study. The first step was to define the criteria tree that would define the path towards energy sustainability understood from the capital approach. Next, a computational tool, i.e. the MASTER.MC model, was developed that represented the Spanish energy sector and that allowed its optimization in 2030 and 2050. This model attended the algebraic structure of the framework presented in the thesis, that is to say, a compromise programming with restrictions that represented critical limits.

The conclusions of this exercise were very promising. Among others, a number of very relevant conflicts between criteria were revealed that would have to be taken into account when designing policies towards energy transition. In addition, the crucial role played by critical limits was confirmed. They significantly limited the possibility of optimizing well-being when we are close to the frontier of socio-environmental resilience.

At the end of the tour, the feeling is that more questions than answers have been given. Yet I do not consider this a failure, quite the contrary. I think that it is rather a meta-manifestation of the complex epistemology that so inspired this exercise. Sustainability is a living challenge that asks to be accompanied, not caged.

8.1 Main contributions

The main contributions made by this thesis are briefly summarized below. For the sake of clarity, they have been divided into different areas.

1. Framework

   The main theoretical contribution of this thesis is the development of the weak-strong integrated framework proposal. It is based on Linares' preliminary proposal [157], and the present thesis (1) has formally developed it defining the objective function as a compromise programming problem and endogenously incorporating equity concerns. Additionally, (2) it has been enriched by providing the theoretical foundation based on a capital-based sustainability theory and (3) has put it into practice in a case study of the analysis of the energy transition in Spain to 2030 and 2050.

   Nevertheless, the first contribution to be highlighted is the state-of-the-art analysis of different frameworks applicable to the challenge of the sustainability of an energy system, especially those that derive from the tradition of the theory of complex thought. Although they have not been used directly in the framework proposal, as mentioned above, they have inspired some of its most outstanding elements.

2. Weak and Strong Sustainability

   In the revision of these two schools of thought regarding sustainability presented in the chapters 2 and 3, the main contribution has been to put them into dialogue. In addition, this dialogue has been endorsed with the study of sustainability on the Spanish Costa del Sol between 2007 and 2015, in the chapter 4. This study also includes several new features: (1) the ISEW methodology has been adapted to respond to the characteristics of the study; (2) the eMergetic and EEA methodologies have also been adapted to obtain the carrying capacity indicators in the region; and (3) a comparative study between the two proposals has been presented, resulting in a weak-strong integrated analysis approach. Additionally, three computational tools have been developed for the calculation of the indicators, i.e. eMergy, EEA and ISEW, that can be adapted to perform different analyses in the future.

The result of the study has shown the convenience of carrying out weak-strong integrated studies when evaluating performance in terms of sustainability of territories, although it could be extended to other systems and other scales.

3. Energy Poverty

   In the area of energy poverty presented in the chapter 6, the main contributions have been (1) the revision of the methodology and the calculation for the first time for Spain of the LIHC and MIS-based indicators and (2) the proposal of a novel method of calculating the indicator based on the MIS. In relation to the concrete results obtained in the calculation of the indicators to the Spanish case, some conclusions are highlighted: (1) the identification of false positives in one of the indicators, that of 10%, and (2) the justification of the choice of one of the methodologies as the most appropriate, namely the MIS-based, highlighting, however, its great dependence on the reference MIS used.

4. MASTER.MC model

   Finally, the MASTER.MC computational tool developed for the case study of the chapter 7 incorporates several new features.

   - A multi-objective model based on compromise programming covering the entire energy sector has been developed and applied to a real case study: the Spanish energy system in 2030 and 2050. Eventually, several graphic tools have been implemented and integrated in the model to produce the different graphs[1] for the case study, namely, Sankey diagrams, web diagrams and circular diagrams, that can also be adapted and re-used in future developments.
   - In relation to the criteria incorporated, (1) the energy poverty criterion has been integrated into the model in a novel way, as a representative of the equity aspects in the achievement of the global sustainability objectives. This criterion

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[1] These tools are based on D3 javascript library (https://d3js.org). I thank Mike Bostok for providing such a great tool for free and Renato Rodrigues for his template for Sankey Diagrams (https://www.comillas.edu/Documentos/BP/sankey_energy.html).

divides the demand for domestic services into two groups: vulnerable and non-vulnerable, which allows particular attention to be paid to the first group, making it a criterion within the compromise programming methodology. (2) Additionally, air pollution criteria such as SO_2, $PM_{2.5}$ and NO_x have also been incorporated. Eventually, (3) the jobs criteria in the energy sector has also been included.

- The inclusion of the CO_2 life cycle emissions calculation in the MASTER.MC is another novel contribution. Although it has not been used as decision criteria, the model allows it to be used if required.
- As a result of the application of the model to the case study of the energy transition in Spain to 2030 and 2050, some relevant results have been obtained. The main one is the existence of conflicts between criteria that condition the search for the social optimum. Among them, it is worth highlighting the conflict between emissions of $PM_{2.5}$ and those of CO_2, as well as those of the latter with the criterion of energy poverty. In the same way, it has been detected that the introduction of absolute limits representing critical capitals conditions the solution of the model in a very meaningful way. In this sense, it is worth highlighting the rigidity of the model in 2050 in relation to emissions of CO_2 and $PM_{2.5}$. Another conclusion resulting from the application of the model to a real case has to do with the role of equity. When analyzing the behavior of vulnerable households, it is observed that the technological solutions adopted by them differ significantly from those adopted by non-vulnerable households. In view of the above, a fair energy transition must take this phenomenon into account and focus social policies on these groups as a matter of priority.

8.2 Future work

As the reader will have been able to see as he or she progresses through the reading of this document, many issues and disciplines have been addressed in the development of the thesis. One could say that one of the main efforts that the author has had to face has been to approach disciplines that are in principle far from his training in order to be able to complement some necessary aspect of the research. Sustainability, as a concept or even as a science, is by nature open and interdisciplinary, which makes the lines of work that are born of this work so too. It has therefore been decided to group by disciplines the possible future lines for research that emerge from this thesis. It is important to note that this list is not intended to be exhaustive either in the enumeration of the possible lines to be followed or in their description, it is simply an outline that will have to be developed or eventually discarded.

1. Ethical

   This is probably the area farthest from the engineering discipline from which this thesis was approached, and yet it is perceived to be the most important.

   As already mentioned in the introduction to this thesis, the challenge of sustainability, rather than technical, is a fundamentally ethical one. The bottom line is that we must be able to create value, that this value has a fair impact on our society and that this does not mean that the resilience of the environment is put at risk.

   The fact that the adjective 'fair' appears in the above definition is not anecdotal. An energy transition to a sustainable model that does not take this key element into account will be probably failing before it begins.

   For this reason, I would like to highlight this line as a priority for further studies. More specifically, what I propose is that the integrated framework proposed be re-read from the perspective of ethical schools. Let us look at some of them:

   - Its utilitarian inspiration is clear [177];
   - so is the contractualist one coming from Rawls' theory of justice [229]).
   - and its normative contribution through the imposition of rigid limits [135].
   - However, there is still an interesting path to explore from the eudaimonic perspective [9]: Is there a concept of virtue in this approach?
   - Or also the re-reading of the framework from the point of view of the ethics of discourse and its subsequent development of deliberative democracy: To what extent, for example, do the consensuses reached by the stakeholders really represent the preferences or needs of the entire population? It would be very interesting to explore O'Hara's proposals in this regard [210].
   - Finally, another line of work to explore within this ethical scope is Sen's theory of capabilities [259] . This framework assumes that well-being drinks from different capitals, so that by generating value (capital surplus) we will be guaranteeing that well-being. Yet, might this approach be enriched if we start from Sen's definition of well-being as capability to achieve valuable functions?

   Many more lines could emerge from this ethical reflection. The above are just a few examples.

2. Weak and strong indicators

One of the first efforts made during the development of the thesis was to review the state of the art of sustainability indicators, especially those applicable to the energy sector. The author is aware that the task remains unfinished. Literature is abundant and there is much room for further study and systematization. At the same time, there is also room for further delving into the complementarities and incompatibilities between the two classic approaches to sustainability.

In relation to the specific work on the Costa del Sol, it would be interesting to propose a specific study on the impact of tourism on the sustainability of the region, based again on the two strong and weak approaches, i.e. eMergy and ISEW, respectively.

3. Frameworks

   With regard to the frameworks, I highlight the enormous gap to be explored within the field of complexity. A very concrete possible line of work would be to use Beer's VSM theory for long-term energy planning. Replicating the case study developed in this thesis by changing the multi-criteria methodology to one based on complex systems, namely VSM or SOHO, seems a very promising future line of research. However, how operational this proposal may become is something that will have to be tested.

   Additionally, the full implementation of justice/equity concerns is a pending task for future research. In this sense, a first limited exercise of this proposal was carried out within the case study by disaggregating Spanish households into two (vulnerable and non-vulnerable) and specifically addressing the energy demand of the former. Identifying other vulnerable groups and incorporating them into the analysis is a pending task. This would be a possible first exercise, but a more far-reaching one would consist of a complete revision of the very concept of equity used so that it incorporates dimensions yet to be explored.

   Besides, the sustainability analysis of the Costa del Sol in Chapter 4 could be reformulated into a multi-criteria ex-ante analysis for strategic decision-making. In this hypothetical study, the ISEW could be taken as a welfare proxy (the aggregation of capital), constituting in itself the target variable to be optimized, while different eMergetic indicators could be used to define the absolute limits that reflect the resilience or the carrying capacity of the environment. Of course, all this would work on a model of the region in which the corresponding decision variables had been defined.

4. Energy poverty

   Following on from another of the main contributions, that of energy poverty, I also find ample space for further studies. A first touchstone is found in the indicators used. As highlighted in the Chapter 6, classic indicators have problems that deserve to be solved in order to obtain more appropriate metrics. On the other hand, there is an urgent need for an approach to the issue of energy poverty that does not only start with data from a generalist survey such as the EPF or the ECV, but also takes as its starting point the specific reality of the most vulnerable households. In other words, there is a need for a bottom-up approach that complements the classical top-down approaches used to date. In addition, there is still a long way to go in the regulatory field. Within the palliative measures, such as the social tariff, there is still a need to improve the targeting of the vulnerable groups, as well as the appropriate fiscal instruments to sustain it. With regard to structural measures, there is a lack of energy efficiency policies that allow households to reduce their demand.

5. MASTER.MC

   Finally, this section presents the possible future lines related to the case study and, more specifically, to the MASTER.MC computational tool developed for it.

   - Criteria selection

     This is a very important point. Following Giampietro's distinction between analysis and assessment [99], the exercise proposed in this case study is a sustainability analysis of the Spanish energy sector where the criteria to be evaluated were substantially decided by the author although based on the literature. It would be very interesting to extend the exercise from an analysis to an assessment where the choice of criteria itself would arise from a participatory consultation process where the different stakeholders would come into play. Checkland's Soft System Methodology (SSM) [49] could help guide this process, as well as Santos' participatory methodology in the case of rural electrification [218].

   - Criteria methodologies

     Here there is much room for improvement in practically all of them. For instance, in energy poverty we could go to a much more exhaustive categorization of vulnerable households by sub-levels; in energy security we could review the surplus price assigned to energy raw materials; and in fossil-fuel dependence we could go to a calculation of eMergetic dependence.

   - LCA

     Eventually, a revision of the methodology used to calculate LCA emissions will be necessary. For the time being, the calculation of these embedded emissions has been limited to the most relevant end-use technologies (transport and main household appliances). The calculation must be therefore extended to the rest of the embedded emissions not only in the final sectors but in the whole input-output energy process.

- Final sectors

  There is also room for improvement in the so-called fifth column of the MASTER.SO model that inherits MASTER.MC. It is mainly divided into three sectors, namely, residential/services, transport and industry. As mentioned above, a series of ESSTs covering the different services are defined in each of them. The improvements in the first two sectors would be precisely to update these ESSTs to better represent possible technological improvements. With regard to industry, the way in which the model meets this demand could be reformulated, using, for example, detailed modelling of the different manufacturing processes [247, 220]. In the original design of the MASTER.SO model, other sectors such as residential or transport to industry were prioritised, considering that the margin for improvement in savings and efficiency in these sectors was greater than in the former. This being essentially true, there is no doubt that the industrial sector in Spain represents a very significant percentage of demand and, although the relative margin for improvement in efficiency may be scarce, its impact in absolute terms can be more significant. For this reason, it is proposed to include in the modeling a specific module for industry that breaks down energy consumption into the different sub-processes linked to the main industries in Spain, namely steel and cement.

- Risk management

  One of the least developed aspects in the current proposal is the temporal aspect of SD. No explicit mention of tools for intergenerational evaluation such as the discount rate[2] from a weak perspective, or the generic principle of prudence from a strong perspective are included. In order to be able to incorporate this dimension, I consider that the theory of risk management can be very useful. It is therefore indicated this possible future course of integrating these risk considerations into the MASTER.MC model. Eventually, completing the multi-criteria analysis by incorporating robustness analysis techniques, in line with what was proposed by Linares [156], would be another interesting future development with regard to risk management.

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[2] Although a WACC (9%) has already been used for investments in the MASTER.MC model.

8.3 Main publications and working papers

- Romero, J. C. and Linares, P. (2014). “Exergy as a global energy sustainability indicator. a review of the state of the art.” *Renewable and Sustainable Energy Reviews*, 33(0):427 - 442.

- Romero, J. C., Linares, P., and López, X. (2018). “The policy implications of energy poverty indicators.” *Energy Policy*, 115:98 - 108.

- Romero, J. C. and Linares, P. (2016). “Strong versus weak sustainability indexes in a conurbation context: A case example in spain.” *Working Paper. Institute for Research in Technology (IIT), Universidad Pontificia Comillas.*

- Romero, J. C. and Linares, P. (2018). “Framing energy sustainability.” *Working Paper. Institute for Research in Technology (IIT), Universidad Pontificia Comillas.*

- Romero, J. C. and Linares, P. (2018). “Illustrating the conflicts in the Spanish sustainable energy roadmap towards 2050.” *Working Paper. Institute for Research in Technology (IIT), Universidad Pontificia Comillas.*

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Appendix A

Sustainomics

This annex briefly describes Mohan Munasinghe's Sustainomics proposal. It is a possible study framework applicable to the analysis of energy sustainability. It cannot be included in the multi-criteria or systemic proposals, but it is still interesting to mention it, so it was decided to bring it to this annex.

Sustainomics is a neologism introduced by Mohan Munasinghe to describe his proposal for a framework, or rather a "trandisciplinary goal-framework that allows the knowledge contributed by different disciplines to be transformed into new methods that can capture the different facets of sustainability, from the concept to its practical realization" [187]. Sustainomics aims to provide a comprehensive and eclectic knowledge base to support different efforts in the field of sustainable development [186].

This framework, as he defines it, is based on the already mentioned division of sustainability into three poles, and can be applied to different problems, including the one we are dealing with: energy sustainability. It is a decision-making framework that integrates the different actors and criteria within a single environment.

In terms of concrete applications, it was successfully applied to improving the decision-making process in the electricity sector in Sri Lanka in 2000 [187].

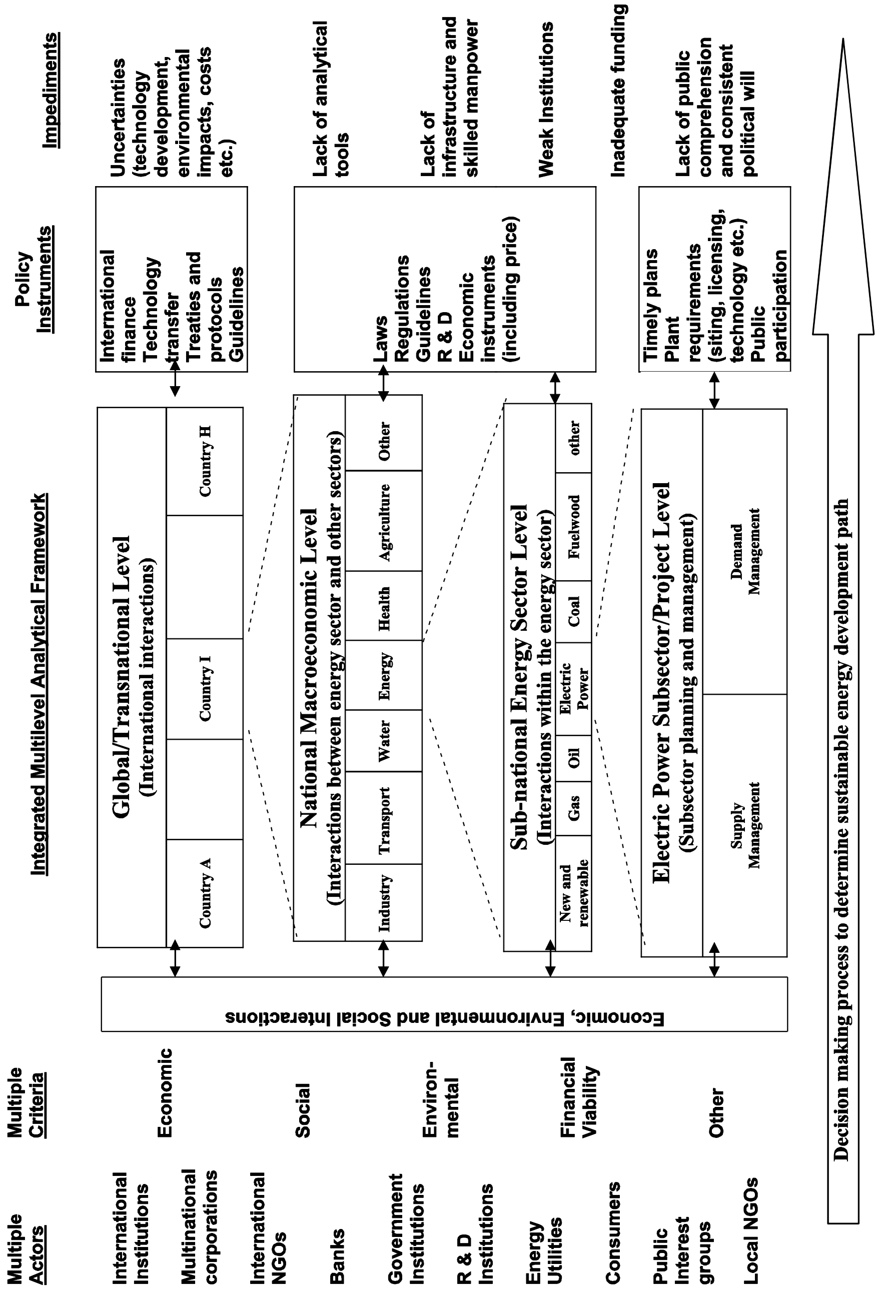

Fig. A.1 Sustainomics model. Adapted from [187]

Fig. A.1 shows an schematic representation of Munasinghe's proposal applied to energy systems. The middle column shows the core of the framework comprising an integrated multilevel analysis. At the top level, individual countries constitute elements of an international matrix. The next level focuses on the multi-sectoral national economy, of which the energy sector is one element. At the third or sub-national level, the energy sector as a separate entity composed of sub-sectors is described. Finally, the most disaggregate and lowest hierarchical level belongs to energy analysis within each of the energy sub-sectors.

In practice, the various levels of analysis merge and overlap considerably, requiring that inter-sectoral linkages are carefully analyzed.

Despite being a very interesting proposal, the Sustainomics framework has not gone far beyond the author's own works. In my opinion, this proposal, although it does not make explicit its systemic affiliation, partially draws on it, especially with regard to its interdisciplinary character and the hierarchization of the system at different nested levels.

Appendix B

Thermodynamic roots of the exergy concept

This annex delves into the thermodynamic roots of exergy. For clarity purposes, it was decided to bring this more detailed analysis into an annex rather than keeping it in the corresponding section of the state of the art. The objective of this description is none other than to continue delving into the characteristics of exergy in order to provide more knowledge that will help to understand the limitations and potentialities of exergy as a sustainability indicator described above.

Before delving into the details of thermodynamic roots of the exergy concept, it is worth mentioning the important role that *thermodynamic efficiency* plays in this debate. The total exergy value of a system is a worthless figure if not compared with other ones coming from a different system or that same system in a different situation (spatial or temporal). Efficiency will provide this information, yet obtaining that value is not trivial. The next section provides a short insight into this important issue.

B.1 Efficiency

Before presenting the different definitions of efficiency, it should be noted that efficiency improvement and sustainability are not synonymous. Improving the efficiency of thermal processes is always good news, but it does not ensure that sustainability goals are being met. Many other factors contribute to real sustainability that are not related with efficiency improvements, as has already been shown on numerous occasions in this text.

Different formulations have been proposed for thermodynamic efficiency, opening a controversial debate among authors. Nevertheless, some degree of agreement has been achieved.

According to Sciubba and Wall [258], the fruitful debate in the sixties converged to the following three definitions:

The Second Law or Exergy Efficiency:

$$\varepsilon = \frac{useful\ exergy\ output}{used\ exergy\ input} \tag{B.1}$$

The degree of reversibility:

$$\Psi = \frac{exergy\ of\ products}{\sum (used\ exergy\ input)} \tag{B.2}$$

The coefficient of exergetic destruction:

$$\xi = \frac{annihilated\ exergy}{total\ exergy\ input} = \frac{T_0 \Delta s_{irr}}{\sum (exergy\ inputs)} \tag{B.3}$$

Cornelissen [57], in his PhD thesis included a description of three different exergetic efficiencies, which are, nevertheless, formally equivalent to Wall's and Sciubba's proposals presented here.

Depending on the application under study, one or another efficiency definition will have to be used and some further derivations of them will have to be done.

B.2 Thermodynamic basis

Performing a complete derivation of exergy is out of the scope of this thesis. Nevertheless, to introduce some basic concepts is absolutely necessary. It is worth mentioning the contribution made by Gorän Wall, who started an open tutorial divulgation project called *Exergetics* [321] intended for students and researchers interested in exergy.

Besides, Dincer's contributions regarding the definition of the exergy concept from a thermodynamic point of view [69] are highly recommended because of their accuracy and rigour.

As mentioned in the introduction, although the exergy concept may go beyond its own technical definition, it was born into the Thermodynamic theory. Therefore, some basic notions must be highlighted in order to understand it properly. The First and Second Principles of thermodynamics are the milestones for any building which is to be constructed over it. Hence, a brief review of them is presented here.

First Principle of thermodynamics: The internal energy of an isolated system is constant. [181].

A state function U called *internal energy* emerges from this principle. Since energy is never destroyed, its balance will always be achieved. In a system S which is absorbing a certain amount of heat Q, is producing work W and is changing from state 1 with kinetic energy E_{c1} and potential energy[1] E_{p1} (affected by the gravitational field of the earth) to another state 2 with energies E_{c2} and E_{p2} respectively, the energy balance equation which mathematically express the First Principle would be the following:

$$Q - W = \Delta U + \Delta E_p + \Delta E_c \tag{B.4}$$

Second Principle of thermodynamics: "Heat cannot spontaneously flow from a colder location to a hotter location" (Carnot's formulation) [46]. Similarly to the first principle, in which a state function called "internal energy" was defined, this second principle suggests the need to define a second state function which condenses this experimental verification. Entropy S was the chosen one. Its main property is the next: "entropy can always be created but never destroyed". The importance of this principle is such that Gorän Wall dared to state [320] that "time and evolution are consequences of the second principle of thermodynamics".

The differential increment of entropy of a system S whose thermodynamic properties are fixed, and which is exchanging matter and energy with a defined environment, can be calculated applying the next formula:

$$dS = dS_e + dS_i \tag{B.5}$$

$$dS = \frac{\delta Q}{T} \tag{B.6}$$

$$dS_i \geq 0 \tag{B.7}$$

$$dS \geq \frac{\delta Q}{T} \tag{B.8}$$

where dS_e indicates *external entropy* and dS_i *internal entropy*.

As stated in Eq. (B.5), the balance equation of entropy cannot exclude the environment. This point is critical for this explanation, since the exergy concept will derive from it.

Reversibility and irreversibility are also crucial concepts related to this Second Principle. Reversible processes are theoretical abstractions in which there is no entropy generation dS_i

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[1] Kinetic and potential energies are usually neglected in closed systems.

at all. No pure reversible processes can be found in nature but it is a very useful concept in thermodynamics, since it establishes the maximum theoretical level of availability of energy in a system. The exergy concept will directly emerge from this abstraction.

For further developments on this topic, Szargut's description of this phenomenon [278] is highly recommended because of its clarity and accuracy.

Once the first and the second principles of thermodynamics have been introduced, another step is required to obtain useful and complete expressions of exergy.

Instead of proposing a general expression which normally implies a difficult physical interpretation, many authors divide this issue in two parts regarding the type of thermodynamic system under study, i.e closed or open. In order to be faithful to the aim of clarity, this alternative was chosen here.

B.2.1 Closed systems

A closed system can exchange heat and work but not matter with its surroundings.

The available energy of a closed system S is defined as the maximum *useful work* obtainable when the system is brought from its initial state (T, p) to a death state (T_0, p_0) by means of reversible processes.

It is important to notice that the final state here is not the *environmental state* but the *death state*. It implies that complete equilibrium (physical and chemical) has been reached. Since closed systems do not exchange matter with the surroundings, chemical exergy will be equal to free (Gibbs') enthalpy[2] and no further derivations must be done. It will not be the case in open systems as will be described in the next section.

The main formulation for this *useful work* is the following:

$$W_u = (U_1 + p_0V_1 - T_0S_1) - (U_0 + p_0V_0 - T_0S_0) \tag{B.9}$$

If the function L (exergy without flow) is defined according to the next formula:

$$L \equiv U + p_0V - T_0S \tag{B.10}$$

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[2] When a system changes from a well-defined initial state to a well-defined final state, the Gibbs' free energy equals the work exchanged by the system with its surroundings, minus the work of the pressure forces, during a reversible transformation of the system from the same initial state to the same final state: $G = U + p_oV - T_0S$.

equation (B.9) can be reformulated like this:

$$A = L - L_0 \tag{B.11}$$

where A is the *available energy* or *exergy* in a closed system.

Alternatively, the expression for the differential change in available energy in closed systems would be:

$$dA = \left(1 - \frac{T_0}{T}\right)\delta Q - \delta W_u - T_0 dS_i \tag{B.12}$$

which is very useful in thermal optimization applications.

Hence, in reversible processes where no entropy is generated (or available energy destroyed):

$$dA_{max} = \left(1 - \frac{T_0}{T}\right)\delta Q - \delta W_u \tag{B.13}$$

and

$$dA_d = -T_0 \cdot dS_i \leq 0 \tag{B.14}$$

This is Gouy-Stodola's theorem for a closed system: "In a closed system, the available energy destroyed when the system is brought from its initial state to the state of equilibrium is equal to the temperature of the environment times the entropy generated" [272].

B.2.2 Open systems

An open system in steady state can exchange heat, work and matter with its surroundings.

In open systems in steady state a certain amount of matter crosses the boundaries of a system S, absorbs a specific heat (per unit of mass) q and performs a specific useful work w_u. Total specific work w will be obtained adding to the balance the *work of flow* due to the displacement of the control surface A from A_1 to A_2.

$$w = w_u + p_2 v_2 - p_1 v_1 \tag{B.15}$$

The change of total specific energy in the system would be:

$$\begin{aligned} q = \left(u_2 + \frac{1}{2}c_2^2 + g z_2\right) - \left(u_1 + \frac{1}{2}c_1^2 + g z_1\right) + \\ +(w_u + p_2 v_2 - p_1 v_1) \end{aligned} \tag{B.16}$$

hence

$$q - w_u = h_2 - h_1 + e_{c2} - e_{c1} + e_{p2} - e_{p1} \tag{B.17}$$

where h, e_c and e_p represent the specific enthalpy, kinetic energy and potential energy, respectively. Enthalpy is a crucial thermodynamic state variable. It includes the internal energy of the system and the work of flow in an specific control volume. Therefore, Eq. (B.17) represents the First Principle for an open system in steady state.

The next step consists of deducing the equation for exergy from previous results. As stated before, exergy will be the maximum useful work obtainable when an open system S is brought from its initial state to a final state of equilibrium[3]. In open systems, distinguishing between environmental and death state is relevant. In this section I will assume that the final state is the environmental one. Hence, only physical exergy is calculated here.

$$b \equiv W_{u,max} = h - h_0 + q_{rev} \tag{B.18}$$

where q_{rev}, if the reversible process is operated in two steps, i.e. adiabatic and isothermal, is equal to:

$$q_{rev} = T_0(s_0 - s) \tag{B.19}$$

Hence, the final expression for b is:

$$b = (h - T_0 s) - (h_0 - T_0 s_0) \tag{B.20}$$

Besides, the expression for the differential increment of exergy in an open system derived from the first and the second principle and the previous results, take the next form:

$$db = \left(1 - \frac{T_0}{T}\right) \delta q - \delta w_u - T_0 ds_i \tag{B.21}$$

A new expression of the Gouy-Stodola's theorem has been obtained here:

$$db_d = T_0 ds_i \tag{B.22}$$

where db_d is the differential exergy destruction in the open system described above.

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[3] Kinetic and potential energy will not be taken into account. In most applications their relative importance regarding the internal exergy is despicable.

So far, equations for exergy in closed and open systems have been obtained. Yet, taking a closer look at these equations, the existence of different contributions to the total exergy of a system is revealed. Dealing separately with these contributions can be very useful in order to achieve a better understanding of the exergy concept. The next section develops this topic.

B.2.3 Components of total exergy

According to Szargut [278] and Bejan[4] [18], the exergy of a defined system can be divided into the following elements:

$$B = B_k + B_p + B_{ph} + B_{ch} \tag{B.23}$$

where B_k expresses Kinetic Exergy, B_p Potential Exergy, B_{ph} Physical Exergy and B_{ch} Chemical Exergy, respectively.

Some authors include two more components to exergy: electro-magnetic exergy and nuclear exergy. Hermann's contribution to this topic is relevant [122]. Nevertheless, a high degree of uncertainty is present in their derivation. Moreover, both components are usually neglected in thermal applications. Therefore, they will not be included in the present derivation.

Additionally, in most exergy formulations, kinetic exergy (equal to the kinetic energy when the velocity is considered relative to the surface of the earth) and potential exergy (equal to the potential energy when it is evaluated with respect to the average level of the surface of the earth) are normally neglected, for average values for environmental condition are assumed.

This way, only chemical and physical exergies are always relevant and their sum is usually called *thermal exergy*[5] B_{th}:

$$B_{th} = B_{ph} + B_{ch} \tag{B.24}$$

I will now describe more in detail these two components to understand them better.

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[4] Both authors divide exergy into the same elements, but the notation is different. Szargut uses B for exergy, whereas Bejan uses E. Since E is normally used for Energy, in order not to mislead the readers, Szargut's notation was chosen.

[5] Different suggestions have been done for this separation among partial contributions to the total exergy of a system. Recently, a very interesting proposal by Simpson [263] suggests a distinction between *internal* and *external* exergy, as well as a detailed derivation of the physical and the chemical exergy.

Many different derivations of exergy can be found in the technical literature. Unfortunately many of them present a problematic lack of clarity in the derivation process, which is added to the inherent complexity of thermodynamics.

Montes' et al. contribution [179] was the one chosen because of its simplicity.

Physical Exergy. *Physical Exergy* (B_{ph}) is the work obtainable by taking the system through a reversible physical processes from its initial state temperature T and pressure p, to the state determined by the temperature T_0 and the pressure p_0 of the environment.

Some important cases will be analyzed: *incompressible substances*, *ideal gases* and *ideal mixtures*.

For *incompressible substances* (liquids and solids), the difference of enthalpies is equal to:

$$\tilde{h} - \tilde{h}_0 = \int_{T_0}^{T} C_p(T)dT + \tilde{v}(p - p_0) \tag{B.25}$$

hence, applying this result to Eq. B.20, the expression for total molar exergy $\tilde{b}_f$ is:

$$\tilde{b}_f = \int_{T^0}^{T} C_p(T)\left[1 - \frac{T^0}{T}\right] dT + \tilde{v}(p - p_0) \tag{B.26}$$

For *ideal gases*, the derivation is similar to the previous one. The value of $\tilde{b}_f$ is:

$$\tilde{b}_f = \int_{T^0}^{T} C_p(T)\left[1 - \frac{T^0}{T}\right] dT + RT^0 \ln \frac{p}{p^0} \tag{B.27}$$

For *ideal gases mixtures*[6], calculating the increment of entropy when separated gases are brought to the final mixture represents a very interesting study.

If S_m is the final entropy of the mixture in the state (T, p) and S_i is the entropy of each gas (T, p_i) before the mixture is obtained, we obtain the following expression:

$$S_m(T, p) = \sum_{1}^{n} n_i S_i(T, p_i) \tag{B.29}$$

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[6] A mixture of gases or a solution is ideal when the following linear expression can be adopted for the chemical potential of each substance:

$$\mu_i = \mu_i^o + RT^o \ln x_i \tag{B.28}$$

where μ_i^o is the chemical potential of the substance i at the temperature T^o and pressure p^o of the mixture.

If all the gases in the mixture are ideal gases, the differential increment of entropy of each gas would be:

$$dS_i = S_i(T, p_i) - S_i(T, p) = -R \ln \frac{p_i}{p} \tag{B.30}$$

and adding all the contribution of the different gases, the total differential increment of entropy in the mixture would be[7]:

$$dS = -R \sum_1^n n_i \ln x_i \tag{B.31}$$

where x_i represents the molar fraction of gas i in the mixture. Hence, the final equation for molar exergy would be:

$$\tilde{b}_{mixture} = \sum_1^n x_i \tilde{b}_i^o + RT^o \sum_1^n x_i \ln x_i \tag{B.33}$$

where $\tilde{b}_i^o$ is the molar exergy of gas i at T^o and p^o, that is, the temperature and pressure of the final mixture. The first addend on the right side of the equation represents the contribution of each gas separately, and the second addend incorporates the effect of mixing and bringing them to the temperature T^o and partial pressure x_i of the final state.

Chemical Exergy. The chemical exergy of a mixture of substances is the maximum useful work obtainable when it is brought from the environmental state (T_o, p_o, μ_o) to the death state (T_o, p_{oo}, μ_{oo}) by means of reversible processes[8].

Chemical exergy can also be defined as the minimum useful work needed to synthesize a compound and to bring it to the environmental state from the elements present in that same environment [310]. This second definition is very interesting from the point of view of thermal optimization.

An extensive literature can be found regarding chemical exergy: [104, 292, 169, 165]. However, since Szargut's [278] contribution has become the most accepted one, it was the one I chose for the present development.

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[7] Dalton's law has been applied here:

$$\frac{p_i}{p} = \frac{n_i}{\sum n_i} = \frac{n_i}{n} = x_i \tag{B.32}$$

[8] This process can be modeled by means of semi-permeable membranes. Szargut's model [278] has been profusely used, yet it has been widely criticized as well [96].

In the death state, the following expression is verified:

$$\sum p_{ooi} = p_o \tag{B.34}$$

and

$$W_{u,r} = -\Delta G = \sum_i n_i \mu_{oi} - \sum_i n_i \mu_{ooi} = \sum_i n_i(\mu_{oi} - \mu_{ooi}) \tag{B.35}$$

where μ_{ooi} are the *Standard Chemical Potentials* of each substance involved. As Baierlein brilliantly stated [14], comprehending the notion of Chemical Potential is not an easy task. Similarly to other physical potentials, it represents a capacity to produce work inherent to a system, whose origin is not clearly known. In his paper, he offers three interesting characterizations of this elusive concept.

Moreover, previous results are only valid when all the constituents of the reaction are present in the Reference Environment (RE). If that is not the case, a further development must be done. Let us consider the next reference reaction for a compound X which does not belong to the RE:

$$X + \sum_j n_j C_j = \sum_k n_k C_k \tag{B.36}$$

where C_j and C_k are co-reactives and products of the chemical reaction which are present in the RE.

The useful work obtainable in the previous reversible reaction at temperature T_o and pressure p_o of the environment is:

$$\tilde{w}_{u,r} = -\Delta \tilde{g}_o \tag{B.37}$$

Next, it is necessary to add to Eq. (B.37) the work produced and consumed by the products and reactives (effluents and influents) of the reaction, respectively.

$$\tilde{w}_{products} = \sum_k n_k(\mu_{ok} - \mu_{ook}) = \sum_k n_k \tilde{b}_{ok} \tag{B.38}$$

$$\tilde{w}_{reactives} = -\sum_j n_j(\mu_{oj} - \mu_{ooj}) = -\sum_j n_j \tilde{b}_{oj} \tag{B.39}$$

Hence, the exergy of the reaction of a compound X which is not present in the RE would be the following:

$$\tilde{b}_o(X) = -\Delta \tilde{g}_o - \sum_j n_j \tilde{b}_{oj} + \sum_k n_k \tilde{b}_{ok} \tag{B.40}$$

In case X belongs to the RE, taking Eq. (B.36) into account is not necessary, therefore, applying Eq. (B.35) to a single species it would be obtained the expression for molar exergy of that specie X:

$$\tilde{b}_o(X) = \mu_o(X) - \mu_{oo}(X) \tag{B.41}$$

Although previous equations provide the theoretical framework for the calculation of chemical exergy of any mixture or single species, usually *standard exergy values* for common substances are used. These values have been profusely calculated and tabulated [181, 278, 7, 303].

Since these standard chemical exergies are so widely used, some notes following Szargut and Morris [275, 277, 185, 276] will be added regarding this important and practical issue.

Standard Chemical Exergy is related to the substance in the standard state at normal temperature and pressure ($T_n = 298.15K$, $p_n = 101.325kPa$), with the assumption that the conventional mean concentrations[9] or partial pressures species in the environment have been taken into account.

Szargut's model for calculating this Standard Chemical Exergy is clearly highlighted in Section 2.3.2 of [278].

According to Szargut, the calculation of the Standard Chemical Exergy for every substance is usually inconvenient. It is sufficient to calculate it for some pure chemical elements having simple reference reactions. From these values, the following equation can be used for other chemical elements and for chemical compounds. Hence:

$$b^o_{ch} = \Delta_f G^o + \sum_{el} n_{el} b^o_{ch,el} \tag{B.42}$$

where $\Delta_f G^o$ is the standard normal free exergy of formation; n_{el} is the number of moles in the compound under consideration and $b^o_{ch,el}$ the standard chemical exergy of each element.

This equation is formally equivalent to Eq. (B.36) and can be used in an inverse mode to calculate the free normal exergy of a reversible reaction:

$$\Delta_f G^o = \sum_k n_k b^o_{ch,k} - \sum_i n_i b^o_{ch,i} \tag{B.43}$$

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[9] These values are widely tabulated in the bibliography, i.e. [181].

The contribution of the Exercoecology group to these calculations is noteworthy. They developed an on-line Exergy Calculator which is able to calculate standard chemical exergies of a vast database of compounds based on their reference species [83].

Finally, after revising an extensive literature regarding chemical exergy, it is fair to say that some difficulties and inconsistencies have been found. Most of these problems are related to the different REs used. Undoubtedly, this is a critical point that needs further attention.

Reference Environment. In previous sections, the calculation methods for physical and chemical exergies of closed and open systems have been introduced.

As was mentioned above, talking about exergy implies defining a system under study and the Reference Environment (RE) where that systems belongs and shares energy and/or matter with. If physical exergy is the only component of total exergy of interest, defining this RE is not very problematic, since just temperature and pressure (static or dynamically) must be fixed. Yet, when chemical exergy is relevant (for instance, when combustion processes of fuels are involved, what is quite common in thermal optimization applications), reference species and their concentrations must be fixed as well, and that is not a trivial task at all.

As stated by Valero and Szargut [279], contributions to the determination of REs could be divided into two main groups: *partial* and *comprehensive* approaches.

Some authors such as Bosnjakovitz [26] and Gaggioli [93] established that the RE should be defined according to the specific characteristics of the process analyzed (*partial approach*). This criterion is based on the fact that some ‘a priori’ possible evolutions of the system cannot be attained because of process limitations. Hence, only possibilities of evolution that the system can practically attain are to be analyzed. According to them, “the RE is not a “dead state” anymore but a reference state directly related to the process under study. Therefore, there is no need for a comprehensive RE”.

However, if the proposal of the research is not only to improve the efficiency of certain industrial process but to deal with global aims, i.e. studying climate change or determining the natural capital of earth, no ‘a priori’ process limitations can be set, for the resources can follow an uncertain evolution process toward the dead state. In this case, defining a *comprehensive* RE is required.

Among all the different comprehensive approaches to REs some differences may be found. Valero groups them in three sets: *death state’s criterion* (Szargut [277]), *chemical equilibrium* (Ahrendts [7]) and *abundance* (Ranz [227]). Although each approach presents advantages and disadvantages, Szargut’s proposal is the most extended. It is based upon the following principle: “among a group of reasonable abundant substances, the most stable will be chosen if it also complies with the *Earth similarity criterion*” [279].

It is worth mentioning that Gaudreau, in his PhD dissertation [95], made a thorough review of the literature regarding REs. In fact, his criticism toward exergy as a global sustainability indicator comes from the apparent lack of accuracy of these RE definitions. In Section 3.2.4.4 this issue was addressed in depth.

Appendix C

eMergy Tables. Costa del Sol. 2001-2015

This annex presents the tables obtained in the different eMergetic calculations applied to the Costa del Sol in the years 2001, 2004, 2007, 2010, 2012 and 2015. There are three types of tables. Firstly, the eMergy inputs, which contain the natural eMergy flows to the system (taking as reference those of the year 2007). Secondly, imports, which collect the eMergy flows that enter the systems from international trade for all years. Finally, exports, similar to the previous ones but in the opposite direction.

Table C.1 eMergy flows. Costa del Sol

No	Input	Unit	Amount	Ref. Amount	Transformity (sej/unit)	Ref. Transformity	eMergy
	Renewable inputs (R)						
1	Sunlight	J/yr	7.88E+16	[6]	1.00E+00	[204]	7.57E+16
2	Rain (chemical potential)	J/yr	2.65E+15		3.06E+04	[204]	7.77E+19
3	Rain (geopotential)	J/yr	1.64E+15	[6]	1.76E+04	[204]	2.77E+19
4	Wind kinetic energy	J/yr	2.25E+16	[6]	2.52E+04	[204]	5.45E+20
5	Waves	J/yr	3.19E+16	[6]	5.14E+04	[204]	**1.57E+21**
6	Tides	J/yr	1.64E+10	[6]	7.39E+04	[204]	1.16E+15
7	Earth cycle	J/yr	1.70E+15	[159]	1.20E+04	[204]	1.96E+19
	Indigenous non-renewable inputs (N0)						
8	Net topsoil loss	J/yr	5.36E+12	[130]	1.05E+05	[204]	5.40E+17
	Indigenous non-renewable inputs (N1)						
9	Limestone	g/yr	0.00E+00	[131]	9.50E+09	[204]	0.00E+00

Table C.2 eMergy imports. Costa del Sol. 2001

No	Input	Unit	Amount	Ref. Amount	Transformity (sej/unit)	Ref. Transformity	eMergy
10	Oil and petroleum derived products	J/yr	4.00E+16	[131]	9.06E+04	[204]	3.48E+21
11	Coal	J/yr	7.20E+12	[131]	6.71E+04	[204]	4.64E+17
12	Natural gas	J/yr	1.98E+15	[131]	8.05E+04	[204]	1.53E+20
13	Electricity	J/yr	1.23E+16	[131]	3.36E+04	[204]	3.96E+20
14	Livestocks and products	J/yr	4.13E+13	[5]	5.33E+06	[204]	2.11E+20
15	Agriculture and forest products	J/yr	5.91E+14	[5]	1.75E+05	[204]	9.93E+19
16	Food industry products	g/yr	5.42E+10	[5]	3.36E+04	[204]	1.75E+15
17	Plastics	g/yr	1.21E+10	[5]	3.20E+09	[204]	3.71E+19
18	Minerals	g/yr	4.28E+11	[5]	1.68E+09	[204]	6.90E+20
19	Steel and pig iron	g/yr	5.03E+09	[5]	3.69E+09	[204]	1.78E+19
20	Mechanical and transport equipment	g/yr	1.36E+10	[5]	1.13E+10	[204]	1.48E+20
21	Leather and products	J/yr	2.81E+13	[5]	1.44E+07	[204]	3.89E+20
22	Textils	J/yr	1.30E+14	[5]	6.38E+06	[204]	7.99E+20
23	Wood and products	J/yr	2.77E+14	[5]	5.86E+04	[204]	1.56E+19
24	Paper	g/yr	6.26E+09	[5]	6.55E+09	[204]	3.94E+19
25	Chemicals	g/yr	2.27E+09	[5]	6.38E+08	[204]	1.39E+18
26	Rubber	g/yr	6.59E+08	[5]	7.22E+09	[204]	4.57E+18
27	Total Services	$/yr	7.84E+08	[16]	1.85E+12	[37]	1.39E+21
28	Total Tourism	$/yr	1.69E+08	[16]	1.85E+12	[37]	3.01E+20

Table C.3 eMergy imports. Costa del Sol. 2004

No	**Input**	**Unit**	**Amount**	**Ref. Amount**	**Transformity (sej/unit)**	**Ref. Transformity**	**eMergy**
10	Oil and petroleum derived products	J/yr	5.02E+16	[131]	9.06E+04	[204]	4.37E+21
11	Coal	J/yr	9.04E+12	[131]	6.71E+04	[204]	5.82E+17
12	Natural gas	J/yr	2.49E+15	[131]	8.05E+04	[204]	1.93E+20
13	Electricity	J/yr	1.54E+16	[131]	3.36E+04	[204]	4.98E+20
14	Livestocks and products	J/yr	5.58E+13	[5]	5.33E+06	[204]	2.86E+20
15	Agriculture and forest products	J/yr	4.76E+14	[5]	1.75E+05	[204]	8.00E+19
16	Food industry products	g/yr	1.45E+11	[5]	3.36E+04	[204]	4.67E+15
17	Plastics	g/yr	1.93E+10	[5]	3.20E+09	[204]	5.93E+19
18	Minerals	g/yr	6.16E+11	[5]	1.68E+09	[204]	9.94E+20
19	Steel and pig iron	g/yr	1.09E+10	[5]	3.69E+09	[204]	3.88E+19
20	Mechanical and transport equipment	g/yr	2.12E+10	[5]	1.13E+10	[204]	2.31E+20
21	Leather and products	J/yr	3.15E+13	[5]	1.44E+07	[204]	4.36E+20
22	Textils	J/yr	2.46E+14	[5]	6.38E+06	[204]	1.51E+21
23	Wood and products	J/yr	3.96E+14	[5]	5.86E+04	[204]	2.23E+19
24	Paper	g/yr	5.38E+09	[5]	6.55E+09	[204]	3.38E+19
25	Chemicals	g/yr	3.21E+09	[5]	6.38E+08	[204]	1.97E+18
26	Rubber	g/yr	1.06E+09	[5]	7.22E+09	[204]	7.33E+18
27	Total Services	$/yr	9.36E+08	[16]	1.85E+12	[37]	1.66E+21
28	Total Tourism	$/yr	2.42E+08	[16]	1.85E+12	[37]	4.29E+20

Table C.4 eMergy imports. Costa del Sol. 2007

No	Input	Unit	Amount	Ref. Amount	Transformity (sej/unit)	Ref. Transformity	eMergy
10	Oil and petroleum derived products	J/yr	4.14E+16	[131]	9.06E+04	[204]	3.60E+21
11	Coal	J/yr	0.00E+00	[131]	6.71E+04	[204]	0.00E+00
12	Natural gas	J/yr	3.61E+15	[131]	8.05E+04	[204]	2.79E+20
13	Electricity	J/yr	1.71E+16	[131]	3.36E+04	[204]	5.51E+20
14	Livestocks and products	J/yr	1.53E+14	[5]	5.33E+06	[204]	7.85E+20
15	Agriculture and forest products	J/yr	1.05E+15	[5]	1.75E+05	[204]	1.76E+20
16	Food industry products	g/yr	1.45E+11	[5]	3.36E+04	[204]	4.67E+15
17	Plastics	g/yr	1.98E+10	[5]	3.20E+09	[204]	6.10E+19
18	Minerals	g/yr	4.91E+10	[5]	1.68E+09	[204]	7.92E+19
19	Steel and pig iron	g/yr	2.97E+09	[5]	3.69E+09	[204]	1.05E+19
20	Mechanical and transport equipment	g/yr	2.03E+10	[5]	1.13E+10	[204]	2.20E+20
21	Leather and products	J/yr	3.94E+13	[5]	1.44E+07	[204]	5.45E+20
22	Textils	J/yr	3.39E+14	[5]	6.38E+06	[204]	2.08E+21
23	Wood and products	J/yr	3.16E+14	[5]	5.86E+04	[204]	1.78E+19
24	Paper	g/yr	1.08E+10	[5]	6.55E+09	[204]	6.78E+19
25	Chemicals	g/yr	5.13E+09	[5]	6.38E+08	[204]	3.15E+18
26	Rubber	g/yr	1.40E+09	[5]	7.22E+09	[204]	9.69E+18
27	Total Services	$/yr	2.11E+09	[16]	1.85E+12	[37]	3.74E+21
28	Total Tourism	$/yr	4.39E+08	[16]	1.85E+12	[37]	7.80E+20

Table C.5 eMergy imports. Costa del Sol. 2010

No	Input	Unit	Amount	Ref. Amount	Transformity (sej/unit)	Ref. Transformity	eMergy
10	Oil and petroleum derived products	J/yr	4.61E+16	[131]	9.06E+04	[204]	4.01E+21
11	Coal	J/yr	0.00E+00	[131]	6.71E+04	[204]	0.00E+00
12	Natural gas	J/yr	2.82E+15	[131]	8.05E+04	[204]	2.18E+20
13	Electricity	J/yr	1.81E+16	[131]	3.36E+04	[204]	5.86E+20
14	Livestocks and products	J/yr	8.13E+13	[5]	5.33E+06	[204]	4.16E+20
15	Agriculture and forest products	J/yr	7.55E+14	[5]	1.75E+05	[204]	1.27E+20
16	Food industry products	g/yr	1.68E+11	[5]	3.36E+04	[204]	5.43E+15
17	Plastics	g/yr	1.33E+10	[5]	3.20E+09	[204]	4.09E+19
18	Minerals	g/yr	1.52E+11	[5]	1.68E+09	[204]	2.45E+20
19	Steel and pig iron	g/yr	5.86E+09	[5]	3.69E+09	[204]	2.08E+19
20	Mechanical and transport equipment	g/yr	1.91E+10	[5]	1.13E+10	[204]	2.08E+20
21	Leather and products	J/yr	3.21E+13	[5]	1.44E+07	[204]	4.44E+20
22	Textils	J/yr	3.06E+14	[5]	6.38E+06	[204]	1.87E+21
23	Wood and products	J/yr	6.16E+14	[5]	5.86E+04	[204]	3.46E+19
24	Paper	g/yr	8.59E+09	[5]	6.55E+09	[204]	5.40E+19
25	Chemicals	g/yr	1.04E+10	[5]	6.38E+08	[204]	6.36E+18
26	Rubber	g/yr	7.18E+08	[5]	7.22E+09	[204]	4.97E+18
27	Total Services	$/yr	1.43E+09	[16]	1.85E+12	[37]	2.55E+21
28	Total Tourism	$/yr	3.38E+08	[16]	1.85E+12	[37]	6.01E+20

Table C.6 eMergy imports. Costa del Sol. 2012

No	Input	Unit	Amount	Ref. Amount	Transformity (sej/unit)	Ref. Transformity	eMergy
10	Oil and petroleum derived products	J/yr	4.01E+16	[131]	9.06E+04	[204]	3.49E+21
11	Coal	J/yr	0.00E+00	[131]	6.71E+04	[204]	0.00E+00
12	Natural gas	J/yr	3.15E+15	[131]	8.05E+04	[204]	2.44E+20
13	Electricity	J/yr	1.68E+16	[131]	3.36E+04	[204]	5.40E+20
14	Livestocks and products	J/yr	1.26E+14	[5]	5.33E+06	[204]	6.45E+20
15	Agriculture and forest products	J/yr	4.35E+14	[5]	1.75E+05	[204]	7.31E+19
16	Food industry products	g/yr	8.77E+10	[5]	3.36E+04	[204]	2.83E+15
17	Plastics	g/yr	9.69E+09	[5]	3.20E+09	[204]	2.98E+19
18	Minerals	g/yr	4.99E+10	[5]	1.68E+09	[204]	8.05E+19
19	Steel and pig iron	g/yr	2.47E+09	[5]	3.69E+09	[204]	8.76E+18
20	Mechanical and transport equipment	g/yr	1.18E+10	[5]	1.13E+10	[204]	1.29E+20
21	Leather and products	J/yr	2.18E+13	[5]	1.44E+07	[204]	3.02E+20
22	Textils	J/yr	2.41E+14	[5]	6.38E+06	[204]	1.48E+21
23	Wood and products	J/yr	2.83E+14	[5]	5.86E+04	[204]	1.59E+19
24	Paper	g/yr	7.27E+09	[5]	6.55E+09	[204]	4.57E+19
25	Chemicals	g/yr	1.03E+10	[5]	6.38E+08	[204]	6.28E+18
26	Rubber	g/yr	3.66E+08	[5]	7.22E+09	[204]	2.54E+18
27	Total Services	$/yr	1.59E+09	[16]	1.85E+12	[37]	2.82E+21
28	Total Tourism	$/yr	3.25E+08	[16]	1.85E+12	[37]	5.78E+20

Table C.7 eMergy imports. Costa del Sol. 2015

No	**Input**	**Unit**	**Amount**	**Ref. Amount**	**Transformity (sej/unit)**	**Ref. Transformity**	**eMergy**
10	Oil and petroleum derived products	J/yr	4.14E+16	[131]	9.06E+04	[204]	3.60E+21
11	Coal	J/yr	0.00E+00	[131]	6.71E+04	[204]	0.00E+00
12	Natural gas	J/yr	3.61E+15	[131]	8.05E+04	[204]	2.79E+20
13	Electricity	J/yr	1.71E+16	[131]	3.36E+04	[204]	5.51E+20
14	Livestocks and products	J/yr	1.53E+14	[5]	5.33E+06	[204]	7.85E+20
15	Agriculture and forest products	J/yr	1.05E+15	[5]	1.75E+05	[204]	1.76E+20
16	Food industry products	g/yr	1.45E+11	[5]	3.36E+04	[204]	4.67E+15
17	Plastics	g/yr	1.98E+10	[5]	3.20E+09	[204]	6.10E+19
18	Minerals	g/yr	4.91E+10	[5]	1.68E+09	[204]	7.92E+19
19	Steel and pig iron	g/yr	2.97E+09	[5]	3.69E+09	[204]	1.05E+19
20	Mechanical and transport equipment	g/yr	2.03E+10	[5]	1.13E+10	[204]	2.20E+20
21	Leather and products	J/yr	3.94E+13	[5]	1.44E+07	[204]	5.45E+20
22	Textils	J/yr	3.39E+14	[5]	6.38E+06	[204]	2.08E+21
23	Wood and products	J/yr	3.16E+14	[5]	5.86E+04	[204]	1.78E+19
24	Paper	g/yr	1.08E+10	[5]	6.55E+09	[204]	6.78E+19
25	Chemicals	g/yr	5.13E+09	[5]	6.38E+08	[204]	3.15E+18
26	Rubber	g/yr	1.40E+09	[5]	7.22E+09	[204]	9.69E+18
27	Total Services	$/yr	2.11E+09	[16]	1.85E+12	[37]	3.74E+21
28	Total Tourism	$/yr	4.39E+08	[16]	1.85E+12	[37]	7.80E+20

Table C.8 eMergy exports. Costa del Sol. 2001

No	Input	Unit	Amount	Ref. Amount	Transformity (sej/unit)	Ref. Transformity	eMergy
29	Livestock and products	J/yr	1.26E+14	[5]	5.33E+06	[204]	6.43E+20
30	Agriculture and forest products	g/yr	4.09E+14	[5]	1.75E+05	[204]	6.87E+19
31	Food industry products	g/yr	3.77E+10	[5]	3.36E+04	[204]	1.22E+15
32	Plastics	g/yr	3.29E+08	[5]	3.20E+09	[204]	1.01E+18
33	Minerals	g/yr	2.30E+11	[5]	1.68E+09	[204]	3.70E+20
34	Steel and pig iron	g/yr	6.46E+07	[5]	3.69E+09	[204]	2.29E+17
35	Mechanical and transport equipment	g/yr	1.15E+10	[5]	1.13E+10	[204]	1.25E+20
36	Leather and products	J/yr	6.79E+12	[5]	1.44E+07	[204]	9.39E+19
37	Textils	J/yr	5.20E+13	[5]	6.38E+06	[204]	3.18E+20
38	Wood and products	J/yr	2.36E+13	[5]	5.86E+04	[204]	1.33E+18
39	Paper	g/yr	7.90E+08	[5]	6.55E+09	[204]	4.97E+18
40	Chemicals	g/yr	7.75E+09	[5]	6.38E+08	[204]	4.75E+18
41	Rubber	g/yr	3.03E+08	[5]	7.22E+09	[204]	2.10E+18
42	Total Services	$/yr	7.37E+08	[16]	3.09E+12	[37]	2.19E+21
43	Total Tourism	$/yr	6.70E+08	[16]	3.09E+12	[37]	1.99E+21

Table C.9 eMergy exports. Costa del Sol. 2004

No	Input	Unit	Amount	Ref. Amount	Transformity (sej/unit)	Ref. Transformity	eMergy
29	Livestock and products	J/yr	1.68E+14	[5]	5.33E+06	[204]	8.62E+20
30	Agriculture and forest products	g/yr	1.15E+15	[5]	1.75E+05	[204]	1.94E+20
31	Food industry products	g/yr	7.79E+10	[5]	3.36E+04	[204]	2.51E+15
32	Plastics	g/yr	1.38E+09	[5]	3.20E+09	[204]	4.24E+18
33	Minerals	g/yr	2.38E+11	[5]	1.68E+09	[204]	3.84E+20
34	Steel and pig iron	g/yr	2.15E+08	[5]	3.69E+09	[204]	7.62E+17
35	Mechanical and transport equipment	g/yr	1.24E+10	[5]	1.13E+10	[204]	1.35E+20
36	Leather and products	J/yr	3.77E+12	[5]	1.44E+07	[204]	5.21E+19
37	Textils	J/yr	6.94E+13	[5]	6.38E+06	[204]	4.25E+20
38	Wood and products	J/yr	1.46E+13	[5]	5.86E+04	[204]	8.24E+17
39	Paper	g/yr	3.38E+08	[5]	6.55E+09	[204]	2.13E+18
40	Chemicals	g/yr	5.13E+09	[5]	6.38E+08	[204]	3.14E+18
41	Rubber	g/yr	9.60E+08	[5]	7.22E+09	[204]	6.65E+18
42	Total Services	$/yr	8.16E+08	[16]	3.09E+12	[37]	2.42E+21
43	Total Tourism	$/yr	1.20E+09	[16]	3.09E+12	[37]	3.55E+21

Table C.10 eMergy exports. Costa del Sol. 2007

No	Input	Unit	Amount	Ref. Amount	Transformity (sej/unit)	Ref. Transformity	eMergy
29	Livestock and products	J/yr	3.34E+14	[5]	5.33E+06	[204]	1.71E+21
30	Agriculture and forest products	g/yr	5.79E+14	[5]	1.75E+05	[204]	9.72E+19
31	Food industry products	g/yr	1.01E+11	[5]	3.36E+04	[204]	3.27E+15
32	Plastics	g/yr	4.43E+09	[5]	3.20E+09	[204]	1.36E+19
33	Minerals	g/yr	1.03E+12	[5]	1.68E+09	[204]	1.66E+21
34	Steel and pig iron	g/yr	4.11E+08	[5]	3.69E+09	[204]	1.46E+18
35	Mechanical and transport equipment	g/yr	1.44E+10	[5]	1.13E+10	[204]	1.56E+20
36	Leather and products	J/yr	1.89E+12	[5]	1.44E+07	[204]	2.61E+19
37	Textils	J/yr	9.44E+13	[5]	6.38E+06	[204]	5.78E+20
38	Wood and products	J/yr	8.80E+13	[5]	5.86E+04	[204]	4.95E+18
39	Paper	g/yr	2.72E+09	[5]	6.55E+09	[204]	1.71E+19
40	Chemicals	g/yr	2.30E+10	[5]	6.38E+08	[204]	1.41E+19
41	Rubber	g/yr	4.66E+08	[5]	7.22E+09	[204]	3.23E+18
42	Total Services	$/yr	1.81E+09	[16]	3.09E+12	[37]	5.36E+21
43	Total Tourism	$/yr	1.64E+09	[16]	3.09E+12	[37]	4.87E+21

Table C.11 eMergy exports. Costa del Sol. 2010

No	Input	Unit	Amount	Ref. Amount	Transformity (sej/unit)	Ref. Transformity	eMergy
29	Livestock and products	J/yr	2.15E+14	[5]	5.33E+06	[204]	1.10E+21
30	Agriculture and forest products	g/yr	3.42E+14	[5]	1.75E+05	[204]	5.75E+19
31	Food industry products	g/yr	8.66E+10	[5]	3.36E+04	[204]	2.79E+15
32	Plastics	g/yr	3.75E+09	[5]	3.20E+09	[204]	1.15E+19
33	Minerals	g/yr	2.79E+11	[5]	1.68E+09	[204]	4.50E+20
34	Steel and pig iron	g/yr	5.78E+08	[5]	3.69E+09	[204]	2.05E+18
35	Mechanical and transport equipment	g/yr	2.29E+10	[5]	1.13E+10	[204]	2.48E+20
36	Leather and products	J/yr	2.80E+12	[5]	1.44E+07	[204]	3.87E+19
37	Textils	J/yr	4.32E+13	[5]	6.38E+06	[204]	2.64E+20
38	Wood and products	J/yr	4.02E+13	[5]	5.86E+04	[204]	2.26E+18
39	Paper	g/yr	1.58E+09	[5]	6.55E+09	[204]	9.96E+18
40	Chemicals	g/yr	6.56E+09	[5]	6.38E+08	[204]	4.02E+18
41	Rubber	g/yr	3.13E+08	[5]	7.22E+09	[204]	2.17E+18
42	Total Services	$/yr	1.45E+09	[16]	3.09E+12	[37]	4.30E+21
43	Total Tourism	$/yr	1.29E+09	[16]	3.09E+12	[37]	3.82E+21

Table C.12 eMergy exports. Costa del Sol. 2012

No	Input	Unit	Amount	Ref. Amount	Transformity (sej/unit)	Ref. Transformity	eMergy
29	Livestock and products	J/yr	3.14E+14	[5]	5.33E+06	[204]	1.61E+21
30	Agriculture and forest products	g/yr	4.27E+14	[5]	1.75E+05	[204]	7.18E+19
31	Food industry products	g/yr	7.84E+10	[5]	3.36E+04	[204]	2.53E+15
32	Plastics	g/yr	3.98E+09	[5]	3.20E+09	[204]	1.22E+19
33	Minerals	g/yr	2.60E+11	[5]	1.68E+09	[204]	4.20E+20
34	Steel and pig iron	g/yr	2.71E+09	[5]	3.69E+09	[204]	9.61E+18
35	Mechanical and transport equipment	g/yr	2.46E+10	[5]	1.13E+10	[204]	2.67E+20
36	Leather and products	J/yr	1.61E+12	[5]	1.44E+07	[204]	2.23E+19
37	Textils	J/yr	5.87E+13	[5]	6.38E+06	[204]	3.60E+20
38	Wood and products	J/yr	2.68E+14	[5]	5.86E+04	[204]	1.51E+19
39	Paper	g/yr	2.52E+09	[5]	6.55E+09	[204]	1.59E+19
40	Chemicals	g/yr	9.59E+09	[5]	6.38E+08	[204]	5.88E+18
41	Rubber	g/yr	2.45E+08	[5]	7.22E+09	[204]	1.70E+18
42	Total Services	$/yr	1.74E+09	[16]	3.09E+12	[37]	5.16E+21
43	Total Tourism	$/yr	1.49E+09	[16]	3.09E+12	[37]	4.43E+21

Table C.13 eMergy exports. Costa del Sol. 2015

No	Input	Unit	Amount	Ref. Amount	Transformity (sej/unit)	Ref. Transformity	eMergy
29	Livestock and products	J/yr	3.34E+14	[5]	5.33E+06	[204]	1.71E+21
30	Agriculture and forest products	g/yr	5.79E+14	[5]	1.75E+05	[204]	9.72E+19
31	Food industry products	g/yr	1.01E+11	[5]	3.36E+04	[204]	3.27E+15
32	Plastics	g/yr	4.43E+09	[5]	3.20E+09	[204]	1.36E+19
33	Minerals	g/yr	1.03E+12	[5]	1.68E+09	[204]	1.66E+21
34	Steel and pig iron	g/yr	4.11E+08	[5]	3.69E+09	[204]	1.46E+18
35	Mechanical and transport equipment	g/yr	1.44E+10	[5]	1.13E+10	[204]	1.56E+20
36	Leather and products	J/yr	1.89E+12	[5]	1.44E+07	[204]	2.61E+19
37	Textils	J/yr	9.44E+13	[5]	6.38E+06	[204]	5.78E+20
38	Wood and products	J/yr	8.80E+13	[5]	5.86E+04	[204]	4.95E+18
39	Paper	g/yr	2.72E+09	[5]	6.55E+09	[204]	1.71E+19
40	Chemicals	g/yr	2.30E+10	[5]	6.38E+08	[204]	1.41E+19
41	Rubber	g/yr	4.66E+08	[5]	7.22E+09	[204]	3.23E+18
42	Total Services	$/yr	1.81E+09	[16]	3.09E+12	[37]	5.36E+21
43	Total Tourism	$/yr	1.64E+09	[16]	3.09E+12	[37]	4.87E+21

Appendix D

Sensitivity analysis of vulnerability to energy poverty

This annex contains a sensitivity analysis of the vulnerability study presented in Chapter 6. It consists in repeating the econometric analysis based on the MIS-based indicator but to the total households after removing false positives.

Table D.1 Vulnerability to Energy Poverty excluding false positives. Spain. 2015

	Coefficients	**Probablity ratios**
Type of household		
Single	0.2371*	1.2675*
Large family High income	2.4035***	11.0623***
Large family Low income	1.0101***	2.7458***
Normal family		
Tenure status of households		
Mortage	-0.8962***	0.4081***
Without mortage	0.9551***	2.5989***
Rent	1.2606***	3.5275***
Type of house		
Detached house	-0.3176	0.7279
Terraced house	-0.5042	0.6040
Condo less than10 apartments	-0.6353	0.5298
Condo more than 10 apartments	-0.6855	0.5039
Age of the property		
Older than 25 yrs	0.2269***	1.2547**
Heating		
None	-0.3416	0.7107
Electricity	-0.7449	0.4748
Natural gas	-0.8877	0.4116
GLP	-0.8550	0.4253
Liquified fuel	-0.7854	0.4559
Solid fuel	-0.6107	0.5430
Type of employment of the main breadwinner		
Manager	-0.1519	0.8591
Professional	-0.3896*	0.6773*
Administrative employee	0.3504*	1.4196*
Craftman	0.1885	1.2074
Elementary jobs	0.9029***	2.4667***
Employment of the main breadwinner		
Employed	-1.9774***	0.1384***
Leave	-1.8540***	0.1566***
Unemployed	0.7455***	2.1075***
Retired	-1.4799***	0.2277***
Student	0.5481	1.7300
Household tasks	-0.7241**	0.4848**
Permanent disability	-0.8911***	0.4102***
Education level of the main breadwinner		
Primary	0.8499***	2.3394***
Secondary	0.4479***	1.5651***
Area of residence		
Urban	0.1938**	1.2139**
Members of the family under 14 yrs	0.1630***	1.1771***
Members of the family over 65 yrs	-0.7542***	0.4704***
Dummy low energy consumption	0.1756**	1.1919**

Note: Asterisks indicate the level of significance of the parameters, so that
*** indicates significance at 1%, ** at 5% and * at 10%

Appendix E

MASTER.MC

This last annex of the thesis contains information on the MASTER.MC model developed for the case study described in Chapter 7. In the first place a table is included with the main input parameters to the model. Secondly, the results obtained in the stakeholder surveys, based on Saaty's proposal, are presented. Finally, a description of the model itself is included, consisting of the list of parameters, variables and equations.

E.1 Input data

Table E.1 Basic Inputs for MASTER.MC in 2030-2050. Based on BAU scenario in [152]

Type	**Technology**	**Unit**	**2030**	**2050**
Investment cost	Nuclear	€ /kW	4,500	4,000
	Coal supercritic CCS	€ /kW	3,500	3,000
	CCGT	€ /kW	900	800
	OCGT	€ /kW	450	450
	CCGT CCS	€ /kW	1,500	1,300
	OCGT CCS	€ /kW	900	800
	Wind onshore	€ /kW	1,400	1,200
	Wind offshore	€ /kW	2,800	2,000
	PV centralized	€ /kW	900	600
	PV distributed	€ /kW	2,400	1,600
	Solar termoelectric	€ /kW	3,000	2,900
Demand	Industry (mining, construction and materials)	GWh	165,600	212,684
	Industry (chemistry)	GWh	41,575	53,721
	Industry (others)	GWh	70,545	90,430
	Primary	GWh	36647	47066
	Services	km^2	727	845
	Air passengers	Mpkm	26,245	27,967
	Sea passengers	Mpkm	998	1063
	Land passengers	Mpkm	40,5975	43,2622
	Air load	Mtkm	77	104
	Sea load	Mtkm	48,837	65,776
	Land load	Mtkm	311,823	423,943
	Residential (heat)	GWhHEAT	114,464	149,699
	Residential (cold)	GWhCOLD	19,986	49,196
	Residential (hot water)	GWhACS	35,669	56,148
	Residential (light)	Glmh	575,582	1,099,964
	Residential (appliances)	km^2	661	769
	Vulnerable Residential (heat)	GWhHEAT	11,321	14,805
	Vulnerable Residential (cold)	GWhCOLD	1,977	4,866
	Vulnerable Residential (hot water)	GWhACS	3,528	5,553
	Vulnerable Residential (light)	Glmh	56,926	108,788
	Vulnerable Residential (appliances)	km^2	65	76
	Services (heat)	GWhHEAT	56,702	62,046
	Services (cold)	GWhCOLD	93,005	105,091
	Services (hot water)	GWhACS	2,667	3,101
Demography	Households	Million households	19	20
	Rent (GDP)	k€	1,344,798	1,811,248
Fuel prices	Coal	€ /MWh	12	9
	Gas	€ /MWh	25	25
	Oil	€ /MWh	45	37
Finance	WACC	%	9.00	9.00

E.2 Survey

Table E.2 Stakeholders survey. Capitals comparison

Stakeholder	**Econ/Social**	**Econ/Natural**	**Econ/Equity**	**Social/Natural**	**Social/Equityl**	**Natural/Equity**
Academic 1	1	1	1	1	1	1
Academic 2	3	1/5	1/5	1/5	1/3	1/3
Academic 3	3	1/3	1/5	3	2	1/2
Academic 4	1/3	1/8	1/5	1/6	1/3	4
Utility 1	0	0	0	0	0	0
Utility 2	1	5	7	1	7	7
Utility 3	1/3	1/5	1/5	1/2	1/2	1/2
Utility 4	3	3	5	3	3	3
Regulator 1	1/3	1/3	1	1	3	3
Regulator 2	0	0	0	0	0	0
Regulator 3	3	1	8	1	4	3
Regulator 4	1/3	1/5	2	4	1	1/2
Environmentalist 1	3	3	5	3	3	3
Environmentalist 2	1/4	1/6	3	1/4	3	5
Environmentalist 3	0	0	0	0	0	0
Environmentalist 4	5	5	5	5	5	5

Table E.3 Stakeholders survey. Natural capital criteria comparison

Stakeholder	**CO2/SO2**	**CO2/NOx**	**CO2/PM25**	**CO2/Dependence**	**SO2/NOx**	**SO2/PM25**	**SO2/Dependence**	**NOx/PM25**	**NOx/Dependence**	**PM25/Dependence**
Academic 1	1/5	1/6	1/7	1/9	1/2	1/3	1/8	1/8	1	2
Academic 2	1/5	1/3	1/3	5	3	3	3	3	3	3
Academic 3	7	4	4	2	1/4	1/5	1/6	2	1/3	1/4
Academic 4	4	4	4	2	1	1	1/2	1	1/2	1/2
Utility 1	0	0	0	0	0	0	0	0	0	0
Utility 2	1	3	3	1	1	3	3	1	1	1
Utility 3	1	1	1	2	1	1	3	1	3	3
Utility 4	1	1	1	1	1	1	1	1	1	1
Regulator 1	1	1	1	1	1	1	1	1	1	1
Regulator 2	0	0	0	0	0	0	0	0	0	0
Regulator 3	8	6	4	2	1/5	1	1/2	5	1	1/2
Regulator 4	1/3	1/3	1/4	5	1	1/3	4	4	4	3
Environmentalist 1	1/2	1/2	1/5	1	1	1/3	2	1/3	1/3	3
Environmentalist 2	1	1	1/3	1	1	1/3	1	1/3	1	4
Environmentalist 3	0	0	0	0	0	0	0	0	0	0
Environmentalist 4	5	5	5	7	5	5	5	4	5	5

Table E.4 Stakeholders survey. Stakeholder comparison

Stakeholder	**Reg/Priv**	**Reg/Aca**	**Reg/Env**	**Priv/Aca**	**Priv/Env**	**Aca/Env**
Academic 1	2	1/2	3	1/2	2	5
Academic 2	5	3	3	1	1/3	1
Academic 3	2	1/4	1/2	1/3	1/5	1
Academic 4	3	1/7	2	1/7	1/2	1/7
Utility 1	0	0	0	0	0	0
Utility 2	1/7	7	1	9	1	1
Utility 3	2	1/2	2	1/3	1	3
Utility 4	1	1	1	1	1	1
Regulator 1	1/3	1	1	3	3	1
Regulator 2	0	0	0	0	0	0
Regulator 3	2	4	5	5	4	1
Regulator 4	1/4	1/3	1/4	1	1/4	1
Environmentalist 1	5	2	1	1/2	1/2	1
Environmentalist 2	2	5	2	4	1	1/2
Environmentalist 3	0	0	0	0	0	0
Environmentalist 4	7	3	7	3	5	3

E.3 Model code

Symbols

Sets

Name	**Domains**	**Description**
p	*	Time periods of the year
s, as	*	Time subperiods of each period
l, al, aal	*	Load levels in each subperiod
proc	*	System processes: pe,ce,te,esst,rg,dr
pe	proc	Primary energy sources
ce	proc	Energy conversion technologies
te	proc	Energy transportation technologies
esst	proc	Energy service supply technology
rg	proc	Energy trade regions
dr	proc	Domestic region
ds	*	Demand sectors
es	*	Energy services
esvm1-10	*	Energy service variation measure
celoadf	ce	CE modelled with load factors
pelimey	pe	PE with limited energy in the year
mult	*	Multicriteria
peteflows	proc, proc	Possible PETE flows
peceflows	proc, proc	Possible PECE flows
ceteflows	proc, proc	Possible CETE flows
teceflows	proc, proc	Possible TECE flows
esbds	es, ds	Energy service belonging to this demand sector
esvmves	esvm, es	Energy service variation measure varying this energy service
esstses	esst, es	Energy service supply technology supplying this energy service
esvmexcl	esvm1-10	Energy service variation measure exclussion
ceelecentral	ce	CE connected to the centralised electricity grid
ceeledioth	ce	CE connected to the decentralised (other) electricity grid
ceelediind	ce	CE connected to the decentralised (ind) electricity grid

Name	**Domains**	**Description**
allrenceele	ce	All renewable CEs producing electricity in any grid
vul_esst	esst	All ESST belonging to Vulnerable Residential
ce_centr_interm	ce	CE power generation technologies centralised and intermittent
esstbds	esst, ds	Energy service supply technology belongs to this demand sector
teesstflows	te, esst	Energy of type TE that can be delivered to ESST
peesstflows	pe, esst	Energy of type PE that can be delivered to ESST
teorpe2esst	proc, esst	Energy of type TE or PE that can be delivered to ESST
teorpe2esst_ren	proc, esst	RENEWABLE Energy of type TE or PE that can be delivered to ESST
SameAs	*, *	Set Element Comparison Without Checking
cecroilrefin	ce	All crude oil refineries
teoilderiv	te	All TE oil refineries

Parameters

Name	**Domains**	**Description**
MaxCO2Emiss		Maximum allowed emissions in the complete energy sector (in PE, CE, TE and FE) (MtCO2)
CO2EmissCostInObjFunct		Consider CO2 emissions cost in the objective function valued at CO2 price
IncludeAdequacyConstr		Include Adequacy Constraint for electricity generation CEs (elements of set ceelecentral)
IncludeReservesConstr		Include Reserves Constraint for electricity generation CEs (elements of set ceelecentral)
ESVMAllowed		Allow for energy services variation measures
LSESSTAllowed		Allow for load shifting in ESSTs
ElecNetworkCost		Consider electricity network costs
ActivateLinf		Multicriteria L1

Name	**Domains**	**Description**
LANDA		LANDA parameter for multicriteria execution type 2
MinREShare_FE		
MinREShare_Elec		
ActivateMeanElectricityCost		Execution calculating a mean electricity price, i.e. PRICEELECE
PRICEELECE		Electricity price (converging to marginal value) for FIXED electricity price execution
IDEALVULRES		Ideal Vulnerable Residential Tot Cost. For lexicographic execution
IDEALTOTEMISSIONS		Ideal Total Emissions. For lexicographic execution
IDEALENERDEP		Ideal Energy Dependence. For lexicographic execution
LexicoPE		PE Lexicographic execution
LexicoCO		CO2 Lexicographic execution
LexicoDEP		DEP Lexicographic execution
FixedTotteelece		Execution NOT fixing the total electricity consumed (MEANTOTTEELECE)
MEANTOTTEELECE		Mean electricity consumed for FIXED total electricity execution
xDiv1E3		Multiply by this factor to divide by 1E3
xDiv1E6		Multiply by this factor to divide by 1E6
xMul1E6		Multiply by this factor to multiply by 1E6
xEJtoGWh		Multiply by this factor to convert EJ to GWh (GWh/EJ)
xGWhtoEJ		Multiply by this factor to convert GWh to EJ (EJ/GWh)
MULTIDEAL	mult	Ideal value for each criteria
MULTANTIDEAL	mult	Anti-ideal value for each criteria
MULTWEIGHT	mult	Weight applied to each criteria
MULTACTIVE	mult	Weight applied to each criteria
MULTLIMIT	mult	Limit applied to each criteria

Name	**Domains**	**Description**
CO2PRICE		CO2 price _INTERNAL (G€/MtCO2)
CEHYPSTORCYEF		CE Hydro Pumping Storage Cycle Efficiency Factor _INTERNAL (p.u.)
CERESMRG4ADEQ		Required reserve margin over peak demand, 4 adequacy restriction _INTERNAL (p.u.)
CEDEMAVGPRERR4RSRV		Average prediction error in demand, for reserves restriction _INTERNAL (p.u.)
CELOADFAVGPRERR4RSRV		Average prediction error in CE modelled with load factors (celoadf), for reserves restriction. Applied over their mean yearly production _INTERNAL (p.u.)
CELARGCECAP4RSRV		Larger CE capacity to be considered for reserves restriction: the size, in GW, of the larger plant that can fail _INTERNAL (GW)
ESVMCOSTYEAR	esvm	Cost per year of fully implementing each Energy Service Variation Measure _INTERNAL (G€)
ESSTCOSTPACTUY	esst	Energy Service Supply Technology Cost per Activity Unit, Yearly _INTERNAL (G€/unit esst activity)
ESSTLSCOST	esst	ESST Load Shifting Cost in each ESST _INTERNAL (G€/EJ)
ESSTJOBPACTUY	esst	Energy Service Supply Technology JOBS per Activity Unit, Yearly _INTERNAL (Jobs/unit esst activity)
TECAP	te	Capacity in each transport process _INTERNAL (GW)
TELF	te	Total losses in each transport process _INTERNAL (p.u.)
ECOVCTE	te	Economic variable costs of energy transportation _INTERNAL (G€/EJ)

Name	**Domains**	**Description**
CO2EFTE	te	CO2 emission factor of energy transportation _INTERNAL (MtCO2/EJ)
CEPREVCAP	ce	Previous installed capacity in each conversion process _INTERNAL (GW)
CELF	ce	Total losses in each conversion process _INTERNAL (p.u.)
ACECAPFIXDCOSTYEAR	ce	Fixed cost of active CE capacity PER YEAR _INTERNAL (G€/GW-year)
CEMAXACTIVECAP	ce	Maximum active capacity in each conversion process _INTERNAL (GW)
CEFIRMNESS4ADEQ	ce	Electricity generation technology firmness factor for the adequacy requirement in reliability constraints _INTERNAL (p.u.)
CEFLEXIBILITY4RSRV	ce	Electricity generation technology flexibility factor for the reserves requirement in reliability constraints _INTERNAL (p.u.)
CECONSJOB	ce	Number of new jobs for new power installations (job/GW)
CEOPJOB	ce	Number of new jobs for operation and maintenance of power plants (job/GW)
PEDOMCONSCAP	pe	Domestic primary energy consumption capacity _INTERNAL (GW)
PEMAXECONSYEAR	pe	Maximum energy consumption in a year for each PE. Used only for subset pelimey _INTERNAL (EJ)
ECOVCPEDOM	pe	Economic variable cost of domestic primary energy consumption _INTERNAL (G€/EJ)
ECOVSECPEDOM	pe	Economic variable cost of SECURITY domestic primary energy consumption _INTERNAL (G€/EJ)

Name	**Domains**	**Description**
CO2PEDOMEF	pe	CO2 emission factor of PE domestic consumption _INTERNAL (MtCO2/EJ)
PEID	pe	PE import dependence _INTERNAL (p.u.)
HYDRONRGMONTH	p	Hidraulicity per month _INTERNAL (EJ)
RURIVNRGSHARE	p	Share of the hydro energy each moth with is Run off the River _INTERNAL (p.u.)
PEIMPAVERAGECOST	pe	Primary energy importation avarage cost _INTERNAL (G€/EJ)
TEIMPAVERAGECOST	te	Transport energy importation average cost _INTERNAL (G€/EJ)
D	p, s, l	Duration of the year's periods and subperiods _INTERNAL (h)
ESDEMY	es, ds	Energy service demand numerical data, obtained from d_ESDEMY table _INTERNAL (dif. units per energy service)
NSFECOST	esst, ds	Non-Supplied Final Energy Cost _INTERNAL (G€/EJ)
FEUEMISSFTE	esst, te	Final Energy Use Emissions Factor per unit of consumed TE _INTERNAL (MtCO2/EJ)
FEUEMISSFPE	esst, pe	Final Energy Use Emissions Factor per unit of consumed PE _INTERNAL (MtCO2/EJ)
ESVMEFFECT	esvm, es	Effect of each ESVM over each ES in percentage _INTERNAL (p.u.)
ESDEMLOADC	es, p, s, l	Load curve of the demand of this ES within the year _INTERNAL (p.u.)
ESVMLOADC	esvm, p, s, l	Load curve of each ESVM within the year _INTERNAL (p.u.)

Name	**Domains**	**Description**
QACTESST2ES	esst, es	Relation between the activity level in each ESST and the amout of each ES that it produces _INTERNAL (units es / units activity esst)
TE2QACTESST	esst, te	Needed TE energy (not power!!!) to create a unit of activity level in each ESST _INTERNAL (units activity esst / EJ)
PE2QACTESST	esst, pe	Needed PE energy (not power!!!) to create a unit of activity level in each ESST _INTERNAL (units activity esst / EJ)
ESSTLSPOSTE	esst, te	ESST Load Shifting Possibility for TE _INTERNAL (natural number (0,1,or 2))
ESSTLSPOSPE	esst, pe	ESST Load Shifting Possibility for PE _INTERNAL (natural number (0,1,or 2))
FEUEMISNOFTE	esst, te	Final Energy Use NO Emissions Factor per unit of consumed TE _INTERNAL (MtCO2/EJ)
FEUEMISNOFPE	esst, pe	Final Energy Use NO Emissions Factor per unit of consumed PE _INTERNAL (MtCO2/EJ)
FEUEMISSOFTE	esst, te	Final Energy Use SO Emissions Factor per unit of consumed TE _INTERNAL (MtCO2/EJ)
FEUEMISSOFPE	esst, pe	Final Energy Use SO Emissions Factor per unit of consumed PE _INTERNAL (MtCO2/EJ)
FEUEMISPMFTE	esst, te	Final Energy Use PM Emissions Factor per unit of consumed TE _INTERNAL (MtCO2/EJ)

Name	**Domains**	**Description**
FEUEMISPMFPE	esst, pe	Final Energy Use PM Emissions Factor per unit of consumed PE _INTERNAL (MtCO2/EJ)
FEUEMISSFTELCA	esst, te	Final Energy Use LCA Emissions Factor per unit of consumed TE _INTERNAL (MtCO2/EJ)
CEINSHARETE	ce, te	Input share of each transformed energy in each conversion process _INTERNAL (p.u.)
CEINSHAREPE	ce, pe	Input share of each primary energy in each conversion process _INTERNAL (p.u.)
CEMAXTEOUTSHARE	ce, te	Maximum output share of each transformed energy in each conversion process _INTERNAL (p.u.)
CEMINTEOUTSHARE	ce, te	Minimum output share of each transformed energy in each conversion process _INTERNAL (p.u.)
CEMEANTEOUTSHARE	ce, te	Mean output share of each transformed energy in each conversion process _INTERNAL (p.u.)
ECOVCCE	ce, te	Economic variable costs of energy conversion _INTERNAL (G€/EJ)
CO2EFCE	ce, te	CO2 emission factor of energy conversion _INTERNAL (MtCO2/EJ)
SOEFCE	ce, te	SOx emission factor of energy conversion _INTERNAL (MtSOx/EJ)
NOEFCE	ce, te	NOx emission factor of energy conversion _INTERNAL (MtNOx/EJ)
PMEFCE	ce, te	PM25 emission factor of energy conversion _INTERNAL (MtPM25/EJ)
TEIMPCAP	te, rg	Transformed energy importation capacity _INTERNAL (GW)
TEIMPCOST	te, rg	Transformed energy importation cost _INTERNAL (G€/EJ)

Name	**Domains**	**Description**
TEEXPCAP	te, rg	Transformed energy exportation capacity _INTERNAL (GW)
TEEXPREVE	te, rg	Transformed energy exportation revenue _INTERNAL (G€/EJ)
PEIMPCAP	pe, rg	Primary energy importation capacity _INTERNAL (GW)
PEIMPCOST	pe, rg	Primary energy importation cost _INTERNAL (G€/EJ)
PEEXPCAP	pe, rg	Primary energy exportation capacity _INTERNAL (GW)
PEEXPREVE	pe, rg	Primary energy exportation revenue _INTERNAL (G€/EJ)
PEIMPSECCOST	pe, rg	Primary energy SECURITY importation cost _INTERNAL (G€/EJ)
TEIMPSECCOST	te, rg	Transformed energy SECURITY importation cost _INTERNAL (G€/EJ)
NEWICAPINVCOSTYEAR	proc	New installed capacity investment cost per year (unitary amortization) (G€/GW)
MAXDEMYR	te	Maximum demand of each TE in the year (GW)
CEELERSRVCOST	ce	Reserve cost of each electricity generation technology, for TEELECE (G€/EJ)
CELOADFACTORP	celoadf, p	MONTHLY load factor (% of hours functionning at full capacity) of each CE. Used only for renewables(p.u.)
ng_current_cap		Current natural gas network capacity expressed as the annual energy demand that can be delivered with the current network (GWh)
ng_network_cost		Cost of extensions to the natural gas network beyond current capacity (€/MWh)
methane_leakage		methane leakage factor (pu)
methane_CO2eq		conversion from EJ of methane to Mtn CO2 equivalent (MtCO2eq/EJ)

Name	Domains	Description
unitarynetwokcost	te	unitary network cost per unit of new installed capacity of solar + wind + cogeneration (€/kW)

Variables

Name	Domains	Description
OFVA_TOTSUPCOSTOPERINVST_P23		Obj. Funct. Var. Aggregated. Tot. energy supply cost, operation, + investment with / without previous capacities. ModelType 2 / 3(G€)
OFVA_TOTSUPCOSTVULRES_P23		Obj. Funct. Var. Aggregated. Tot. energy supply cost vulnerable residential 2 / 3(G€)
OFVA_TOTEMISSIONS_P23		Obj. Funct. Var. Aggregated. Tot. CO2 Emissions 2 / 3 (Mton)
OFVA_ENERGY_DEPENDENCE_P23		Obj. Funct. Var. Aggregated. Energy dependence 2 / 3(G€)
OFVA_TOTSECCOST_P23		Obj. Funct. Var. Aggregated. Tot. SECURITY costs (G€)
OFVA_JOBS_P23		Obj. Funct. Var. Aggregated. Tot. JOBS (jobs)
OFVA_TOTEMISNO_P23		Obj. Funct. Var. Aggregated. Total Emissions NO2

Name	**Domains**	**Description**
OFVA_TOTEMISSO_P23		Obj. Funct. Var. Aggregated. Total Emissions SO2
OFVA_TOTEMISPM_P23		Obj. Funct. Var. Aggregated. Total Emissions PM10
OFVA_MULTICRITERIA_P23		Obj. Funct. Multicriteria L1
OFVA_MULTICRITERIALINF_P23		Obj. Funct. Multicriteria Linf
OFVA_MULTICRITERIALANDA_P23		Obj. Funct. Multicriteria LANDA
OFVP_DOPECONSCOST		Objective Function Variable Part. Domestic PE consumption cost(G€)
OFVP_DOPECOEMCOST		Objective Function Variable Part. Domestic PE consumption emissions cost(G€)
OFVP_PEIMPORTCOST		Objective Function Variable Part. PE imports cost(G€)
OFVP_PEEXPORTREVE		Objective Function Variable Part. PE exports revenue(G€)
OFVP_CECONVERCOST		Objective Function Variable Part. CE conversion cost(G€)
OFVP_CECONVEMCOST		Objective Function Variable Part. CE conversion emissions cost(G€)

Name	**Domains**	**Description**
OFVP_TETRANSPCOST		Objective Function Variable Part. TE transportation cost. Total(G€)
OFVP_TETRANSPCOST_TE	te	Objective Function Variable Part. TE transportation cost. Each TE(G€)
OFVP_TETRANEMCOST		Objective Function Variable Part. TE transportation emissions cost(G€)
OFVP_TEIMPORTCOST		Objective Function Variable Part. TE imports cost(G€)
OFVP_TEEXPORTREVE		Objective Function Variable Part. TE exports revenue(G€)
OFVP_FEUEMISSCOST		Objective Function Variable Part. FE use emissions cost(G€)
OFVP_NONSUPFECOST		Objective Function Variable Part. Non-supplied FE cost, Total(G€)
OFVP_NONSUPFECOST_DS	ds	Objective Function Variable Part. Non-supplied FE cost, per DS(G€)
OFVP_ACAPFIXDCOST		Objective Function Variable Part. Active capacity fixed costs(G€)

Name	**Domains**	**Description**
OFVP_NCAPINVSCOST		Objective Function Variable Part. New capacity investment costs(G€)
OFVP_CELERSRVCOST		Objective Function Variable Part. Electricity generation reserve cost(G€)
OFVP_ESVMPROMOCOST		Objective Function Variable Part. Energy Services Variation Measures promotion costs(G€)
OFVP_ESSTLSTOTCOST		Objective Function Variable Part. Total Costs of Load Shifting in ESSTs(G€)
OFVP_ESSTACTTOTCOST		Objective Function Variable Part. Total Costs ESSTs Activity (excluding energy costs)(G€)
OFVP_PEIMPORTSECCOST		Objective Function Variable Part. PE SECURITY imports cost(G€)
OFVP_TEIMPORTSECCOST		Objective Function Variable Part. TE SECURITY imports cost(G€)
OFVP_CONSJOB		Objective Function Variable Part. Construction JOBS (jobs)

Name	Domains	Description
OFVP_OPJOB		Objective Function Variable Part. O&M JOBS (jobs)
OFVP_ESSTJOB		Objective Function Variable Part. ESST JOBS (jobs)
OFVP_NONSUPVULFECOST		Objective Function Variable Part. Non-supplied FE cost, Total(G€)
OFVP_NONSUPVULFECOST_DS		Objective Function Variable Part. Non-supplied FE cost, per DS(G€)
OFVP_VULESSTACTTOTCOST		Objective Function Variable Part. Total Costs ESSTs Activity (excluding energy costs)(G€)
OFVP_TOTTEVULCONSUM	te	Objective Function Variable Part. Total TE consumption Vulnerable Residential (GWh)
OFVP_TOTPEVULCONSUM	pe	Objective Function Variable Part. Total PE consumption Vulnerable Residential (GWh)
QPWR	proc, proc, p, s, l	Quantity of power flowing from process to process in period p, subperiod s and level l (GW)

Name	**Domains**	**Description**
PREVACTIVECAP	proc	Previously installed active capacity (paying fixed O&M costs) in each month (GW)
NEWINSTALLCAP	proc	Newly installed active capacity (paying investment and fixed O&M costs) in the year (GW)
CEELERSRVPWR	proc, p, s, l	Electricity generation power providing reserve (GW)
QPWRNS	proc, esst, p, s, l	Quantity of non-supplied energy (power) of type TE or PE to end-use technology ESST in period p, subperiod s and level l (GW)
QACTESST	esst, p, s, l	Activity level in each ESST, in each period p, subperiod s and level l (units of this esst's activity)
ESVMLVL	esvm	Level of application of energy service variation measure in the year (p.u.)
ESSTLS_ACC	proc, esst, p, s, l	Load shifting of TE or PE in each ESST in each time slice. Acumuluation of energy by ESST (p,s,l) (GW)

Name	Domains	Description
ESSTLS_RLS	proc, esst, p, s, l	Load shifting of TE or PE in each ESST in each time slice. Releasing of energy (to supply ES) by ESST (p,s,l) (GW)
TEELECEPECOST		PE cost of electricity (G€)
TEELECECECOST		CE cost of electricity (G€)
TEELECETECOST		TE cost of electricity (G€)
TEELECENCAPINVSCOST		New Capacity investment cost of electricity (G€)
TOTTEELECE		Total electricity produced (GWh)
MEANELECOST		Mean electricity cost (€/MWh)
MEANGASCOST		Mean GAS cost (€/MWh)
MEANGASCOSTNEWCAP		Mean Gas Cost (€/MWh)
MEANGASCOSTACTCAP		Mean Gas Cost (€/MWh)
MEANGASCOSTVAR		Mean Gas Cost (€/MWh)
TOTTENAGAS		Tot. TENAGAS (GWh-year)
MEANBIOETHCOST		Mean Bioetanol cost (€/MWh)
MEANBIOETHCOSTNEWCAP		Mean Bioetanol Cost (€/MWh)
MEANBIOETHCOSTACTCAP		Mean Bioetanol Cost (€/MWh)

Name	**Domains**	**Description**
MEANBIOETHCOSTVAR		Mean Bioetanol Cost (€/MWh)
TOTTEBIOETH		Tot. TEBIOETH (GWh-year)
MEANBIODIECOST		Mean Biodiesel cost (€/MWh)
MEANBIODIECOSTNEWCAP		Mean Biodiesel Cost (€/MWh)
MEANBIODIECOSTACTCAP		Mean Biodiesel Cost (€/MWh)
MEANBIODIECOSTVAR		Mean Biodiesel Cost (€/MWh)
TOTTEBIODIE		Tot. TEBIODIE (GWh-year)
MEANOILDERIVCOST	*	Mean OIL DERIVATIVES cost (€/MWh)
MEANOILCOSTNEWCAP		Mean OIL Cost (€/MWh)
MEANOILCOSTACTCAP		Mean OIL Cost (€/MWh)
MEANOILDERIVCOSTVAR	*	Mean OILD DERIVATIVES Cost (€/MWh)
TOTTEOP	*	Tot. TEOP (GWh-year)
TOT_ENERGY_USED_DOMyIMP_EJ		Total energy Domestic + Imported
TOT_ENERGY_USED_DOM_EJ		Total Domestic energy
MULTLINF_CT		LINF MULTICRITERIA. Total cost
MULTLINF_PE		LINF MULTICRITERIA. Energy Poverty
MULTLINF_CO		LINF MULTICRITERIA. CO2 Emissions
MULTLINF_DE		LINF MULTICRITERIA. Energy Dependence

Name	Domains	Description
MULTLINF_SO		LINF MULTICRITERIA. SO2 Emissions
MULTLINF_NO		LINF MULTICRITERIA. NOx Emissions
MULTLINF_PM		LINF MULTICRITERIA. PM25 Emissions
MULTLINF_SE		LINF MULTICRITERIA. Security cost
MULTLINF_JO		LINF MULTICRITERIA. Jobs
DMULT		Auxiliary variable for Linf Multicriteria
TOTQTEIN	te, p, s, l	Total quantity of transported energy (input) in TE in period p, subperiod s and level l (GW)
TOTQTEOUT	te, p, s, l	Total quantity of transported energy (output) in TE in period p, subperiod s and level l (GW)
TOTQCEIN	ce, p, s, l	Total quantity of converted energy (input) in CE in period p, subperiod s and level l (GW)
TOTQCEOUT	ce, p, s, l	Total quantity of converted energy (output) in CE in period p, subperiod s and level l (GW)
TOTQPEOUT	pe, p, s, l	Total quantity of primary energy (output) in PE in period p, subperiod s and level l (GW)
QLCE	ce, p, s, l	Quantity of lost energy in CE in period p, subperiod s and level l (GW)

Name	**Domains**	**Description**
QLTE	te, p, s, l	Quantity of lost energy in TE in period p, subperiod s and level l (GW)
EMPE	pe, p, s, l	Emissions in primary energy consumption (MtCO2/h)
EMCE	ce, te, p, s, l	Emissions in energy conversion (MtCO2/h)
EMCESO	ce, te, p, s, l	Emissions in energy conversion (MtSOx/h)
EMCENO	ce, te, p, s, l	Emissions in energy conversion (MtNOx/h)
EMCEPM	ce, te, p, s, l	Emissions in energy conversion (MtPM25/h)
EMTE	te, p, s, l	Emissions in energy transportation (MtCO2/h)
EMFE	ds, p, s, l	Emissions in final energy use (MtCO2/h)
EMFE_ESST	esst, p, s, l	Emissions in final energy use in each ESST (MtCO2/h)
EMFELCA	ds, p, s, l	LCA Emissions in final energy use (MtCO2/h)
EMFELCA_ESST	esst, p, s, l	LCA Emissions in final energy use in each ESST (MtCO2/h)
TOTEM		Total Emissions in complete energy sector (MtCO2)
TOTEM_PE		Total Emissions in PE (MtCO2)
TOTEM_CE		Total Emissions in CE (MtCO2)

Name	Domains	Description
TOTEM_TE		Total Emissions in TE (MtCO2)
TOTEM_FE		Total Emissions in FE (MtCO2)
TOTEMLCA_FE		Total LCA Emissions in FE (MtCO2)
TOTEM_METHLEAK		Total Emissions from methane leakage (MtCO2)
NOEMFE	ds, p, s, l	NOx Emissions in final energy use (MtNO2/h)
NOEMFE_ESST	esst, p, s, l	NOx Emissions in final energy use in each ESST (MtNO2/h)
SOEMFE	ds, p, s, l	SOx Emissions in final energy use (MtSO2/h)
SOEMFE_ESST	esst, p, s, l	SOx Emissions in final energy use in each ESST (MtSO2/h)
PMEMFE	ds, p, s, l	PM25 Emissions in final energy use (MtPM10/h)
PMEMFE_ESST	esst, p, s, l	PM25 Emissions in final energy use in each ESST (MtPM10/h)
TOTEM_NOFE		Total NOx Emissions in FE (MtNOx)
TOTEM_SOFE		Total SOx Emissions in FE (MtSOx)
TOTEM_PMFE		Total PM25 Emissions in FE (MtPM25)
TOTACTIVECAP	proc	Total active capacity (GW)

Name	**Domains**	**Description**
ADDED_NGNETWORK_CAP		Additional natural gas network capacity in year p with respect to current capacity (GWh)
TOTLSTEENERGY	esst, te	Total shifted energy of type TE in technology ESST (throughout the complete year) (EJ)
TOTLSPEENERGY	esst, pe	Total shifted energy of type PE in technology ESST (throughout the complete year) (EJ)
TOT_REELECGEN_EJ		Total renewable electricity generation (throughout the complete year, centralised or distrib) (EJ)
TOT_ELECGEN_EJ		Total electricity generation (throughout the complete year, centralised or distrib) (EJ)
TOT_FE_TEyPE		Total final energy consumed (TE and PE) (EJ)
TOT_FEren_TEyPE		Total RENEWABLE final energy consumed (TE and PE) (EJ)

Equations

Name	**Description**
OBF_OFVA_TOTSUPCOSTOPERINVST_P23	Objective function model type 2 and 3. Tot. energy supply cost, operation, + investment with /without previous capacities(G€)
OBF_OFVA_TOTSUPCOSTVULRES_P23	Objective function model type 2 and 3. Tot. energy supply cost for vulnerable residence (G€)
OBF_OFVA_TOTEMISSIONS_P23	Objective function model type 2 and 3. Tot. Emissions (Mton)
OBF_OFVA_ENERGY_DEPENDENCE_P23	Objective function model type 2 and 3. Total energy dependence
OBF_OFVA_TOTSECCOST_P23	Objective function model type 2 and 3. Tot. SECURITY costs (G€)
OBF_OFVA_JOBS_P23	Objective function model type 2 and 3. Tot. jobs (jobs)
OBF_OFVA_TOTEMISNO_P23	Objective function model type 2 and 3. Total Emissions NO2
OBF_OFVA_TOTEMISSO_P23	Objective function model type 2 and 3. Total Emissions SO2
OBF_OFVA_TOTEMISPM_P23	Objective function model type 2 and 3. Total Emissions PM10
OBF_OFVA_MULTICRITERIA_P23	Objective function multicriteria L1
OBF_OFVA_MULTICRITERIALINF_P23	Objective function multicriteria Linf
OBF_OFVA_MULTICRITERIALANDA_P23	Objective function multicriteria LANDAE
OBF_OFVA_IDEALTOTSUPCOSTVULRES_P23	Addtional constraint for PE lexicographic execution

Name	**Description**
OBF_OFVA_IDEALTOTEMISSIONS_P23	Addtional constraint for CO lexicographic execution
OBF_OFVA_IDEALENERGY_DEPENDENCE_P23	Additional constraint for DEP lexicographic execution
OBF_TEELECEPECOST_P23	PE cost of electricity (G€)
OBF_TEELECECECOST_P23	CE cost of electricity (G€)
OBF_TEELECETECOST_P23	TE cost of electricity (G€)
OBF_TEELECENCAPINVSCOST_P23	New Capacity investment cost of electricity (G€)
OBF_TOTTEELECE_P23	Total electricity produced (GWh)
OBF_MEANTOTTEELECE_P23	Mean Total electricity produced (GWh)
OBF_MEANELECOST_P23	Mean electricity Cost (€/MWh)
OBF_FIXEDMEANELECOST_P23	Fixed Mean electricity Cost (€/MWh)
OBF_MEANGASCOST_P23	Mean Gas Cost (€/MWh)
OBF_MEANBIOETHCOST_P23	Mean Bioetanol Cost (€/MWh)
OBF_MEANBIODIECOST_P23	Mean Biodiesel Cost (€/MWh)
OBF_MEANOILDERIVCOST_P23	Mean OIL DERIVATIVES Cost (€/MWh)
OBF_MULTLINF_CT	OFVP. LINF MULTICRITERIA. Total cost
OBF_MULTLINF_PE	OFVP. LINF MULTICRITERIA. Energy Poverty
OBF_MULTLINF_CO	OFVP. LINF MULTICRITERIA. CO2 Emissions
OBF_MULTLINF_DE	OFVP. LINF MULTICRITERIA. Energy Dependence
OBF_MULTLINF_SO	OFVP. LINF MULTICRITERIA. SO2 Emissions

Name	**Description**
OBF_MULTLINF_NO	OFVP. LINF MULTICRITERIA. NOx Emissions
OBF_MULTLINF_PM	OFVP. LINF MULTICRITERIA. PM25 Emissions
OBF_MULTLINF_SE	OFVP. LINF MULTICRITERIA. Total Security Cost
OBF_MULTLINF_JO	OFVP. LINF MULTICRITERIA. Total Jobs
REL_OFVP_DOPECONSCOST_P123	Objective Function Variable Part Definition (OFVP). Domestic PE consumption cost(G€)
REL_OFVP_DOPECOEMCOST_P123	OFVP. Domestic PE consumption emissions cost(G€)
REL_OFVP_PEIMPORTCOST_P123	OFVP. PE imports cost(G€)
REL_OFVP_PEEXPORTREVE_P123	OFVP. PE exports revenue(G€)
REL_OFVP_CECONVERCOST_P123	OFVP. CE conversion cost(G€)
REL_OFVP_CECONVEMCOST_P123	OFVP. CE conversion emissions cost(G€)
REL_OFVP_TETRANSPCOST_P123	OFVP. TE transportation cost. Total (G€)
REL_OFVP_TETRANSPCOST_TEGENEQ_P123	OFVP. TE transportation cost. General equation for each TE (G€)
REL_OFVP_PEIMPORTSECCOST_P123	OFVP. PE SECURITY imports cost(G€)
REL_OFVP_TEIMPORTSECCOST_P123	OFVP. TE SECURITY imports cost(G€)
REL_OFVP_CONSJOB_P123	OFVP. Construction jobs (jobs)
REL_OFVP_OPJOB_P123	OFVP. O&M jobs (jobs)
REL_OFVP_ESSTJOB_P123	OFVP. ESST (jobs)

Name	Description
REL_OFVP_TETRANSPCOST_TENAGAS_P123	OFVP. TE transportation cost. Equation defining the cost of TENAGAS (G€)
REL_OFVP_TETRANSPCOST_TEELECE_P123	OFVP. TE transportation cost. Equation defining the cost of TEELECE (G€)
REL_OFVP_TETRANSPCOST_TEELEDIIND_P123	OFVP. TE transportation cost. Equation defining the cost of TEELEDIIND (G€)
REL_OFVP_TETRANSPCOST_TEELEDIOTH_P123	OFVP. TE transportation cost. Equation defining the cost of TEELEDIOTH (G€)
REL_OFVP_TETRANEMCOST_P123	OFVP. TE transportation emissions cost(G€)
REL_OFVP_TEIMPORTCOST_P123	OFVP. TE imports cost(G€)
REL_OFVP_TEEXPORTREVE_P123	OFVP. TE exports revenue(G€)
REL_OFVP_FEUEMISSCOST_P123	OFVP. FE use emissions cost(G€)
REL_OFVP_NONSUPFECOST_P123	OFVP. Non-supplied FE cost, Total(G€)
REL_OFVP_NONSUPFECOST_DS_P123	OFVP. Non-supplied FE cost, per DS(G€)
REL_OFVP_CELERSRVCOST_P123	OFVP. Electricity generation reserve cost(G€)
REL_OFVP_ACAPFIXDCOST_P123	OFVP. Active capacity fixed costs(G€)
REL_OFVP_NCAPINVSCOST_P23	OFVP. New capacity investment costs(G€)
REL_OFVP_ESVMPROMOCOST_P23	OFVP. Energy Services Variation Measures promotion costs(G€)
REL_OFVP_ESSTLSTOTCOST_P123	OFVP. Total Costs of Load Shifting in ESSTs(G€)

Name	**Description**
REL_OFVP_ESSTACTTOTCOST_P123	OFVP. Total Costs ESSTs Activity (excluding energy costs)(G€)
REL_OFVP_NONSUPVULFECOST_P123	OFVP. Non-supplied VUL FE cost, Total(G€)
REL_OFVP_NONSUPVULFECOST_DS_P123	OFVP. Non-supplied VUL FE cost, per DS(G€)
REL_OFVP_VULESSTACTTOTCOST_P123	OFVP. Total Costs ESSTs Activity (excluding energy costs)(G€)
REL_TOT_ENERGY_USED_DOMyIMP_EJ	Total energy domestic + imported
REL_TOT_ENERGY_USED_DOM_EJ	Total energy domestic
REL_OFVP_TOTTEVULCONSUM_P123	OFVP. Total TE energy consumption Vulnerable Residential (GWh)
REL_OFVP_TOTPEVULCONSUM_P123	OFVP. Total PE energy consumption Vulnerable Residential (GWh)
REL_MEANGASCOSTNEWCAP	Mean Gas Cost (€/MWh)
REL_MEANGASCOSTACTCAP	Mean Gas Cost (€/MWh)
REL_MEANGASCOSTVAR	Mean Gas Cost (€/MWh)
REL_TOTTENAGAS	Total. TENAGAS (GWh-year)
REL_MEANBIOETHCOSTNEWCAP	Mean Bioetanol Cost (€/MWh)
REL_MEANBIOETHCOSTACTCAP	Mean Bioetanol Cost (€/MWh)
REL_MEANBIOETHCOSTVAR	Mean Bioetanol Cost (€/MWh)
REL_TOTTEBIOETH	Total. TEBIOETH (GWh-year)
REL_MEANBIODIECOSTNEWCAP	Mean Biodiesel Cost (€/MWh)

Name	**Description**
REL_MEANBIODIECOSTACTCAP	Mean Biodiesel Cost (€/MWh)
REL_MEANBIODIECOSTVAR	Mean Biodiesel Cost (€/MWh)
REL_TOTTEBIODIE	Total. TEBIODIE (GWh-year)
REL_MEANOILCOSTNEWCAP	Mean OIL Cost (€/MWh)
REL_MEANOILCOSTACTCAP	Mean OIL Cost (€/MWh)
REL_MEANOILDERIVCOSTVAR	Mean OIL DERIVATIVES Cost (€/MWh)
REL_TOTTEOP	Total. TEOP (GWh-year)
REL_MULTLINF_CT	REL. LINF MULTICRITERIA. Total cost
REL_MULTLINF_PE	REL. LINF MULTICRITERIA. Energy Poverty
REL_MULTLINF_CO	REL. LINF MULTICRITERIA. CO2 Emissions
REL_MULTLINF_DE	REL. LINF MULTICRITERIA. Energy Dependence
REL_MULTLINF_SO	REL. LINF MULTICRITERIA. SO2 Emissions
REL_MULTLINF_NO	REL. LINF MULTICRITERIA. NOx Emissions
REL_MULTLINF_PM	REL. LINF MULTICRITERIA. PM25 Emissions
REL_MULTLINF_SE	REL. LINF MULTICRITERIA. Security Cost
REL_MULTLINF_JO	REL. LINF MULTICRITERIA. Jobs
REL_TOTLSTEENERGY_P123	Relation. Total shifted energy of type TE in technology ESST (throughout the complete year) (EJ)

Name	**Description**
REL_TOTLSPEENERGY_P123	Relation. Total shifted energy of type PE in technology ESST (throughout the complete year) (EJ)
REL_TOTQTEIN_P123	Relation. Total quantity of input to TE (GW)
REL_TOTQTEOUT_P123	Relation. Total quantity of output from TE (GW)
REL_TELOSSES_P123	Relation. Transformed energy losses (GW)
REL_NGNETWORK_CAP	Total natural gas network capacity equals currently existing network + added network (GWh)
REL_TOTQCEIN_P123	Relation. Total quantity of input to CE (GW)
REL_TOTQCEOUT_P123	Relation. Total quantity of output from CE (GW)
REL_CELOSSES_P123	Relation. Converted energy losses (GW)
REL_CETOTACTIVECAP_P123	Relation. Defines total active capacity (GW)
REL_TOTQPEOUT_P123	Relation. Total quantity of output from PE (GW)
REL_PEDOMESTIC_P123	Relation. Domestic primary energy consumption (GW)
REL_EMPE_P123	Relation. Emissions in primary energy consumption (MtCO2/h)
REL_EMCE_P123	Relation. Emissions in energy conversion (MtCO2/h)
REL_EMCESO_P123	Relation. Emissions in energy conversion (MtSOx/h)
REL_EMCENO_P123	Relation. Emissions in energy conversion (MtNOx/h)

Name	**Description**
REL_EMCEPM_P123	Relation. Emissions in energy conversion (MtPM25/h)
REL_EMTE_P123	Relation. Emissions in energy transportation (MtCO2/h)
REL_EMFE_P123	Relation. Emissions in final energy use (MtCO2/h)
REL_EMFE_ESST_P123	Relation. Emissions in final energy use in each ESST technology (MtCO2/h)
REL_EMFELCA_P123	Relation. Emissions in final energy use (MtCO2/h)
REL_EMFELCA_ESST_P123	Relation. Emissions in final energy use in each ESST technology (MtCO2/h)
REL_TOTEM_P123	Relation. Total emissions in complete energy sector (MtCO2)
REL_TOTEM_PE_P123	Relation. Total emissions in PE (MtCO2)
REL_TOTEM_CE_P123	Relation. Total emissions in CE (MtCO2)
REL_TOTEM_TE_P123	Relation. Total emissions in TE (MtCO2)
REL_TOTEM_FE_P123	Relation. Total emissions in FE (MtCO2)
REL_TOTEMLCA_FE_P123	Relation. Total LCA emissions in FE (MtCO2)
REL_TOTEM_METHLEAK_P123	Relation. Total emissions from methane leakage (MtCO2)
REL_NOEMFE_P123	Relation. NO2 Emissions in final energy use (MtNO2/h)
REL_NOEMFE_ESST_P123	Relation. NO2 Emissions in final energy use in each ESST technology (MtNO2/h)

Name	**Description**
REL_SOEMFE_P123	Relation. SO2 Emissions in final energy use (MtSO2/h)
REL_SOEMFE_ESST_P123	Relation. SO2 Emissions in final energy use in each ESST technology (MtSO2/h)
REL_PMEMFE_P123	Relation. PM10 Emissions in final energy use (MtPM10/h)
REL_PMEMFE_ESST_P123	Relation. PM10 Emissions in final energy use in each ESST technology (MtPM10/h)
REL_TOTEM_NOFE_P123	Relation. Total NO2 emissions in FE (MtNO2)
REL_TOTEM_SOFE_P123	Relation. Total SO2 emissions in FE (MtSO2)
REL_TOTEM_PMFE_P123	Relation. Total PM10 emissions in FE (MtPM10)
REL_TOT_REELECGEN_EJ_P123	Relation. Total renewable electricity generation (throughout the complete year, centralised or distrib) (EJ)
REL_TOT_ELECGEN_EJ_P123	Relation. Total electricity generation (throughout the complete year, centralised or distrib) (EJ)
CONSTR_ESBALANCE_P123	Constraint. Energy Service balance (each energy service's units)
CONSTR_ESVMEXCLUSSION_P123	Constraint. ESVM exclussion (p.u.)
CONSTR_ENERGYBALESST_TE_P123	Constraint. Energy balance of EACH energy TE in each ESST (each ESST's activity units)

Name	**Description**
CONSTR_ENERGYBALESST_PE_P123	Constraint. Energy balance of EACH energy PE in each ESST (each ESST's activity units)
CONSTR_LOADSHIFTLIMTE_P123	Constraint. Load shifting limitations of energy TE in each ESST (GWh)
CONSTR_LOADSHIFTLIMPE_P123	Constraint. Load shifting limitations of energy PE in each ESST (GWh)
CONSTR_ESBALANCE_LIM_P123	Limit for Demand Supply
CONSTR_TEBALANCE_P123	Constraint. Transformed energy balance (GW)
CONSTR_TECAPLIM_P123	Constraint. Transformed energy capacity limitation (GW)
CONSTR_CEPREVCAPACTIV_P123	Constraint. Previous installed capacity activation (GW)
CONSTR_CECAPLIM_P123	Constraint. Converted energy capacity limitation (GW)
CONSTR_CEBALANCE_P123	Constraint. Converted energy balance (GW)
CONSTR_CEBALANCE_PS_P123	Constraint. Energy balance for Pumping Storage in each day (EJ)
CONSTR_CEBALANCE_RSCAP_P123	Constraint. Energy balance in CEHYRSCAP (hydro generation plants) in each period (EJ)
CONSTR_CEBALANCE_RURIV_P123	Constraint. Energy balance in CEHYRURIV (run off river plants) in each period (EJ)
CONSTR_CEOUTMAXSHARELIM_P123	Constraint. Converted energy maximum output share limitation (GW)

Name	**Description**
CONSTR_CEOUTMINSHARELIM_P123	Constraint. Converted energy minimum output share limitation (GW)
CONSTR_CEINPESHAREREQ_P123	Constraint. Converted energy PE input share requirements (GW)
CONSTR_CEINTESHAREREQ_P123	Constraint. Converted energy TE input share requirements (GW)
CONSTR_CETOTACTIVECAPLIM_P123	Constraint. Total active capacity limitation (GW)
CONSTR_CETOTACTIVECAPLIMOUT_P123	Constraint. Total active capacity limitation (GW)
CONSTR_CELOADFPROD_P123	Constraint. Production of each CE modelled through load factors (GW)
CONSTR_CEELERELIABADEQ_P23	Constraint. Adequacy constraint applicable to electricity generation CEs in set ceelecentral (GW)
CONSTR_CEELERELIABRSRV_P123	Constraint. Reserves constraint applicable to electricity generation CEs in set ceelecentral (GW)
CONSTR_CEREGASIFMINOUTPUT_P123	Constraint. Regasification terminals minimum output (technical minimum) (GW)
CONSTR_PEBALANCE_P123	Constraint. Primary energy balance (GW)
CONSTR_PEDOMCAPLIM_P123	Constraint. Domestic primary energy capacity limitation (GW)
CONSTR_PEMAXECONSYEAR_P123	Constraint. Primary energy yearly limitation for the elements in pelimey(EJ)

Name	Description
CONSTR_IMPTECAPLIM_P123	Constraint. Imported transformed energy capacity limitation (GW)
CONSTR_EXPTECAPLIM_P123	Constraint. Exported transformed energy capacity limitation (GW)
CONSTR_IMPPECAPLIM_P123	Constraint. Imported primary energy capacity limitation (GW)
CONSTR_EXPPECAPLIM_P123	Constraint. Exported primary energy capacity limitation (GW)

Equation Definitions

OBF_OFVA_TOTSUPCOSTOPERINVST_P23

$$\begin{aligned}&\mathrm{OFVA\_TOTSUPCOSTOPERINVST\_P23} = \mathrm{OFVP\_DOPECONSCOST} + \mathrm{OFVP\_DOPECOEMCOST} +\\&\mathrm{OFVP\_PEIMPORTCOST} - \mathrm{OFVP\_PEEXPORTREVE} + \mathrm{OFVP\_CECONVERCOST} +\\&\mathrm{OFVP\_CECONVEMCOST} + \mathrm{OFVP\_TETRANSPCOST} + \mathrm{OFVP\_TETRANEMCOST} +\\&\mathrm{OFVP\_TEIMPORTCOST} - \mathrm{OFVP\_TEEXPORTREVE} + \mathrm{OFVP\_FEUEMISSCOST} +\\&\mathrm{OFVP\_NONSUPFECOST} + \mathrm{OFVP\_CELERSRVCOST} + \mathrm{OFVP\_ACAPFIXDCOST} +\\&\mathrm{OFVP\_NCAPINVSCOST} + \mathrm{OFVP\_ESVMPROMOCOST} + \mathrm{OFVP\_ESSTLSTOTCOST} +\\&\mathrm{OFVP\_ESSTACTTOTCOST}\end{aligned}$$

OBF_OFVA_TOTSUPCOSTVULRES_P23

$$\begin{aligned}&\mathrm{OFVA\_TOTSUPCOSTVULRES\_P23} =\\[1em]&\mathrm{OFVP\_TOTTEVULCONSUM}_{\mathtt{TEELECE}} \cdot \mathrm{xGWhtoEJ} \cdot \mathrm{MEANELECOST} \cdot \mathrm{ActivateMeanElectricityCost} +\\[1em]&\mathrm{OFVP\_TOTTEVULCONSUM}_{\mathtt{TEELECE}} \cdot \mathrm{xGWhtoEJ} \cdot \mathrm{PRICEELECE} \cdot (1 - \mathrm{ActivateMeanElectricityCost}) +\\[1em]&\mathrm{OFVP\_TOTTEVULCONSUM}_{\mathtt{TEELEDIOTH}} \cdot \mathrm{xGWhtoEJ} \cdot \mathrm{MEANELECOST} \cdot \mathrm{ActivateMeanElectricityCost} +\\[1em]&\mathrm{OFVP\_TOTTEVULCONSUM}_{\mathtt{TEELEDIOTH}} \cdot \mathrm{xGWhtoEJ} \cdot \mathrm{PRICEELECE} \cdot (1 - \mathrm{ActivateMeanElectricityCost}) +\end{aligned}$$

$$\text{OFVP\_TOTTEVULCONSUM}_{\texttt{TENAGAS}} \cdot \text{xGWhtoEJ} \cdot \text{MEANGASCOST} \cdot \text{ActivateMeanElectricityCost} +$$

$$\sum_{teoilderiv} (\text{OFVP\_TOTTEVULCONSUM}_{teoilderiv} \cdot \text{xGWhtoEJ} \cdot \text{MEANOILDERIVCOST}_{teoilderiv}) \cdot \text{ActivateMeanElectricityCost} +$$

$$\text{OFVP\_TOTTEVULCONSUM}_{\texttt{TEBIOETH}} \cdot \text{xGWhtoEJ} \cdot \text{MEANBIOETHCOST} \cdot \text{ActivateMeanElectricityCost} +$$

$$\text{OFVP\_TOTTEVULCONSUM}_{\texttt{TEBIODIE}} \cdot \text{xGWhtoEJ} \cdot \text{MEANBIODIECOST} \cdot \text{ActivateMeanElectricityCost} +$$

$$\text{OFVP\_TOTTEVULCONSUM}_{\texttt{TECOAL}} \cdot \text{xGWhtoEJ} \cdot \text{TEIMPAVERAGECOST}_{\texttt{TECOAL}} +$$

$$\text{OFVP\_TOTTEVULCONSUM}_{\texttt{TEBIOMA}} \cdot \text{xGWhtoEJ} \cdot \text{TEIMPAVERAGECOST}_{\texttt{TEBIOMA}} +$$

$$\sum_{pe} (\text{OFVP\_TOTPEVULCONSUM}_{pe} \cdot \text{xGWhtoEJ} \cdot \text{PEIMPAVERAGECOST}_{pe}) + \text{OFVP\_NONSUPVULFECOST} +$$

$$\text{OFVP\_VULESSTACTTOTCOST}$$

OBF_OFVA_TOTEMISSIONS_P23

$$\text{OFVA\_TOTEMISSIONS\_P23} = \text{TOTEM}$$

OBF_OFVA_ENERGY_DEPENDENCE_P23

$$\text{OFVA\_ENERGY\_DEPENDENCE\_P23} = \frac{\text{TOT\_ENERGY\_USED\_DOMyIMP\_EJ} - \text{TOT\_ENERGY\_USED\_DOM\_EJ}}{\text{TOT\_ENERGY\_USED\_DOMyIMP\_EJ} + EPS}$$

OBF_OFVA_TOTSECCOST_P23

$$\text{OFVA\_TOTSECCOST\_P23} = \text{OFVP\_PEIMPORTSECCOST} + \text{OFVP\_TEIMPORTSECCOST}$$

OBF_OFVA_JOBS_P23

$$\text{OFVA\_JOBS\_P23} = (\text{OFVP\_CONSJOB} + \text{OFVP\_OPJOB} + \text{OFVP\_ESSTJOB}) \cdot \text{xDiv1E6}$$

OBF_OFVA_TOTEMISNO_P23

$$\text{OFVA\_TOTEMISNO\_P23} = \text{TOTEM\_NOFE}$$

OBF_OFVA_TOTEMISSO_P23

$$\text{OFVA\_TOTEMISSO\_P23} = \text{TOTEM\_SOFE}$$

OBF_OFVA_TOTEMISPM_P23

OFVA_TOTEMISPM_P23 = TOTEM_PMFE

OBF_OFVA_MULTICRITERIA_P23

OFVA_MULTICRITERIA_P23 =

$$\text{MULTWEIGHT}_{\texttt{COST}} \cdot \frac{\text{OFVA\_TOTSUPCOSTOPERINVST\_P23}-\text{MULTIDEAL}_{\texttt{COST}}}{\text{MULTANTIDEAL}_{\texttt{COST}}-\text{MULTIDEAL}_{\texttt{COST}}} \cdot \text{MULTACTIVE}_{\texttt{COST}} +$$

$$\text{MULTWEIGHT}_{\texttt{PE}} \cdot \frac{\text{OFVA\_TOTSUPCOSTVULRES\_P23}-\text{MULTIDEAL}_{\texttt{PE}}}{\text{MULTANTIDEAL}_{\texttt{PE}}-\text{MULTIDEAL}_{\texttt{PE}}} \cdot \text{MULTACTIVE}_{\texttt{PE}} +$$

$$\text{MULTWEIGHT}_{\texttt{CO2}} \cdot \frac{\text{OFVA\_TOTEMISSIONS\_P23}-\text{MULTIDEAL}_{\texttt{CO2}}}{\text{MULTANTIDEAL}_{\texttt{CO2}}-\text{MULTIDEAL}_{\texttt{CO2}}} \cdot \text{MULTACTIVE}_{\texttt{CO2}} +$$

$$\text{MULTWEIGHT}_{\texttt{DEP}} \cdot \frac{\text{OFVA\_ENERGY\_DEPENDENCE\_P23}-\text{MULTIDEAL}_{\texttt{DEP}}}{\text{MULTANTIDEAL}_{\texttt{DEP}}-\text{MULTIDEAL}_{\texttt{DEP}}} \cdot \text{MULTACTIVE}_{\texttt{DEP}} +$$

$$\text{MULTWEIGHT}_{\texttt{SO2}} \cdot \frac{\text{OFVA\_TOTEMISSO\_P23}-\text{MULTIDEAL}_{\texttt{SO2}}}{\text{MULTANTIDEAL}_{\texttt{SO2}}-\text{MULTIDEAL}_{\texttt{SO2}}} \cdot \text{MULTACTIVE}_{\texttt{SO2}} +$$

$$\text{MULTWEIGHT}_{\texttt{NOX}} \cdot \frac{\text{OFVA\_TOTEMISNO\_P23}-\text{MULTIDEAL}_{\texttt{NOX}}}{\text{MULTANTIDEAL}_{\texttt{NOX}}-\text{MULTIDEAL}_{\texttt{NOX}}} \cdot \text{MULTACTIVE}_{\texttt{NOX}} +$$

$$\text{MULTWEIGHT}_{\texttt{PM25}} \cdot \frac{\text{OFVA\_TOTEMISPM\_P23}-\text{MULTIDEAL}_{\texttt{PM25}}}{\text{MULTANTIDEAL}_{\texttt{PM25}}-\text{MULTIDEAL}_{\texttt{PM25}}} \cdot \text{MULTACTIVE}_{\texttt{PM25}} +$$

$$\text{MULTWEIGHT}_{\texttt{SEC}} \cdot \frac{\text{OFVA\_TOTSECCOST\_P23}-\text{MULTIDEAL}_{\texttt{SEC}}}{\text{MULTANTIDEAL}_{\texttt{SEC}}-\text{MULTIDEAL}_{\texttt{SEC}}} \cdot \text{MULTACTIVE}_{\texttt{SEC}} +$$

$$\text{MULTWEIGHT}_{\texttt{JOB}} \cdot \frac{|(\text{MULTIDEAL}_{\texttt{JOB}}-\text{OFVA\_JOBS\_P23})|}{\text{MULTIDEAL}_{\texttt{JOB}}-\text{MULTANTIDEAL}_{\texttt{JOB}}} \cdot \text{MULTACTIVE}_{\texttt{JOB}} \qquad | \ (\text{ActivateLinf} = 0)$$

OBF_OFVA_MULTICRITERIALINF_P23

OFVA_MULTICRITERIALINF_P23 = DMULT | (ActivateLinf = 1)

OBF_OFVA_MULTICRITERIALANDA_P23

OFVA_MULTICRITERIALANDA_P23 =

$$\text{LANDA} \cdot (\text{MULTWEIGHT}_{\texttt{COST}} \cdot \frac{\text{OFVA\_TOTSUPCOSTOPERINVST\_P23}-\text{MULTIDEAL}_{\texttt{COST}}}{\text{MULTANTIDEAL}_{\texttt{COST}}-\text{MULTIDEAL}_{\texttt{COST}}} \cdot \text{MULTACTIVE}_{\texttt{COST}} +$$
$$\text{MULTWEIGHT}_{\texttt{PE}} \cdot \frac{\text{OFVA\_TOTSUPCOSTVULRES\_P23}-\text{MULTIDEAL}_{\texttt{PE}}}{\text{MULTANTIDEAL}_{\texttt{PE}}-\text{MULTIDEAL}_{\texttt{PE}}} \cdot \text{MULTACTIVE}_{\texttt{PE}} +$$

$$\text{MULTWEIGHT}_{\texttt{CO2}} \cdot \frac{\text{OFVA\_TOTEMISSIONS\_P23}-\text{MULTIDEAL}_{\texttt{CO2}}}{\text{MULTANTIDEAL}_{\texttt{CO2}}-\text{MULTIDEAL}_{\texttt{CO2}}} \cdot \text{MULTACTIVE}_{\texttt{CO2}} +$$

$$\mathrm{MULTWEIGHT}_{\mathtt{DEP}} \cdot \frac{\mathrm{OFVA\_ENERGY\_DEPENDENCE\_P23} - \mathrm{MULTIDEAL}_{\mathtt{DEP}}}{\mathrm{MULTANTIDEAL}_{\mathtt{DEP}} - \mathrm{MULTIDEAL}_{\mathtt{DEP}}} \cdot \mathrm{MULTACTIVE}_{\mathtt{DEP}} +$$

$$\mathrm{MULTWEIGHT}_{\mathtt{SO2}} \cdot \frac{\mathrm{OFVA\_TOTEMISSO\_P23} - \mathrm{MULTIDEAL}_{\mathtt{SO2}}}{\mathrm{MULTANTIDEAL}_{\mathtt{SO2}} - \mathrm{MULTIDEAL}_{\mathtt{SO2}}} \cdot \mathrm{MULTACTIVE}_{\mathtt{SO2}} +$$

$$\mathrm{MULTWEIGHT}_{\mathtt{NOX}} \cdot \frac{\mathrm{OFVA\_TOTEMISNO\_P23} - \mathrm{MULTIDEAL}_{\mathtt{NOX}}}{\mathrm{MULTANTIDEAL}_{\mathtt{NOX}} - \mathrm{MULTIDEAL}_{\mathtt{NOX}}} \cdot \mathrm{MULTACTIVE}_{\mathtt{NOX}} +$$

$$\mathrm{MULTWEIGHT}_{\mathtt{PM25}} \cdot \frac{\mathrm{OFVA\_TOTEMISPM\_P23} - \mathrm{MULTIDEAL}_{\mathtt{PM25}}}{\mathrm{MULTANTIDEAL}_{\mathtt{PM25}} - \mathrm{MULTIDEAL}_{\mathtt{PM25}}} \cdot \mathrm{MULTACTIVE}_{\mathtt{PM25}} +$$

$$\mathrm{MULTWEIGHT}_{\mathtt{SEC}} \cdot \frac{\mathrm{OFVA\_TOTSECCOST\_P23} - \mathrm{MULTIDEAL}_{\mathtt{SEC}}}{\mathrm{MULTANTIDEAL}_{\mathtt{SEC}} - \mathrm{MULTIDEAL}_{\mathtt{SEC}}} \cdot \mathrm{MULTACTIVE}_{\mathtt{SEC}} +$$

$$\mathrm{MULTWEIGHT}_{\mathtt{JOB}} \cdot \frac{|(\mathrm{MULTIDEAL}_{\mathtt{JOB}} - \mathrm{OFVA\_JOBS\_P23})|}{\mathrm{MULTIDEAL}_{\mathtt{JOB}} - \mathrm{MULTANTIDEAL}_{\mathtt{JOB}}} \cdot \mathrm{MULTACTIVE}_{\mathtt{JOB}}) +$$

$$(1 - \mathrm{LANDA}) \cdot \mathrm{DMULT} \qquad | \ (\mathrm{ActivateLinf} = 2)$$

OBF_OFVA_IDEALTOTSUPCOSTVULRES_P23

$$\mathrm{OFVA\_TOTSUPCOSTVULRES\_P23} \leq \mathrm{IDEALVULRES} \qquad | \ \mathrm{LexicoPE}$$

OBF_OFVA_IDEALTOTEMISSIONS_P23

$$\mathrm{OFVA\_TOTEMISSIONS\_P23} \leq \mathrm{IDEALTOTEMISSIONS} \qquad | \ \mathrm{LexicoCO}$$

OBF_OFVA_IDEALENERGY_DEPENDENCE_P23

$$\mathrm{OFVA\_ENERGY\_DEPENDENCE\_P23} \leq \mathrm{IDEALENERDEP} \qquad | \ (\mathrm{MULTACTIVE}_{\mathtt{DEP}} \land \mathrm{LexicoDEP})$$

OBF_TEELECEPECOST_P23

$$\mathrm{TEELECEPECOST} =$$

$$\sum_{pe}\Big(\sum_{ceelecentral,p,s,l} (\mathrm{D}_{p,s,l} \cdot \mathrm{QPWR}_{pe,ceelecentral,p,s,l}) \cdot \mathrm{xGWhtoEJ} \cdot \mathrm{PEIMPAVERAGECOST}_{pe}\Big) +$$
$$\sum_{te}\Big(\sum_{ceelecentral,p,s,l} (\mathrm{D}_{p,s,l} \cdot \mathrm{QPWR}_{te,ceelecentral,p,s,l}) \cdot \mathrm{xGWhtoEJ} \cdot \mathrm{TEIMPAVERAGECOST}_{te}\Big)$$

OBF_TEELECECECOST_P23

$$\mathrm{TEELECECECOST} =$$

$$\sum_{ceelecentral,p,s,l} (\mathrm{QPWR}_{ceelecentral,\mathtt{TEELECE},p,s,l} \cdot \mathrm{D}_{p,s,l} \cdot \mathrm{xGWhtoEJ} \cdot \mathrm{ECOVCCE}_{ceelecentral,\mathtt{TEELECE}}) +$$
$$\sum_{ceelediind,p,s,l} (\mathrm{QPWR}_{ceelediind,\mathtt{TEELEDIIND},p,s,l} \cdot \mathrm{D}_{p,s,l} \cdot \mathrm{xGWhtoEJ} \cdot \mathrm{ECOVCCE}_{ceelediind,\mathtt{TEELEDIIND}}) +$$
$$\sum_{ceeledioth,p,s,l} (\mathrm{QPWR}_{ceeledioth,\mathtt{TEELEDIOTH},p,s,l} \cdot \mathrm{D}_{p,s,l} \cdot \mathrm{xGWhtoEJ} \cdot \mathrm{ECOVCCE}_{ceeledioth,\mathtt{TEELEDIOTH}}) +$$

$$\sum_{ceelecentral} (\text{TOTACTIVECAP}_{ceelecentral} \cdot \text{ACECAPFIXDCOSTYEAR}_{ceelecentral}) + \sum_{ceelediind} (\text{TOTACTIVECAP}_{ceelediind} \cdot \text{ACECAPFIXDCOSTYEAR}_{ceelediind}) + \sum_{ceelediothh} (\text{TOTACTIVECAP}_{ceelediothh} \cdot \text{ACECAPFIXDCOSTYEAR}_{ceelediothh})$$

OBF_TEELECETECOST_P23

$$\text{TEELECETECOST} = \text{OFVP\_TETRANSPCOST\_TE}_{\texttt{TEELECE}} + \text{OFVP\_TETRANSPCOST\_TE}_{\texttt{TEELEDIIND}} + \text{OFVP\_TETRANSPCOST\_TE}_{\texttt{TEELEDIOTH}}$$

OBF_TEELECENCAPINVSCOST_P23

$$\text{TEELECENCAPINVSCOST} = \sum_{ceelecentral} (\text{NEWINSTALLCAP}_{ceelecentral} \cdot \text{NEWICAPINVCOSTYEAR}_{ceelecentral}) + \sum_{ceelediind} (\text{NEWINSTALLCAP}_{ceelediind} \cdot \text{NEWICAPINVCOSTYEAR}_{ceelediind}) + \sum_{ceelediothh} (\text{NEWINSTALLCAP}_{ceelediothh} \cdot \text{NEWICAPINVCOSTYEAR}_{ceelediothh})$$

OBF_TOTTEELECE_P23

$$\text{TOTTEELECE} = \sum_{ceelecentral,p,s,l} (\text{QPWR}_{ceelecentral,\texttt{TEELECE},p,s,l} \cdot \text{D}_{p,s,l}) + \sum_{ceelediind,p,s,l} (\text{QPWR}_{ceelediind,\texttt{TEELEDIIND},p,s,l} \cdot \text{D}_{p,s,l}) + \sum_{ceelediothh,p,s,l} (\text{QPWR}_{ceelediothh,\texttt{TEELEDIOTH},p,s,l} \cdot \text{D}_{p,s,l}) \quad | \ (\text{FixedTotteelece} = 0)$$

OBF_MEANTOTTEELECE_P23

$$\text{TOTTEELECE} = \text{MEANTOTTEELECE} \quad | \ \text{FixedTotteelece}$$

OBF_MEANELECOST_P23

$$\text{MEANELECOST} = \frac{\text{TEELECEPECOST+TEELECECECOST+TEELECETECOST+TEELECENCAPINVSCOST}}{\text{TOTTEELECE}+EPS} \cdot \text{xMul1E6}$$

$$| \ (\text{ActivateMeanElectricityCost} \wedge (\text{FixedTotteelece} = 0))$$

OBF_FIXEDMEANELECOST_P23

$$\mathrm{MEANELECOST} = \frac{\mathrm{TEELECEPECOST}+\mathrm{TEELECECECOST}+\mathrm{TEELECETECOST}+\mathrm{TEELECENCAPINVSCOST}}{\mathrm{MEANTOTTEELECE}+EPS} \cdot \mathrm{xMul1E6}$$

$$\mid (\mathrm{ActivateMeanElectricityCost} \wedge \mathrm{FixedTotteelece})$$

OBF_MEANGASCOST_P23

$$\mathrm{MEANGASCOST} = \mathrm{TEIMPAVERAGECOST}_{\mathtt{TENAGAS}} + \frac{\mathrm{MEANGASCOSTNEWCAP}+\mathrm{MEANGASCOSTACTCAP}+\mathrm{MEANGASCOSTVAR}}{\mathrm{TOTTENAGAS}+EPS}$$

OBF_MEANBIODIECOST_P23

$$\mathrm{MEANBIODIECOST} = \mathrm{TEIMPAVERAGECOST}_{\mathtt{TEBIODIE}} + \frac{\mathrm{MEANBIODIECOSTNEWCAP}+\mathrm{MEANBIODIECOSTACTCAP}+\mathrm{MEANBIODIECOSTVAR}}{\mathrm{TOTTEBIODIE}+EPS}$$

OBF_MEANBIOETHCOST_P23

$$\mathrm{MEANBIOETHCOST} = \mathrm{TEIMPAVERAGECOST}_{\mathtt{TEBIOETH}} + \frac{\mathrm{MEANBIOETHCOSTNEWCAP}+\mathrm{MEANBIOETHCOSTACTCAP}+\mathrm{MEANBIOETHCOSTVAR}}{\mathrm{TOTTEBIOETH}+EPS}$$

OBF_MEANOILDERIVCOST_P23$_{teoilderiv}$

$$\mathrm{MEANOILDERIVCOST}_{teoilderiv} = \mathrm{TEIMPAVERAGECOST}_{teoilderiv} + \frac{\mathrm{MEANOILCOSTNEWCAP}\cdot\mathrm{CEMEANTEOUTSHARE}+\mathrm{MEANOILCOSTACTCAP}\cdot\mathrm{CEMEANTEOUTSHARE}+\mathrm{MEANOILDERIVCOSTVAR}}{\mathrm{TOTTEOP}_{teoilderiv}+EPS} \qquad \forall teoilderiv$$

OBF_MULTLINF_CT

$$\mathrm{MULTLINF\_CT} \leq \mathrm{DMULT} \qquad \mid ((\mathrm{ActivateLinf} = 1) \vee (\mathrm{ActivateLinf} = 2) \wedge (\mathrm{LANDA} \neq 1))$$

OBF_MULTLINF_PE

$$\mathrm{MULTLINF\_PE} \leq \mathrm{DMULT} \qquad \mid ((\mathrm{ActivateLinf} = 1) \vee (\mathrm{ActivateLinf} = 2) \wedge (\mathrm{LANDA} \neq 1))$$

OBF_MULTLINF_CO

$$\mathrm{MULTLINF\_CO} \leq \mathrm{DMULT} \qquad \mid ((\mathrm{ActivateLinf} = 1) \vee (\mathrm{ActivateLinf} = 2) \wedge (\mathrm{LANDA} \neq 1))$$

OBF_MULTLINF_DE

$$\text{MULTLINF\_DE} \leq \text{DMULT} \qquad | \ ((\text{ActivateLinf} = 1) \lor (\text{ActivateLinf} = 2) \land (\text{LANDA} \neq 1))$$

OBF_MULTLINF_SO

$$\text{MULTLINF\_SO} \leq \text{DMULT} \qquad | \ ((\text{ActivateLinf} = 1) \lor (\text{ActivateLinf} = 2) \land (\text{LANDA} \neq 1))$$

OBF_MULTLINF_NO

$$\text{MULTLINF\_NO} \leq \text{DMULT} \qquad | \ ((\text{ActivateLinf} = 1) \lor (\text{ActivateLinf} = 2) \land (\text{LANDA} \neq 1))$$

OBF_MULTLINF_PM

$$\text{MULTLINF\_PM} \leq \text{DMULT} \qquad | \ ((\text{ActivateLinf} = 1) \lor (\text{ActivateLinf} = 2) \land (\text{LANDA} \neq 1))$$

OBF_MULTLINF_SE

$$\text{MULTLINF\_SE} \leq \text{DMULT} \qquad | \ ((\text{ActivateLinf} = 1) \lor (\text{ActivateLinf} = 2) \land (\text{LANDA} \neq 1))$$

OBF_MULTLINF_JO

$$\text{MULTLINF\_JO} \leq \text{DMULT} \qquad | \ ((\text{ActivateLinf} = 1) \lor (\text{ActivateLinf} = 2) \land (\text{LANDA} \neq 1))$$

REL_OFVP_DOPECONSCOST_P123

$$\text{OFVP\_DOPECONSCOST} = \sum_{dr,pe,p,s,l} (\text{QPWR}_{dr,pe,p,s,l} \cdot \text{D}_{p,s,l} \cdot \text{xGWhtoEJ} \cdot \text{ECOVCPEDOM}_{pe})$$

REL_OFVP_DOPECOEMCOST_P123

$$\text{OFVP\_DOPECOEMCOST} = (\sum_{pe,p,s,l} (\text{D}_{p,s,l} \cdot \text{EMPE}_{pe,p,s,l}) \cdot \text{CO2PRICE})[(\text{CO2EmissCostInObjFunct} = 1)]$$

REL_OFVP_PEIMPORTCOST_P123

$$\text{OFVP\_PEIMPORTCOST} = \sum_{rg,pe,p,s,l|(\text{PEIMPCAP}_{pe,rg}>0)} (\text{QPWR}_{rg,pe,p,s,l} \cdot \text{D}_{p,s,l} \cdot \text{xGWhtoEJ} \cdot \text{PEIMPCOST}_{pe,rg})$$

REL_OFVP_PEEXPORTREVE_P123

$$\text{OFVP\_PEEXPORTREVE} = \sum_{pe,rg,p,s,l|(\text{PEEXPCAP}_{pe,rg}>0)} (\text{QPWR}_{pe,rg,p,s,l} \cdot \text{D}_{p,s,l} \cdot \text{xGWhtoEJ} \cdot \text{PEEXPREVE}_{pe,rg})$$

REL_OFVP_CECONVERCOST_P123

$$\text{OFVP\_CECONVERCOST} = \sum_{ce,te,p,s,l,ceteflows_{ce,te}} (\text{QPWR}_{ce,te,p,s,l} \cdot \text{D}_{p,s,l} \cdot \text{xGWhtoEJ} \cdot \text{ECOVCCE}_{ce,te})$$

REL_OFVP_CECONVEMCOST_P123

$$\text{OFVP\_CECONVEMCOST} = \left(\sum_{ce,te,p,s,l,ceteflows_{ce,te}} (\text{D}_{p,s,l} \cdot \text{EMCE}_{ce,te,p,s,l}) \cdot \text{CO2PRICE}\right)[(\text{CO2EmissCostInObjFunct} = 1)]$$

REL_OFVP_TETRANSPCOST_P123

$$\text{OFVP\_TETRANSPCOST} = \sum_{te} \text{OFVP\_TETRANSPCOST\_TE}_{te}$$

REL_OFVP_TETRANSPCOST_TEGENEQ_P123$_{te}$

$$\text{OFVP\_TETRANSPCOST\_TE}_{te} = \sum_{p,s,l} (\text{TOTQTEIN}_{te,p,s,l} \cdot \text{D}_{p,s,l} \cdot \text{xGWhtoEJ} \cdot \text{ECOVCTE}_{te}) \qquad \forall te \mid (\neg((te = \texttt{TEELECE}) \lor (te = \texttt{TEELEDIIND}) \lor (te = \texttt{TEELEDIOTH})))$$

REL_OFVP_TETRANSPCOST_TENAGAS_P123$_{te}$

$$\text{OFVP\_TETRANSPCOST\_TE}_{te} = \frac{\text{ADDED\_NGNETWORK\_CAP} \cdot \text{ng\_network\_cost}}{1000000} \qquad \forall te \mid (te = \texttt{TENAGAS})$$

REL_OFVP_TETRANSPCOST_TEELECE_P123$_{te}$

$$\text{OFVP\_TETRANSPCOST\_TE}_{te} = (\text{unitarynetwokcost}_{\texttt{TEELECE}} \cdot \sum_{ce\_centr\_interm} \text{NEWINSTALLCAP}_{ce\_centr\_interm} \cdot \text{xDiv1E3})[\text{ElecNetworkCost}] \; \forall te \mid (te = \texttt{TEELECE})$$

REL_OFVP_TETRANSPCOST_TEELEDIIND_P123$_{te}$

$$\text{OFVP\_TETRANSPCOST\_TE}_{te} = (\text{unitarynetwokcost}_{\texttt{TEELEDIIND}} \cdot \sum_{ce,ceteflows_{ce,te}} \text{NEWINSTALLCAP}_{ce} \cdot \text{xDiv1E3})[\text{ElecNetworkCost}] \; \forall te \mid (te = \texttt{TEELEDIIND})$$

REL_OFVP_TETRANSPCOST_TEELEDIOTH_P123$_{te}$

$$\text{OFVP\_TETRANSPCOST\_TE}_{te} = (\text{unitarynetwokcost}_{\texttt{TEELEDIOTH}} \cdot \sum_{ce,ceteflows_{ce,te}} \text{NEWINSTALLCAP}_{ce} \cdot \text{xDiv1E3})[\text{ElecNetworkCost}] \; \forall te \mid (te = \texttt{TEELEDIOTH})$$

REL_OFVP_TETRANEMCOST_P123

$$\text{OFVP\_TETRANEMCOST} = \Big(\sum_{te,p,s,l} (\mathrm{D}_{p,s,l} \cdot \mathrm{EMTE}_{te,p,s,l}) \cdot \text{CO2PRICE}\Big)[(\text{CO2EmissCostInObjFunct} = 1)]$$

REL_OFVP_TEIMPORTCOST_P123

$$\text{OFVP\_TEIMPORTCOST} = \sum_{rg,te,p,s,l|(\text{TEIMPCAP}_{te,rg}>0)} (\text{QPWR}_{rg,te,p,s,l} \cdot \mathrm{D}_{p,s,l} \cdot \text{xGWhtoEJ} \cdot \text{TEIMPCOST}_{te,rg})$$

REL_OFVP_TEEXPORTREVE_P123

$$\text{OFVP\_TEEXPORTREVE} = \sum_{te,rg,p,s,l|(\text{TEEXPCAP}_{te,rg}>0)} (\text{QPWR}_{te,rg,p,s,l} \cdot \mathrm{D}_{p,s,l} \cdot \text{xGWhtoEJ} \cdot \text{TEEXPREVE}_{te,rg})$$

REL_OFVP_FEUEMISSCOST_P123

$$\text{OFVP\_FEUEMISSCOST} = \Big(\sum_{ds,p,s,l} (\mathrm{D}_{p,s,l} \cdot \mathrm{EMFE}_{ds,p,s,l}) \cdot \text{CO2PRICE}\Big)[(\text{CO2EmissCostInObjFunct} = 1)]$$

REL_OFVP_CELERSRVCOST_P123

$$\text{OFVP\_CELERSRVCOST} = \sum_{ceelecentral,p,s,l} (\text{CEELERSRVPWR}_{ceelecentral,p,s,l} \cdot \mathrm{D}_{p,s,l} \cdot \text{xGWhtoEJ} \cdot \text{CEELERSRVCOST}_{ceelecentral})$$

REL_OFVP_ACAPFIXDCOST_P123

$$\text{OFVP\_ACAPFIXDCOST} = \sum_{ce} (\text{TOTACTIVECAP}_{ce} \cdot \text{ACECAPFIXDCOSTYEAR}_{ce})$$

REL_OFVP_NCAPINVSCOST_P23

$$\text{OFVP\_NCAPINVSCOST} = \sum_{ce} (\text{NEWINSTALLCAP}_{ce} \cdot \text{NEWICAPINVCOSTYEAR}_{ce})$$

REL_OFVP_NONSUPFECOST_P123

$$\text{OFVP\_NONSUPFECOST} = \sum_{ds} \text{OFVP\_NONSUPFECOST\_DS}_{ds}$$

REL_OFVP_NONSUPFECOST_DS_P123$_{ds}$

$$\text{OFVP\_NONSUPFECOST\_DS}_{ds} = \sum_{esst,p,s,l,esstbds_{esst,ds}} (\text{NSFECOST}_{esst,ds} \cdot \text{D}_{p,s,l} \cdot \text{xGWhtoEJ} \cdot (\sum_{te,teesstflows_{te,esst}} \text{QPWRNS}_{te,esst,p,s,l} + \sum_{pe,peesstflows_{pe,esst}} \text{QPWRNS}_{pe,esst,p,s,l}))$$

$\forall ds$

REL_OFVP_NONSUPVULFECOST_P123

$$\text{OFVP\_NONSUPVULFECOST} = \text{OFVP\_NONSUPVULFECOST\_DS}$$

REL_OFVP_NONSUPVULFECOST_DS_P123

$$\text{OFVP\_NONSUPVULFECOST\_DS} = \sum_{esst,p,s,l,esstbds_{esst,'DSOTH_VULRES'}} (\text{NSFECOST}_{esst,\texttt{DSOTH\_VULRES}} \cdot \text{D}_{p,s,l} \cdot \text{xGWhtoEJ} \cdot (\sum_{te,teesstflows_{te,esst}} \text{QPWRNS}_{te,esst,p,s,l} + \sum_{pe,peesstflows_{pe,esst}} \text{QPWRNS}_{pe,esst,p,s,l}))$$

REL_OFVP_ESVMPROMOCOST_P23

$$\text{OFVP\_ESVMPROMOCOST} = \sum_{esvm} (\text{ESVMLVL}_{esvm} \cdot \text{ESVMCOSTYEAR}_{esvm})[(\text{ESVMAllowed} = 1)]$$

REL_OFVP_ESSTLSTOTCOST_P123

$$\text{OFVP\_ESSTLSTOTCOST} = \sum_{esst} (\text{ESSTLSCOST}_{esst} \cdot (\sum_{te,teesstflows_{te,esst}} \text{TOTLSTEENERGY}_{esst,te} + \sum_{pe,peesstflows_{pe,esst}} \text{TOTLSPEENERGY}_{esst,pe}))$$

REL_OFVP_ESSTACTTOTCOST_P123

$$\text{OFVP\_ESSTACTTOTCOST} = \sum_{esst,p,s,l} (\text{QACTESST}_{esst,p,s,l} \cdot \text{ESSTCOSTPACTUY}_{esst})$$

REL_OFVP_VULESSTACTTOTCOST_P123

$$\text{OFVP\_VULESSTACTTOTCOST} = \sum_{vul\_esst,p,s,l} (\text{QACTESST}_{vul\_esst,p,s,l} \cdot \text{ESSTCOSTPACTUY}_{vul\_esst})$$

REL_OFVP_TOTTEVULCONSUM_P123$_{te}$

$$\text{OFVP\_TOTTEVULCONSUM}_{te} = \sum_{vul\_esst,p,s,l} (\text{QPWR}_{te,vul\_esst,p,s,l} \cdot \text{D}_{p,s,l}) \qquad \forall te$$

REL_OFVP_TOTPEVULCONSUM_P123$_{pe}$

$$\text{OFVP\_TOTPEVULCONSUM}_{pe} = \sum_{vul\_esst,p,s,l} (\text{QPWR}_{pe,vul\_esst,p,s,l} \cdot \text{D}_{p,s,l}) \qquad \forall pe$$

REL_OFVP_PEIMPORTSECCOST_P123

$$\text{OFVP\_PEIMPORTSECCOST} = \sum_{rg,pe,p,s,l|(\text{PEIMPCAP}_{pe,rg}>0)} (\text{QPWR}_{rg,pe,p,s,l} \cdot \text{D}_{p,s,l} \cdot \text{xGWhtoEJ} \cdot \text{PEIMPSECCOST}_{pe,rg}) + \sum_{dr,pe,p,s,l|(\text{PEDOMCONSCAP}_{pe}>0)} (\text{QPWR}_{dr,pe,p,s,l} \cdot \text{D}_{p,s,l} \cdot \text{xGWhtoEJ} \cdot \text{ECOVSECPEDOM}_{pe})$$

REL_OFVP_TEIMPORTSECCOST_P123

$$\text{OFVP\_TEIMPORTSECCOST} = \sum_{rg,te,p,s,l|(\text{TEIMPCAP}_{te,rg}>0)} (\text{QPWR}_{rg,te,p,s,l} \cdot \text{D}_{p,s,l} \cdot \text{xGWhtoEJ} \cdot \text{TEIMPSECCOST}_{te,rg})$$

REL_OFVP_CONSJOB_P123

$$\text{OFVP\_CONSJOB} = \sum_{ce} (\text{NEWINSTALLCAP}_{ce} \cdot \text{CECONSJOB}_{ce})$$

REL_OFVP_OPJOB_P123

$$\text{OFVP\_OPJOB} = \sum_{ce} (\text{TOTACTIVECAP}_{ce} \cdot \text{CEOPJOB}_{ce})$$

REL_OFVP_ESSTJOB_P123

$$\text{OFVP\_ESSTJOB} = \sum_{esst,p,s,l} (\text{QACTESST}_{esst,p,s,l} \cdot \text{ESSTJOBPACTUY}_{esst}) \cdot \text{xMul1E6}$$

REL_TOT_ENERGY_USED_DOMyIMP_EJ

$$\text{TOT\_ENERGY\_USED\_DOMyIMP\_EJ} = \text{xGWhtoEJ} \cdot \Big(\sum_{dr,pe,p,s,l} (\text{QPWR}_{dr,pe,p,s,l} \cdot \text{D}_{p,s,l}) + \sum_{rg,pe,p,s,l} (\text{QPWR}_{rg,pe,p,s,l} \cdot \text{D}_{p,s,l}) + \sum_{rg,te,p,s,l} (\text{QPWR}_{rg,te,p,s,l} \cdot \text{D}_{p,s,l}) \Big)$$

REL_TOT_ENERGY_USED_DOM_EJ

$$\text{TOT\_ENERGY\_USED\_DOM\_EJ} = \text{xGWhtoEJ} \cdot \sum_{dr,pe,p,s,l} (\text{QPWR}_{dr,pe,p,s,l} \cdot \text{D}_{p,s,l})$$

REL_MEANGASCOSTNEWCAP

$$\mathrm{MEANGASCOSTNEWCAP} = \mathrm{NEWINSTALLCAP}_{\texttt{CEREGASIF}} \cdot \mathrm{NEWICAPINVCOSTYEAR}_{\texttt{CEREGASIF}}$$

REL_MEANGASCOSTACTCAP

$$\mathrm{MEANGASCOSTACTCAP} = \mathrm{TOTACTIVECAP}_{\texttt{CEREGASIF}} \cdot \mathrm{ACECAPFIXDCOSTYEAR}_{\texttt{CEREGASIF}}$$

REL_MEANGASCOSTVAR

$$\mathrm{MEANGASCOSTVAR} = \sum_{ce,p,s,l} (\mathrm{QPWR}_{ce,\texttt{TENAGAS},p,s,l} \cdot \mathrm{D}_{p,s,l} \cdot \mathrm{xGWhtoEJ} \cdot \mathrm{ECOVCCE}_{ce,\texttt{TENAGAS}})$$

REL_TOTTENAGAS

$$\mathrm{TOTTENAGAS} = \sum_{ce,p,s,l} (\mathrm{QPWR}_{ce,\texttt{TENAGAS},p,s,l} \cdot \mathrm{D}_{p,s,l})$$

REL_MEANOILCOSTNEWCAP$_{ce}$

$$\mathrm{MEANOILCOSTNEWCAP} = \sum_{cecroilrefin} (\mathrm{NEWINSTALLCAP}_{cecroilrefin} \cdot \mathrm{NEWICAPINVCOSTYEAR}_{cecroilrefin}) \qquad \forall ce$$

REL_MEANOILCOSTACTCAP$_{ce}$

$$\mathrm{MEANOILCOSTACTCAP} = \sum_{cecroilrefin} (\mathrm{TOTACTIVECAP}_{cecroilrefin} \cdot \mathrm{ACECAPFIXDCOSTYEAR}_{cecroilrefin}) \qquad \forall ce$$

REL_MEANOILDERIVCOSTVAR$_{teoilderiv}$

$$\mathrm{MEANOILDERIVCOSTVAR}_{teoilderiv} = \sum_{ce,p,s,l} (\mathrm{QPWR}_{ce,teoilderiv,p,s,l} \cdot \mathrm{D}_{p,s,l} \cdot \mathrm{xGWhtoEJ} \cdot \mathrm{ECOVCCE}_{ce,teoilderiv}) \qquad \forall teoilderiv$$

REL_TOTTEOP$_{teoilderiv}$

$$\mathrm{TOTTEOP}_{teoilderiv} = \sum_{ce,p,s,l} (\mathrm{QPWR}_{ce,teoilderiv,p,s,l} \cdot \mathrm{D}_{p,s,l}) \qquad \forall teoilderiv$$

REL_MEANBIOETHCOSTNEWCAP

$$\mathrm{MEANBIOETHCOSTNEWCAP} = \mathrm{NEWINSTALLCAP}_{\texttt{CEBIOETHPP}} \cdot \mathrm{NEWICAPINVCOSTYEAR}_{\texttt{CEBIOETHPP}}$$

REL_MEANBIOETHCOSTACTCAP

$$\mathrm{MEANBIOETHCOSTACTCAP} = \mathrm{TOTACTIVECAP}_{\texttt{CEBIOETHPP}} \cdot \mathrm{ACECAPFIXDCOSTYEAR}_{\texttt{CEBIOETHPP}}$$

REL_MEANBIOETHCOSTVAR

$$\mathrm{MEANBIOETHCOSTVAR} = \sum_{ce,p,s,l} (\mathrm{QPWR}_{ce,\texttt{TEBIOETH},p,s,l} \cdot \mathrm{D}_{p,s,l} \cdot \mathrm{xGWhtoEJ} \cdot \mathrm{ECOVCCE}_{ce,\texttt{TEBIOETH}})$$

REL_TOTTEBIOETH

$$\mathrm{TOTTEBIOETH} = \sum_{ce,p,s,l} (\mathrm{QPWR}_{ce,\texttt{TEBIOETH},p,s,l} \cdot \mathrm{D}_{p,s,l})$$

REL_MEANBIODIECOSTNEWCAP

$$\mathrm{MEANBIODIECOSTNEWCAP} = \mathrm{NEWINSTALLCAP}_{\texttt{CEBIODIEPP}} \cdot \mathrm{NEWICAPINVCOSTYEAR}_{\texttt{CEBIODIEPP}}$$

REL_MEANBIODIECOSTACTCAP

$$\mathrm{MEANBIODIECOSTACTCAP} = \mathrm{TOTACTIVECAP}_{\texttt{CEBIODIEPP}} \cdot \mathrm{ACECAPFIXDCOSTYEAR}_{\texttt{CEBIODIEPP}}$$

REL_MEANBIODIECOSTVAR

$$\mathrm{MEANBIODIECOSTVAR} = \sum_{ce,p,s,l} (\mathrm{QPWR}_{ce,\texttt{TEBIODIE},p,s,l} \cdot \mathrm{D}_{p,s,l} \cdot \mathrm{xGWhtoEJ} \cdot \mathrm{ECOVCCE}_{ce,\texttt{TEBIODIE}})$$

REL_TOTTEBIODIE

$$\mathrm{TOTTEBIODIE} = \sum_{ce,p,s,l} (\mathrm{QPWR}_{ce,\texttt{TEBIODIE},p,s,l} \cdot \mathrm{D}_{p,s,l})$$

REL_MULTLINF_CT

$$\mathrm{MULTLINF\_CT} = \mathrm{MULTWEIGHT}_{\texttt{COST}} \cdot \frac{\mathrm{OFVA\_TOTSUPCOSTOPERINVST\_P23} - \mathrm{MULTIDEAL}_{\texttt{COST}}}{\mathrm{MULTANTIDEAL}_{\texttt{COST}} - \mathrm{MULTIDEAL}_{\texttt{COST}}}$$

$$\mid (((\mathrm{ActivateLinf} = 1) \vee (\mathrm{ActivateLinf} = 2) \wedge (\mathrm{LANDA} \neq 1)) \wedge \mathrm{MULTACTIVE}_{\texttt{COST}})$$

REL_MULTLINF_PE

$$\mathrm{MULTLINF\_PE} = \mathrm{MULTWEIGHT}_{\texttt{PE}} \cdot \frac{\mathrm{OFVA\_TOTSUPCOSTVULRES\_P23} - \mathrm{MULTIDEAL}_{\texttt{PE}}}{\mathrm{MULTANTIDEAL}_{\texttt{PE}} - \mathrm{MULTIDEAL}_{\texttt{PE}}}$$

$$\mid (((\mathrm{ActivateLinf} = 1) \vee (\mathrm{ActivateLinf} = 2) \wedge (\mathrm{LANDA} \neq 1)) \wedge \mathrm{MULTACTIVE}_{\texttt{PE}})$$

REL_MULTLINF_CO

$$\text{MULTLINF\_CO} = \text{MULTWEIGHT}_{\mathtt{CO2}} \cdot \frac{\text{OFVA\_TOTEMISSIONS\_P23} - \text{MULTIDEAL}_{\mathtt{CO2}}}{\text{MULTANTIDEAL}_{\mathtt{CO2}} - \text{MULTIDEAL}_{\mathtt{CO2}}}$$

$$\mid (((\text{ActivateLinf} = 1) \lor (\text{ActivateLinf} = 2) \land (\text{LANDA} \neq 1)) \land \text{MULTACTIVE}_{\mathtt{CO2}})$$

REL_MULTLINF_DE

$$\text{MULTLINF\_DE} = \text{MULTWEIGHT}_{\mathtt{DEP}} \cdot \frac{\text{OFVA\_ENERGY\_DEPENDENCE\_P23} - \text{MULTIDEAL}_{\mathtt{DEP}}}{\text{MULTANTIDEAL}_{\mathtt{DEP}} - \text{MULTIDEAL}_{\mathtt{DEP}}}$$

$$\mid (((\text{ActivateLinf} = 1) \lor (\text{ActivateLinf} = 2) \land (\text{LANDA} \neq 1)) \land \text{MULTACTIVE}_{\mathtt{DEP}})$$

REL_MULTLINF_SO

$$\text{MULTLINF\_SO} = \text{MULTWEIGHT}_{\mathtt{SO2}} \cdot \frac{\text{OFVA\_TOTEMISSO\_P23} - \text{MULTIDEAL}_{\mathtt{SO2}}}{\text{MULTANTIDEAL}_{\mathtt{SO2}} - \text{MULTIDEAL}_{\mathtt{SO2}}}$$

$$\mid (((\text{ActivateLinf} = 1) \lor (\text{ActivateLinf} = 2) \land (\text{LANDA} \neq 1)) \land \text{MULTACTIVE}_{\mathtt{SO2}})$$

REL_MULTLINF_NO

$$\text{MULTLINF\_NO} = \text{MULTWEIGHT}_{\mathtt{NOX}} \cdot \frac{\text{OFVA\_TOTEMISNO\_P23} - \text{MULTIDEAL}_{\mathtt{NOX}}}{\text{MULTANTIDEAL}_{\mathtt{NOX}} - \text{MULTIDEAL}_{\mathtt{NOX}}}$$

$$\mid (((\text{ActivateLinf} = 1) \lor (\text{ActivateLinf} = 2) \land (\text{LANDA} \neq 1)) \land \text{MULTACTIVE}_{\mathtt{NOX}})$$

REL_MULTLINF_PM

$$\text{MULTLINF\_PM} = \text{MULTWEIGHT}_{\mathtt{PM25}} \cdot \frac{\text{OFVA\_TOTEMISPM\_P23} - \text{MULTIDEAL}_{\mathtt{PM25}}}{\text{MULTANTIDEAL}_{\mathtt{PM25}} - \text{MULTIDEAL}_{\mathtt{PM25}}}$$

$$\mid (((\text{ActivateLinf} = 1) \lor (\text{ActivateLinf} = 2) \land (\text{LANDA} \neq 1)) \land \text{MULTACTIVE}_{\mathtt{PM25}})$$

REL_MULTLINF_SE

$$\text{MULTLINF\_SE} = \text{MULTWEIGHT}_{\mathtt{SEC}} \cdot \frac{\text{OFVA\_TOTSECCOST\_P23} - \text{MULTIDEAL}_{\mathtt{SEC}}}{\text{MULTANTIDEAL}_{\mathtt{SEC}} - \text{MULTIDEAL}_{\mathtt{SEC}}}$$

$$\mid (((\text{ActivateLinf} = 1) \lor (\text{ActivateLinf} = 2) \land (\text{LANDA} \neq 1)) \land \text{MULTACTIVE}_{\mathtt{SEC}})$$

REL_MULTLINF_JO

$$\text{MULTLINF\_JO} = \text{MULTWEIGHT}_{\mathtt{JOB}} \cdot \frac{|(\text{MULTIDEAL}_{\mathtt{JOB}} - \text{OFVA\_JOBS\_P23})|}{\text{MULTIDEAL}_{\mathtt{JOB}} - \text{MULTANTIDEAL}_{\mathtt{JOB}}}$$

$$\mid (((\text{ActivateLinf} = 1) \lor (\text{ActivateLinf} = 2) \land (\text{LANDA} \neq 1)) \land \text{MULTACTIVE}_{\mathtt{JOB}})$$

REL_TOTLSTEENERGY_P123$_{esst,te}$

$$\text{TOTLSTEENERGY}_{esst,te} = \text{xGWhtoEJ} \cdot \sum_{p,s,l}(\text{ESSTLS\_RLS}_{te,esst,p,s,l} \cdot \text{D}_{p,s,l}) \qquad \forall esst, te \mid \text{teesstflows}_{te,esst}$$

REL_TOTLSPEENERGY_P123$_{esst,pe}$

$$\text{TOTLSPEENERGY}_{esst,pe} = \text{xGWhtoEJ} \cdot \sum_{p,s,l}(\text{ESSTLS\_RLS}_{pe,esst,p,s,l} \cdot \text{D}_{p,s,l}) \qquad \forall esst, pe \mid \text{peesstflows}_{pe,esst}$$

REL_TOTQTEIN_P123$_{te,p,s,l}$

$$\text{TOTQTEIN}_{te,p,s,l} = \sum_{pe,peteflows_{pe,te}} \text{QPWR}_{pe,te,p,s,l} + \sum_{ce,ceteflows_{ce,te}} \text{QPWR}_{ce,te,p,s,l} + \sum_{rg|(\text{TEIMPCAP}_{te,rg}>0)} \text{QPWR}_{rg,te,p,s,l} \qquad \forall te, p, s, l$$

REL_TOTQTEOUT_P123$_{te,p,s,l}$

$$\text{TOTQTEOUT}_{te,p,s,l} = \sum_{ce,teceflows_{te,ce}} \text{QPWR}_{te,ce,p,s,l} + \sum_{esst,teesstflows_{te,esst}} \text{QPWR}_{te,esst,p,s,l} + \sum_{rg|(\text{TEEXPCAP}_{te,rg}>0)} \text{QPWR}_{te,rg,p,s,l} \qquad \forall te, p, s, l$$

REL_TELOSSES_P123$_{te,p,s,l}$

$$\text{QLTE}_{te,p,s,l} = \text{TELF}_{te} \cdot \text{TOTQTEIN}_{te,p,s,l} \qquad \forall te, p, s, l$$

REL_NGNETWORK_CAP

$$\sum_{p,s,l}(\text{TOTQTEIN}_{\texttt{TENAGAS},p,s,l} \cdot \text{D}_{p,s,l}) \leq \text{ng\_current\_cap} + \text{ADDED\_NGNETWORK\_CAP}$$

REL_TOTQCEIN_P123$_{ce,p,s,l}$

$$\text{TOTQCEIN}_{ce,p,s,l} = \sum_{pe,peceflows_{pe,ce}} \text{QPWR}_{pe,ce,p,s,l} + \sum_{te,teceflows_{te,ce}} \text{QPWR}_{te,ce,p,s,l} \qquad \forall ce, p, s, l$$

REL_TOTQCEOUT_P123$_{ce,p,s,l}$

$$\text{TOTQCEOUT}_{ce,p,s,l} = \sum_{te,ceteflows_{ce,te}} \text{QPWR}_{ce,te,p,s,l} \qquad \forall ce, p, s, l$$

REL_CELOSSES_P123$_{ce,p,s,l}$

$$\text{QLCE}_{ce,p,s,l} = \text{CELF}_{ce} \cdot \text{TOTQCEIN}_{ce,p,s,l} \qquad \forall ce,p,s,l$$

REL_CETOTACTIVECAP_P123$_{ce}$

$$\text{TOTACTIVECAP}_{ce} = \text{PREVACTIVECAP}_{ce} + \text{NEWINSTALLCAP}_{ce} \qquad \forall ce$$

REL_TOTQPEOUT_P123$_{pe,p,s,l}$

$$\text{TOTQPEOUT}_{pe,p,s,l} = \sum_{ce,peceflows_{pe,ce}} \text{QPWR}_{pe,ce,p,s,l} + \sum_{te,peteflows_{pe,te}} \text{QPWR}_{pe,te,p,s,l} + \sum_{esst,peesstflows_{pe,esst}} \text{QPWR}_{pe,esst,p,s,l} + \sum_{rg|(\text{PEEXPCAP}_{pe,rg}>0)} \text{QPWR}_{pe,rg,p,s,l} \qquad \forall pe,p,s,l$$

REL_PEDOMESTIC_P123$_{dr,pe,p,s,l}$

$$\text{QPWR}_{dr,pe,p,s,l} = \text{TOTQPEOUT}_{pe,p,s,l} - \text{PEID}_{pe} \cdot \text{TOTQPEOUT}_{pe,p,s,l} \qquad \forall dr,pe,p,s,l$$

REL_EMPE_P123$_{dr,pe,p,s,l}$

$$\text{EMPE}_{pe,p,s,l} = \text{QPWR}_{dr,pe,p,s,l} \cdot \text{xGWhtoEJ} \cdot \text{CO2PEDOMEF}_{pe} \qquad \forall dr,pe,p,s,l$$

REL_EMCE_P123$_{ceteflows_{ce,te},p,s,l}$

$$\text{EMCE}_{ce,te,p,s,l} = \text{QPWR}_{ce,te,p,s,l} \cdot \text{xGWhtoEJ} \cdot \text{CO2EFCE}_{ce,te} \qquad \forall ceteflows_{ce,te},p,s,l$$

REL_EMCESO_P123$_{ceteflows_{ce,te},p,s,l}$

$$\text{EMCESO}_{ce,te,p,s,l} = \text{QPWR}_{ce,te,p,s,l} \cdot \text{xGWhtoEJ} \cdot \text{SOEFCE}_{ce,te} \qquad \forall ceteflows_{ce,te},p,s,l$$

REL_EMCENO_P123$_{ceteflows_{ce,te},p,s,l}$

$$\text{EMCENO}_{ce,te,p,s,l} = \text{QPWR}_{ce,te,p,s,l} \cdot \text{xGWhtoEJ} \cdot \text{NOEFCE}_{ce,te} \qquad \forall ceteflows_{ce,te},p,s,l$$

REL_EMCEPM_P123$_{ceteflows_{ce,te},p,s,l}$

$$\text{EMCEPM}_{ce,te,p,s,l} = \text{QPWR}_{ce,te,p,s,l} \cdot \text{xGWhtoEJ} \cdot \text{PMEFCE}_{ce,te} \qquad \forall ceteflows_{ce,te},p,s,l$$

REL_EMTE_P123$_{te,p,s,l}$

$$\text{EMTE}_{te,p,s,l} = \text{TOTQTEIN}_{te,p,s,l} \cdot \text{xGWhtoEJ} \cdot \text{CO2EFTE}_{te} \qquad \forall te,p,s,l$$

REL_EMFE_P123$_{ds,p,s,l}$

$$\text{EMFE}_{ds,p,s,l} = \sum_{esst,esstbds_{esst,ds}} \text{EMFE\_ESST}_{esst,p,s,l} \qquad \forall ds, p, s, l$$

REL_EMFE_ESST_P123$_{esst,p,s,l}$

$$\text{EMFE\_ESST}_{esst,p,s,l} = \text{xGWhtoEJ}\cdot\Big(\sum_{te,teesstflows_{te,esst}} (\text{QPWR}_{te,esst,p,s,l}\cdot\text{FEUEMISSFTE}_{esst,te}) + \sum_{pe,peesstflows_{pe,esst}} (\text{QPWR}_{pe,esst,p,s,l}\cdot \text{FEUEMISSFPE}_{esst,pe})\Big) \qquad \forall esst, p, s, l$$

REL_EMFELCA_P123$_{ds,p,s,l}$

$$\text{EMFELCA}_{ds,p,s,l} = \sum_{esst,esstbds_{esst,ds}} \text{EMFELCA\_ESST}_{esst,p,s,l} \qquad \forall ds, p, s, l$$

REL_EMFELCA_ESST_P123$_{esst,p,s,l}$

$$\text{EMFELCA\_ESST}_{esst,p,s,l} = \text{xGWhtoEJ} \cdot \sum_{te,teesstflows_{te,esst}} (\text{QPWR}_{te,esst,p,s,l} \cdot \text{FEUEMISSFTELCA}_{esst,te}) \qquad \forall esst, p, s, l$$

REL_TOTEM_METHLEAK_P123

$$\text{TOTEM\_METHLEAK} = \sum_{p,s,l} (\text{TOTQTEIN}_{\texttt{TENAGAS},p,s,l} \cdot \text{D}_{p,s,l}) \cdot \text{xGWhtoEJ} \cdot \text{methane\_leakage} \cdot \text{methane\_CO2eq}$$

REL_TOTEM_PE_P123

$$\text{TOTEM\_PE} = \sum_{pe,p,s,l} (\text{D}_{p,s,l} \cdot \text{EMPE}_{pe,p,s,l})$$

REL_TOTEM_CE_P123

$$\text{TOTEM\_CE} = \sum_{ce,te,p,s,l,ceteflows_{ce,te}} (\text{D}_{p,s,l} \cdot \text{EMCE}_{ce,te,p,s,l})$$

REL_TOTEM_TE_P123

$$\text{TOTEM\_TE} = \sum_{te,p,s,l} (\text{D}_{p,s,l} \cdot \text{EMTE}_{te,p,s,l})$$

REL_TOTEM_FE_P123

$$\text{TOTEM\_FE} = \sum_{ds,p,s,l} (\text{D}_{p,s,l} \cdot \text{EMFE}_{ds,p,s,l})$$

REL_TOTEMLCA_FE_P123

$$\text{TOTEMLCA\_FE} = \sum_{ds,p,s,l} (\text{D}_{p,s,l} \cdot \text{EMFELCA}_{ds,p,s,l})$$

REL_TOTEM_P123

$$\text{TOTEM} = \text{TOTEM\_PE} + \text{TOTEM\_CE} + \text{TOTEM\_TE} + \text{TOTEM\_FE} + \text{TOTEM\_METHLEAK}$$

REL_NOEMFE_P123$_{ds,p,s,l}$

$$\text{NOEMFE}_{ds,p,s,l} = \sum_{esst,esstbds_{esst,ds}} \text{NOEMFE\_ESST}_{esst,p,s,l} \qquad \forall ds,p,s,l$$

REL_NOEMFE_ESST_P123$_{esst,p,s,l}$

$$\text{NOEMFE\_ESST}_{esst,p,s,l} = \text{xGWhtoEJ}\cdot\Big(\sum_{te,teesstflows_{te,esst}} (\text{QPWR}_{te,esst,p,s,l}\cdot\text{FEUEMISNOFTE}_{esst,te}) + \sum_{pe,peesstflows_{pe,esst}} (\text{QPWR}_{pe,esst,p,s,l}\cdot \text{FEUEMISNOFPE}_{esst,pe})\Big) \qquad \forall esst,p,s,l$$

REL_SOEMFE_P123$_{ds,p,s,l}$

$$\text{SOEMFE}_{ds,p,s,l} = \sum_{esst,esstbds_{esst,ds}} \text{SOEMFE\_ESST}_{esst,p,s,l} \qquad \forall ds,p,s,l$$

REL_SOEMFE_ESST_P123$_{esst,p,s,l}$

$$\text{SOEMFE\_ESST}_{esst,p,s,l} = \text{xGWhtoEJ}\cdot\Big(\sum_{te,teesstflows_{te,esst}} (\text{QPWR}_{te,esst,p,s,l}\cdot\text{FEUEMISSOFTE}_{esst,te}) + \sum_{pe,peesstflows_{pe,esst}} (\text{QPWR}_{pe,esst,p,s,l}\cdot \text{FEUEMISSOFPE}_{esst,pe})\Big) \qquad \forall esst,p,s,l$$

REL_PMEMFE_P123$_{ds,p,s,l}$

$$\text{PMEMFE}_{ds,p,s,l} = \sum_{esst,esstbds_{esst,ds}} \text{PMEMFE\_ESST}_{esst,p,s,l} \qquad \forall ds,p,s,l$$

REL_PMEMFE_ESST_P123$_{esst,p,s,l}$

$$\text{PMEMFE\_ESST}_{esst,p,s,l} = \text{xGWhtoEJ} \cdot \Big(\sum_{te,teesstflows_{te,esst}} (\text{QPWR}_{te,esst,p,s,l} \cdot \text{FEUEMISPMFTE}_{esst,te}) + \sum_{pe,peesstflows_{pe,esst}} (\text{QPWR}_{pe,esst,p,s,l} \cdot \text{FEUEMISPMFPE}_{esst,pe})\Big) \qquad \forall esst,p,s,l$$

REL_TOTEM_NOFE_P123

$$\text{TOTEM\_NOFE} = \sum_{ds,p,s,l} (\text{D}_{p,s,l} \cdot \text{NOEMFE}_{ds,p,s,l}) + \sum_{ce,te,p,s,l,ceteflows_{ce,te}} (\text{D}_{p,s,l} \cdot \text{EMCENO}_{ce,te,p,s,l})$$

REL_TOTEM_SOFE_P123

$$\text{TOTEM\_SOFE} = \sum_{ds,p,s,l} (\text{D}_{p,s,l} \cdot \text{SOEMFE}_{ds,p,s,l}) + \sum_{ce,te,p,s,l,ceteflows_{ce,te}} (\text{D}_{p,s,l} \cdot \text{EMCESO}_{ce,te,p,s,l})$$

REL_TOTEM_PMFE_P123

$$\text{TOTEM\_PMFE} = \sum_{ds,p,s,l} (\text{D}_{p,s,l} \cdot \text{PMEMFE}_{ds,p,s,l}) + \sum_{ce,te,p,s,l,ceteflows_{ce,te}} (\text{D}_{p,s,l} \cdot \text{EMCEPM}_{ce,te,p,s,l})$$

REL_TOT_FE_TEyPE_P123

$$\text{TOT\_FE\_TEyPE} = \text{xGWhtoEJ} \cdot (\sum_{te,esst,p,s,l,teorpe2esst_{te,esst}} (\text{D}_{p,s,l} \cdot \text{QPWR}_{te,esst,p,s,l}) +$$
$$\sum_{pe,esst,p,s,l,teorpe2esst_{pe,esst}} (\text{D}_{p,s,l} \cdot \text{QPWR}_{pe,esst,p,s,l}))$$

REL_TOT_FEren_TEyPE_P123

$$\text{TOT\_FEren\_TEyPE} = \text{xGWhtoEJ} \cdot (\sum_{proc,esst,p,s,l,teorpe2esst\_ren_{proc,esst}} (\text{D}_{p,s,l} \cdot \text{QPWR}_{proc,esst,p,s,l}) +$$
$$\text{MinREShare\_Elec} \cdot (\sum_{esst,p,s,l,teorpe2esst_{'TEELECE',esst}} (\text{D}_{p,s,l} \cdot \text{QPWR}_{\texttt{TEELECE},esst,p,s,l}) +$$
$$\sum_{esst,p,s,l,teorpe2esst_{'TEELEDIIND',esst}} (\text{D}_{p,s,l} \cdot \text{QPWR}_{\texttt{TEELEDIIND},esst,p,s,l}) +$$
$$\sum_{esst,p,s,l,teorpe2esst_{'TEELEDIOTH',esst}} (\text{D}_{p,s,l} \cdot \text{QPWR}_{\texttt{TEELEDIOTH},esst,p,s,l})))$$

REL_TOT_REELECGEN_EJ_P123

$$\text{TOT\_REELECGEN\_EJ} = \text{xGWhtoEJ} \cdot \sum_{ce,te,p,s,l,ceteflows_{ce,te},allrenceele_{ce}} (\text{QPWR}_{ce,te,p,s,l} \cdot \text{D}_{p,s,l})$$

REL_TOT_ELECGEN_EJ_P123

$$\text{TOT\_ELECGEN\_EJ} = \text{xGWhtoEJ} \cdot (\sum_{ce,p,s,l,ceteflows_{ce,'TEELECE'}} (\text{QPWR}_{ce,\texttt{TEELECE},p,s,l} \cdot \text{D}_{p,s,l}) +$$
$$\sum_{ce,p,s,l,ceteflows_{ce,'TEELEDIIND'}} (\text{QPWR}_{ce,\texttt{TEELEDIIND},p,s,l} \cdot \text{D}_{p,s,l}) +$$
$$\sum_{ce,p,s,l,ceteflows_{ce,'TEELEDIOTH'}} (\text{QPWR}_{ce,\texttt{TEELEDIOTH},p,s,l} \cdot \text{D}_{p,s,l}))$$

CONSTR_ESBALANCE_P123$_{ds,es,p,s,l}$

$$\sum_{esst|(\text{esstses}_{esst,es}\wedge\text{esstbds}_{esst,ds})}(\text{QACTESST}_{esst,p,s,l}\cdot\text{QACTESST2ES}_{esst,es})\geq \text{ESDEMY}_{es,ds}\cdot\text{ESDEMLOADC}_{es,p,s,l}+\sum_{esvm|\text{esvmves}_{esvm,es}}(\text{ESVMLVL}_{esvm}\cdot\text{ESVMEFFECT}_{esvm,es}\cdot\text{ESVMLOADC}_{esvm,p,s,l}\cdot \text{ESDEMY}_{es,ds})[(\text{ESVMAllowed}=1)]\qquad\forall ds,es,p,s,l\mid\text{esbds}_{es,ds}$$

CONSTR_ESBALANCE_LIM_P123$_{ds,es,p,s,l}$

$$\sum_{esst|(\text{esstses}_{esst,es}\wedge\text{esstbds}_{esst,ds})}(\text{QACTESST}_{esst,p,s,l}\cdot\text{QACTESST2ES}_{esst,es})\leq 1.1\cdot(\text{ESDEMY}_{es,ds}\cdot\text{ESDEMLOADC}_{es,p,s,l}+\sum_{esvm|\text{esvmves}_{esvm,es}}(\text{ESVMLVL}_{esvm}\cdot\text{ESVMEFFECT}_{esvm,es}\cdot\text{ESVMLOADC}_{esvm,p,s,l}\cdot\text{ESDEMY}_{es,ds})[(\text{ESVMAllowed}=1)])\quad\forall ds,es,p,s,l\mid\text{esbds}_{es,ds}$$

CONSTR_ESVMEXCLUSSION_P123$_{esvm1,esvm2,esvm3,esvm4,esvm5,esvm6,esvm7,esvm8,esvm9,esvm10}$

$$\text{ESVMLVL}_{esvm1}+\text{ESVMLVL}_{esvm2}+\text{ESVMLVL}_{esvm3}+\text{ESVMLVL}_{esvm4}+\text{ESVMLVL}_{esvm5}+\text{ESVMLVL}_{esvm6}+\text{ESVMLVL}_{esvm7}+\text{ESVMLVL}_{esvm8}+\text{ESVMLVL}_{esvm9}+\text{ESVMLVL}_{esvm10}\leq 1\qquad\forall esvm1-10$$

CONSTR_ENERGYBALESST_TE_P123$_{te,esst,ds,p,s,l}$

$$((\text{ESSTLS\_RLS}_{te,esst,p,s,l}-\text{ESSTLS\_ACC}_{te,esst,p,s,l})[((\text{LSESSTAllowed}=1)\wedge(\text{ESSTLSPOSTE}_{esst,te}>0))]+\text{QPWR}_{te,esst,p,s,l})\cdot \text{D}_{p,s,l}\cdot\text{xGWhtoEJ}\cdot\text{TE2QACTESST}_{esst,te}= \text{QACTESST}_{esst,p,s,l}\qquad\forall te,esst,ds,p,s,l\mid(\text{esstbds}_{esst,ds}\wedge\text{teesstflows}_{te,esst}\wedge(\text{TE2QACTESST}_{esst,te}>0))$$

CONSTR_ENERGYBALESST_PE_P123$_{pe,esst,ds,p,s,l}$

$$((\text{ESSTLS\_RLS}_{pe,esst,p,s,l}-\text{ESSTLS\_ACC}_{pe,esst,p,s,l})[((\text{LSESSTAllowed}=1)\wedge(\text{ESSTLSPOSPE}_{esst,pe}>0))]+\text{QPWR}_{pe,esst,p,s,l})\cdot \text{D}_{p,s,l}\cdot\text{xGWhtoEJ}\cdot\text{PE2QACTESST}_{esst,pe}= \text{QACTESST}_{esst,p,s,l}\qquad\forall pe,esst,ds,p,s,l\mid(\text{esstbds}_{esst,ds}\wedge\text{peesstflows}_{pe,esst}\wedge(\text{PE2QACTESST}_{esst,pe}>0))$$

CONSTR_LOADSHIFTLIMTE_P123$_{te,esst,p,s,l}$

$$\text{ESSTLS\_ACC}_{te,esst,p,s,l}[(\text{ESSTLSPOSTE}_{esst,te}=0)]+\sum_{al}(\text{D}_{p,s,al}\cdot(\text{ESSTLS\_ACC}_{te,esst,p,s,al}-\text{ESSTLS\_RLS}_{te,esst,p,s,al}))[(\text{ESSTLSPOSTE}_{esst,te}=1)]+\sum_{as,aal}(\text{D}_{p,as,aal}\cdot(\text{ESSTLS\_ACC}_{te,esst,p,as,aal}-\text{ESSTLS\_RLS}_{te,esst,p,as,aal}))[(\text{ESSTLSPOSTE}_{esst,te}=2)]=0\ \forall te,esst,p,s,l\mid\text{teesstflows}_{te,esst}$$

CONSTR_LOADSHIFTLIMPE_P123$_{pe,esst,p,s,l}$

$$\text{ESSTLS\_ACC}_{pe,esst,p,s,l}[(\text{ESSTLSPOSPE}_{esst,pe} = 0)] +$$
$$\sum_{al}(\text{D}_{p,s,al} \cdot (\text{ESSTLS\_ACC}_{pe,esst,p,s,al} - \text{ESSTLS\_RLS}_{pe,esst,p,s,al}))[(\text{ESSTLSPOSPE}_{esst,pe} = 1)] +$$
$$\sum_{as,aal}(\text{D}_{p,as,aal} \cdot (\text{ESSTLS\_ACC}_{pe,esst,p,as,aal} - \text{ESSTLS\_RLS}_{pe,esst,p,as,aal}))[(\text{ESSTLSPOSPE}_{esst,pe} = 2)] = 0$$
$$\forall pe, esst, p, s, l \mid \text{peesstflows}_{pe,esst}$$

CONSTR_TEBALANCE_P123$_{te,p,s,l}$

$$\text{TOTQTEIN}_{te,p,s,l} - \text{QLTE}_{te,p,s,l} = \text{TOTQTEOUT}_{te,p,s,l} \qquad \forall te, p, s, l$$

CONSTR_TECAPLIM_P123$_{te,p,s,l}$

$$\text{TOTQTEIN}_{te,p,s,l} \leq \text{TECAP}_{te} \qquad \forall te, p, s, l$$

CONSTR_CEPREVCAPACTIV_P123$_{ce,p}$

$$\text{PREVACTIVECAP}_{ce} \leq \text{CEPREVCAP}_{ce} \qquad \forall ce, p$$

CONSTR_CECAPLIM_P123$_{ce,p,s,l}$

$$\text{TOTQCEOUT}_{ce,p,s,l} + \text{CEELERSRVPWR}_{ce,p,s,l} = \text{TOTACTIVECAP}_{ce} \qquad \forall ce, p, s, l$$

CONSTR_CEBALANCE_P123$_{ce,p,s,l}$

$$\text{TOTQCEIN}_{ce,p,s,l} - \text{QLCE}_{ce,p,s,l} = \text{TOTQCEOUT}_{ce,p,s,l} \qquad \forall ce, p, s, l \mid (\neg(ce = \texttt{CEHYPSTOR}))$$

CONSTR_CEBALANCE_PS_P123$_{'TEELECE','CEHYPSTOR',p,s}$

$$\sum_{l}(\text{QPWR}_{\texttt{CEHYPSTOR},\texttt{TEELECE},p,s,l} \cdot \text{D}_{p,s,l}) \cdot \text{xGWhtoEJ} = \sum_{l}(\text{QPWR}_{\texttt{TEELECE},\texttt{CEHYPSTOR},p,s,l} \cdot \text{D}_{p,s,l}) \cdot \text{xGWhtoEJ} \cdot \text{CEHYPSTORCYEF}$$
$$\forall 'TEELECE',' CEHYPSTOR', p, s$$

CONSTR_CEBALANCE_RSCAP_P123$_{'TEELECE','CEHYRSCAP',p}$

$$\sum_{s,l}(\text{QPWR}_{\texttt{CEHYRSCAP},\texttt{TEELECE},p,s,l} \cdot \text{D}_{p,s,l}) \cdot \text{xGWhtoEJ} = \text{HYDRONRGMONTH}_{p} \cdot (1 - \text{RURIVNRGSHARE}_{p})$$
$$\forall 'TEELECE',' CEHYRSCAP', p$$

CONSTR_CEBALANCE_RURIV_P123$_{'TEELECE','CEHYRURIV',p,s,l}$

$$\mathrm{QPWR}_{\mathtt{CEHYRURIV},\mathrm{TEELECE},p,s,l} = \frac{\mathrm{HYDRONRGMONTH}_p \cdot \mathrm{RURIVNRGSHARE}_p \cdot \mathrm{xEJtoGWh}}{\sum_{as,al} \mathrm{D}_{p,as,al}}$$

$\forall 'TEELECE','CEHYRURIV',p,s,l$

CONSTR_CEOUTMAXSHARELIM_P123$_{ceteflows_{ce,te},p,s,l}$

$$\mathrm{QPWR}_{ce,te,p,s,l} \leq \mathrm{TOTQCEOUT}_{ce,p,s,l} \cdot \mathrm{CEMAXTEOUTSHARE}_{ce,te} \qquad \forall ceteflows_{ce,te},p,s,l$$

CONSTR_CEOUTMINSHARELIM_P123$_{ceteflows_{ce,te},p,s,l}$

$$\mathrm{QPWR}_{ce,te,p,s,l} \geq \mathrm{TOTQCEOUT}_{ce,p,s,l} \cdot \mathrm{CEMINTEOUTSHARE}_{ce,te} \qquad \forall ceteflows_{ce,te},p,s,l$$

CONSTR_CEINPESHAREREQ_P123$_{peceflows_{pe,ce},p,s,l}$

$$\mathrm{QPWR}_{pe,ce,p,s,l} = \mathrm{TOTQCEIN}_{ce,p,s,l} \cdot \mathrm{CEINSHAREPE}_{ce,pe} \qquad \forall peceflows_{pe,ce},p,s,l$$

CONSTR_CEINTESHAREREQ_P123$_{teceflows_{te,ce},p,s,l}$

$$\mathrm{QPWR}_{te,ce,p,s,l} = \mathrm{TOTQCEIN}_{ce,p,s,l} \cdot \mathrm{CEINSHARETE}_{ce,te} \qquad \forall teceflows_{te,ce},p,s,l$$

CONSTR_CETOTACTIVECAPLIM_P123$_{ce}$

$$\mathrm{TOTACTIVECAP}_{ce} \leq \mathrm{CEMAXACTIVECAP}_{ce} \qquad \forall ce$$

CONSTR_CETOTACTIVECAPLIMOUT_P123

$$\sum_{ce} \mathrm{TOTACTIVECAP}_{ce} \leq 250$$

CONSTR_CELOADFPROD_P123$_{celoadf,p,s,l}$

$$\mathrm{TOTQCEOUT}_{celoadf,p,s,l} = \mathrm{TOTACTIVECAP}_{celoadf} \cdot \mathrm{CELOADFACTORP}_{celoadf,p} \qquad \forall celoadf,p,s,l$$

CONSTR_CEELERELIABADEQ_P23

$$\sum_{ceelecentral} (\mathrm{TOTACTIVECAP}_{ceelecentral} \cdot \mathrm{CEFIRMNESS4ADEQ}_{ceelecentral}) \geq (1+\mathrm{CERESMRG4ADEQ}) \cdot \mathrm{MAXDEMYR}_{\mathrm{TEELECE}}$$

$|$ (IncludeAdequacyConstr $= 1$)

CONSTR_CEELERELIABRSRV_P123$_{p,s,l}$

$$\sum_{ceelecentral} (\mathrm{CEELERSRVPWR}_{ceelecentral,p,s,l} \cdot \mathrm{CEFLEXIBILITY4RSRV}_{ceelecentral}) \geq$$
$$\mathrm{CELARGCECAP4RSRV} + \sum_{esst,teesstflows_{'TEELECE',esst}} \mathrm{QPWR}_{\mathtt{TEELECE},esst,p,s,l} \cdot \mathrm{CEDEMAVGPRERR4RSRV} +$$
$$\sum_{celoadf} (\mathrm{TOTACTIVECAP}_{celoadf} \cdot \mathrm{CELOADFACTORP}_{celoadf,p}) \cdot \mathrm{CELOADFAVGPRERR4RSRV}$$
$$\forall p, s, l \mid (\mathrm{IncludeReservesConstr} = 1)$$

CONSTR_CEREGASIFMINOUTPUT_P123$_{p,s,l}$

$$\mathrm{QPWR}_{\mathtt{CEREGASIF},\mathtt{TENAGAS},p,s,l} \geq \mathrm{TOTACTIVECAP}_{\mathtt{CEREGASIF}} \cdot 0.25 \qquad \forall p, s, l$$

CONSTR_PEBALANCE_P123$_{dr,pe,p,s,l}$

$$\mathrm{QPWR}_{dr,pe,p,s,l} + \sum_{rg|(\mathrm{PEIMPCAP}_{pe,rg}>0)} \mathrm{QPWR}_{rg,pe,p,s,l} = \mathrm{TOTQPEOUT}_{pe,p,s,l} \qquad \forall dr, pe, p, s, l$$

CONSTR_PEDOMCAPLIM_P123$_{dr,pe,p,s,l}$

$$\mathrm{QPWR}_{dr,pe,p,s,l} \leq \mathrm{PEDOMCONSCAP}_{pe} \qquad \forall dr, pe, p, s, l$$

CONSTR_PEMAXECONSYEAR_P123$_{pelimey}$

$$\sum_{p,s,l} (\mathrm{TOTQPEOUT}_{pelimey,p,s,l} \cdot \mathrm{D}_{p,s,l} \cdot \mathrm{xGWhtoEJ}) \leq$$
$$\mathrm{PEMAXECONSYEAR}_{pelimey} \qquad \forall pelimey \mid (\mathrm{PEMAXECONSYEAR}_{pelimey} \geq 0)$$

CONSTR_IMPTECAPLIM_P123$_{te,rg,p,s,l}$

$$\mathrm{QPWR}_{rg,te,p,s,l} \leq \mathrm{TEIMPCAP}_{te,rg} \qquad \forall te, rg, p, s, l \mid (\mathrm{TEIMPCAP}_{te,rg} \geq 0)$$

CONSTR_EXPTECAPLIM_P123$_{te,rg,p,s,l}$

$$\mathrm{QPWR}_{te,rg,p,s,l} \leq \mathrm{TEEXPCAP}_{te,rg} \qquad \forall te, rg, p, s, l \mid (\mathrm{TEEXPCAP}_{te,rg} \geq 0)$$

CONSTR_IMPPECAPLIM_P123$_{pe,rg,p,s,l}$

$$\mathrm{QPWR}_{rg,pe,p,s,l} \leq \mathrm{PEIMPCAP}_{pe,rg} \qquad \forall pe, rg, p, s, l \mid (\mathrm{PEIMPCAP}_{pe,rg} > 0)$$

$\textbf{CONSTR\_EXPPECAPLIM\_P123}_{pe,rg,p,s,l}$

$\text{QPWR}_{pe,rg,p,s,l} \leq \text{PEEXPCAP}_{pe,rg} \qquad \forall pe, rg, p, s, l \mid (\text{PEEXPCAP}_{pe,rg} > 0)$

$\text{QPWR}_{proc,proc,p,s,l} \geq 0\ \forall proc, proc, p, s, l$

$\text{TEELECEPECOST} \geq 0\ \forall$

$\text{TEELECECECOST} \geq 0\ \forall$

$\text{TOTACTIVECAP}_{proc} \geq 0\ \forall proc$

$\text{TEELECETECOST} \geq 0\ \forall$

$\text{TEELECENCAPINVSCOST} \geq 0\ \forall$

$\text{NEWINSTALLCAP}_{proc} \geq 0\ \forall proc$

$\text{TOTTEELECE} \geq 0\ \forall$

$\text{MEANELECOST} \geq 0\ \forall$

$\text{MEANGASCOSTNEWCAP} \geq 0\ \forall$

$\text{MEANGASCOSTACTCAP} \geq 0\ \forall$

$\text{MEANGASCOSTVAR} \geq 0\ \forall$

$\text{TOTTENAGAS} \geq 0\ \forall$

$\text{MEANGASCOST} \geq 0\ \forall$

$\text{MEANOILCOSTNEWCAP} \geq 0\ \forall$

$\text{MEANOILCOSTACTCAP} \geq 0\ \forall$

$\text{MEANOILDERIVCOSTVAR}_{*} \geq 0\ \forall *$

$\text{TOTTEOP}_{*} \geq 0\ \forall *$

$\text{MEANOILDERIVCOST}_{*} \geq 0\ \forall *$

$\text{MEANBIOETHCOSTNEWCAP} \geq 0\ \forall$

$\text{MEANBIOETHCOSTACTCAP} \geq 0\ \forall$

$\text{MEANBIOETHCOSTVAR} \geq 0\ \forall$

$\text{TOTTEBIOETH} \geq 0\ \forall$

$\text{MEANBIOETHCOST} \geq 0\ \forall$

$\text{MEANBIODIECOSTNEWCAP} \geq 0\ \forall$

$\text{MEANBIODIECOSTACTCAP} \geq 0\ \forall$

$\text{MEANBIODIECOSTVAR} \geq 0\ \forall$

$\text{TOTTEBIODIE} \geq 0\ \forall$

$\text{MEANBIODIECOST} \geq 0\ \forall$

$\text{TOTEM} \geq 0\ \forall$

$\text{TOTEM\_NOFE} \geq 0\ \forall$

$\text{TOTEM\_SOFE} \geq 0\ \forall$

$\text{TOTEM\_PMFE} \geq 0\ \forall$

$\text{TOT\_ENERGY\_USED\_DOMyIMP\_EJ} \geq 0\ \forall$

TOT_ENERGY_USED_DOM_EJ $\geq 0\ \forall$

QACTESST$_{esst,p,s,l} \geq 0\ \forall esst, p, s, l$

MULTLINF_CT $\geq 0\ \forall$

MULTLINF_PE $\geq 0\ \forall$

MULTLINF_CO $\geq 0\ \forall$

MULTLINF_DE $\geq 0\ \forall$

MULTLINF_SO $\geq 0\ \forall$

MULTLINF_NO $\geq 0\ \forall$

MULTLINF_PM $\geq 0\ \forall$

MULTLINF_SE $\geq 0\ \forall$

MULTLINF_JO $\geq 0\ \forall$

DMULT $\geq 0\ \forall$

TOTLSTEENERGY$_{esst,te} \geq 0\ \forall esst, te$

ESSTLS_RLS$_{proc,esst,p,s,l} \geq 0\ \forall proc, esst, p, s, l$

TOTLSPEENERGY$_{esst,pe} \geq 0\ \forall esst, pe$

ESVMLVL$_{esvm} \geq 0\ \forall esvm$

ESSTLS_ACC$_{proc,esst,p,s,l} \geq 0\ \forall proc, esst, p, s, l$

TOTQTEIN$_{te,p,s,l} \geq 0\ \forall te, p, s, l$

TOTQTEOUT$_{te,p,s,l} \geq 0\ \forall te, p, s, l$

QLTE$_{te,p,s,l} \geq 0\ \forall te, p, s, l$

ADDED_NGNETWORK_CAP $\geq 0\ \forall$

TOTQCEIN$_{ce,p,s,l} \geq 0\ \forall ce, p, s, l$

TOTQCEOUT$_{ce,p,s,l} \geq 0\ \forall ce, p, s, l$

QLCE$_{ce,p,s,l} \geq 0\ \forall ce, p, s, l$

PREVACTIVECAP$_{proc} \geq 0\ \forall proc$

CEELERSRVPWR$_{proc,p,s,l} \geq 0\ \forall proc, p, s, l$

TOTQPEOUT$_{pe,p,s,l} \geq 0\ \forall pe, p, s, l$

EMPE$_{pe,p,s,l} \geq 0\ \forall pe, p, s, l$

EMCE$_{ce,te,p,s,l} \geq 0\ \forall ce, te, p, s, l$

EMCESO$_{ce,te,p,s,l} \geq 0\ \forall ce, te, p, s, l$

EMCENO$_{ce,te,p,s,l} \geq 0\ \forall ce, te, p, s, l$

EMCEPM$_{ce,te,p,s,l} \geq 0\ \forall ce, te, p, s, l$

EMTE$_{te,p,s,l} \geq 0\ \forall te, p, s, l$

EMFE$_{ds,p,s,l} \geq 0\ \forall ds, p, s, l$

EMFE_ESST$_{esst,p,s,l} \geq 0\ \forall esst, p, s, l$

EMFELCA$_{ds,p,s,l} \geq 0\ \forall ds, p, s, l$

$\text{EMFELCA\_ESST}_{esst,p,s,l} \geq 0 \ \forall esst, p, s, l$

$\text{TOTEM\_METHLEAK} \geq 0 \ \forall$

$\text{TOTEM\_PE} \geq 0 \ \forall$

$\text{TOTEM\_CE} \geq 0 \ \forall$

$\text{TOTEM\_TE} \geq 0 \ \forall$

$\text{TOTEM\_FE} \geq 0 \ \forall$

$\text{TOTEMLCA\_FE} \geq 0 \ \forall$

$\text{NOEMFE}_{ds,p,s,l} \geq 0 \ \forall ds, p, s, l$

$\text{NOEMFE\_ESST}_{esst,p,s,l} \geq 0 \ \forall esst, p, s, l$

$\text{SOEMFE}_{ds,p,s,l} \geq 0 \ \forall ds, p, s, l$

$\text{SOEMFE\_ESST}_{esst,p,s,l} \geq 0 \ \forall esst, p, s, l$

$\text{PMEMFE}_{ds,p,s,l} \geq 0 \ \forall ds, p, s, l$

$\text{PMEMFE\_ESST}_{esst,p,s,l} \geq 0 \ \forall esst, p, s, l$

$\text{TOT\_FE\_TEyPE} \geq 0 \ \forall$

$\text{TOT\_FEren\_TEyPE} \geq 0 \ \forall$

$\text{TOT\_REELECGEN\_EJ} \geq 0 \ \forall$

$\text{TOT\_ELECGEN\_EJ} \geq 0 \ \forall$

$\text{QPWRNS}_{proc,esst,p,s,l} \geq 0 \ \forall proc, esst, p, s, l$