École polytechnique de Louvain

Study of the Spanish Energy Transition

Authors : **Josep Maria Roselló Martínez**
Supervisors : **Hervé JEANMART**
Readers : **Gauthier LIMPENS, Gian-Marco RIGANESE, Paolo THIRAN**

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Abstract

In today's challenging energy context, the sustainability of national energy systems plays a key role in the development of current and future energy policies. These systems are essential to address energy challenges such as energy security, environmental mitigation in terms of atmospheric emissions and the penetration of more efficient and lower cost energy. In this context, energy modelling tools are becoming increasingly important, as they are able to represent an energy system in a simplified but effective way. These models are assumed to be relevant in helping decision-makers, companies, and organisations to define the best strategies towards an energy transition. These models can define strategies characterised by significant reliability and representative of an energy system consistent with the intrinsic constraints of the system and the country itself, and with a given time horizon. However, the main energy models used are often not freely available or usable, which makes it difficult to compare and evaluate the existing results in the scientific literature on energy systems.

In terms of models, the application of the open-source energy model EnergyScope TD [32] to the Spanish case study is presented to identify the different decarbonisation scenarios of the Spanish energy system for 2030. Firstly, regarding the previous work carried out using this model, the proposed solution model, called *Spanish Energyscope*, adds new resources and energy conversion technologies. Secondly, to check the accuracy and corroborate the optimal performance of the model, a validation of the *Spanish Energyscope* model is carried out in the past reference year of 2015. This year is chosen because the documentation of the real data for this year is available and, therefore, the consistency of the model results with the real data can be checked. Once the reliability of the model has been checked, several decarbonisation scenarios are defined for 2030 to have a broad vision of which technologies should be used to achieve the objectives set by the national and European organisations with competences in energy. From the detailed analysis of the different scenarios, it can be seen that the scenarios without relevant changes do not achieve the environmental objectives by 2030 and that the PNIEC [21] proposes two scenarios that achieve part of the national and European objectives defined. It can also be noted that to walk this difficult path towards the decarbonisation of the Spanish energy system, enormous technical and economic efforts are necessary for the electrification of energy demand in all sectors. To this end, the focus should be on expanding, for example, the use of electric vehicles, heat pumps and the development of renewable energy technologies.

Motivation

On the one hand, after several years of studying for a bachelor's and master's degree in engineering, the possibility of carrying out the master's thesis work on a project abroad is particularly attractive to be able to put into practice all the knowledge learned over the years.

On the other hand, it is very attractive and interesting to be able to carry out a project on a subject of special interest to me and in which I can both put my knowledge into it and, above all, learn a lot more about the subject.

The Erasmus programme together with the UCLouvain University and my university (Universitat Politècnica de Catalunya), have given me the opportunity to work on a project that has already started and that aims to find solutions to many of the questions that are currently being asked about a topic of great social interest such as the energy transition. We live in a fast-changing world where the changes are the order on the agenda. Nowadays, the challenge is focused on the energy transition, and it is of vital importance to put all efforts into trying to solve it. It is an honour for me to try to do my part in helping to achieve this goal.

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Glossary

AEMET	Agencia Estatal de Meteorología
AIDS	Almost Ideal Demand System
BAU	Business as Usual
BEV	Battery Electric Vehicle
CC	Carbon Capture
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
COP	Coefficient of Performance
DENIO	Dynamic Neo-Keynesian Econometric Input-Output
DESIRE	Dissemination Strategy on Electricity Balancing for Large Scale Integration of Renewable Energy
DGT	Dirección General de Tráfico
DHN	District Heating Network
EAFO	European Alternative Fuels Observatory
EC	European Commission
ELP	Estrategia a Largo Plazo
ENTSOE	European Network of Transmission System Operators for Electricity
ESOM	Energy system optimization models
ESTD	EnergyScope Typical Days
ETS	Emission Trading System
ETSAP	Energy Technology Systems Analysis Program)
EU	European Union
EUD	End-Use Demand
EUT	End-Use Type
FAO	Food and Agriculture Organisation of the United Nations

FEC	Final Energy Consumption
GDP	Gross Domestic product
GHG	Greenhouse Gas
GT	Gas Turbine
GWP	Global Potential Warming
H&C	Heating and Cooling
H_2	Hydrogen
HEV	Hybrid electric vehicle
HP	Heat Pump
HT	High Temperature
ICE	Internal Combustion Engine
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
LP	Linear Programming
LT	Low Temperature
LULUCF	Land use, land-use change, and forestry
MITECO	Ministerio para la Transición Ecológica y el Reto Demográfico
NG	Natural Gas
NTC	Net Transfer Capacity
OECD	Organisation for Economic Co-operation and Development
PHEV	Plug-in Hybrid Electric Vehicle
PLCCTE	Proyecto de Ley de Cambio Climático y Transición Energética
PNIEC	Plan Nacional Integrado de Energía y Clima
PV	Photovoltaic
RE	Renewable Energy
REE	Red Eléctrica Española
RES	Renewable Energy Systems
SLF	Synthetic Liquid Fuel

SNG	Synthetic Natural Gas
TD	Typical Days
TIMES	The Integrated MARKAL-EFOM system
TPES	Total Primary Energy Supply
TSO	Transmission System Operator

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Introduction

The main objective of this project is to offer a solution to Spanish people interested in the energy transition to assess the technical, social, and economic potential of the multiple strategies to achieve a decarbonised Spanish energy system. The document is divided into the following chapters:

Chapter 1 aims to provide some background on the current situation regarding the energy transition at global, European, and national level. In addition, it details the different objectives and targets defined by the different organizations with competencies in the energy field. Lastly, it explains the state of the art of the different energy models at global and national level and justifies the choice of the energy model finally selected.

Chapter 2 is dedicated to a detailed description of the *Spanish Energyscope* energy model. It explains the methodology used by the model, the conceptual structure of the energy system proposed for the Spanish model and shows a graphical representation of the application of the *Spanish Energyscope* model to the Spanish case study with all the energy flows involved. Finally, the results of the model validation are presented using a past reference year, in this case 2015, to compare the model results obtained with the real results to check the consistency of the results and verify the correct functioning of the model.

Chapter 3 explains the implementation that has been carried out of the different low-carbon scenarios with the intention of defining the different pathways towards a near-zero emission national energy system. This analysis is carried out using the *Spanish Energyscope* model, validated in chapter 2, and the time horizon of the study is up to 2030. In addition, the different assumptions made in each of the scenarios developed with the model are explained in detail.

Chapter 4 presents the results obtained from the different scenarios modelled. A comparison of the results obtained in all scenarios is made by analysing different topics (e.g., emissions, TPES, power generation, heat generation sector etc.) and checking whether the national and European targets are reached.

Chapter 5 Chapter 5 explains the conclusions reached throughout the project and makes a global reflection on how the profound modifications in the Spanish energy system should be carried out in the coming years to significantly reduce emissions and increase the national RES penetration.

Chapter 1

1. State of Art

1.1. The energy transition

1.1.1. Context

Today we live in a time of climate emergency due to the profound climate change that society has brought about through the intense burning of fossil fuels and the consequent release of large amounts of greenhouse gases (GHG) into the atmosphere. In recent decades, human activity has caused sudden changes in climate that seriously affect health around the world. The situation is particularly serious in cities, which account for 55% of the world's population, claim 75% of all energy produced and generate 80% of all pollution [01]. As a consequence of this sudden climate change, sea levels have risen due to increased heat, polar ice caps and glaciers are melting, and the combination of these two events causes flooding and erosion in coastal and low-lying areas [02]. In addition, there has been a change in weather patterns with more recurrent occurrences of heavy rainfall and other extreme weather events leading to flooding and in some areas a progressive decrease in water resources. The consequences are not only related to changes in climate. There are drastic changes in people's health, especially in the poorest regions of the world. According to the Food and Agriculture Organisation of the United Nations (FAO), population growth and dietary changes will increase consumption patterns by approximately 60% by 2050 [03]. Climate change increases pressure on food systems as livelihoods in agricultural environments are increasingly at risk due to climate threats to crops, livestock, fish stocks, etc. It is for this reason that FAO specifies that "safeguarding food security and eradicating hunger and the particular vulnerability of food production systems to the impacts of climate change is a key priority" [03].
All these consequences demonstrate that following the same pollution patterns and the same social habits, these phenomena will not only continue to appear but will increase in frequency. Therefore, in the light of the scientific evidence and the context in which society is immersed, governments all over the world are stressing the need to draw up decarbonisation paths and policies for their energy and economic systems in the short and long term (up to 2050). These decarbonisation policies must lead the way towards a profound transformation of fossil fuel-based energy systems towards carbon-neutral systems. This transformation should be marked

by an increased penetration of renewable energy (RES) in the energy system, a significant increase in energy efficiency, greater electricity interconnection of countries and a reduction in primary energy consumption. As the energy system is responsible for more than 60% of anthropogenic GHG emissions [04], the Kyoto Protocol defined in 1997 by the United Nations Framework Convention on Climate Change sets emission reduction targets for the first time, committing the signatory industrialised countries to stabilise their emissions. However, although concern and action on climate change is increasingly on the agenda, in most developed and industrialised countries there is still a high dependence on fossil fuels, with more than 80% of the primary energy consumed being based on fossil fuels [05].

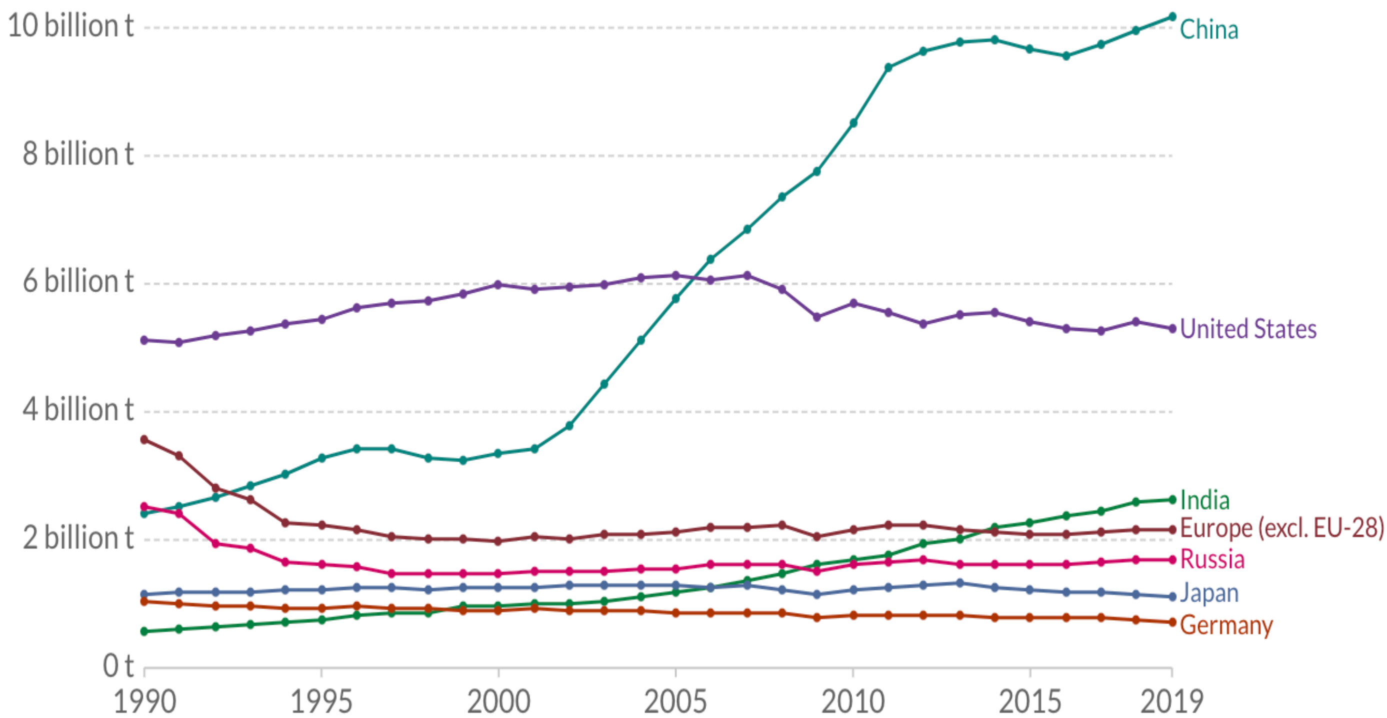

Figure 1.1: Evolution of CO_2 emissions of the major polluters in the world. Data extracted from World in data: Global CO_2 emissions [06]

Figure 1.1 shows the current trend of global CO_2 emissions in the period 1990-2019 for the world's largest emitters in billions of tonnes [06]. As can be seen in the figure, the emission trends of steadily developing countries such as China and India have grown over the period studied. In contrast, the trends in developed countries have remained constant and have even seen a slight decrease in emissions due to the more consistent decarbonisation policies implemented by governments and organisations in these countries. Current trends show that more efforts are clearly needed to mitigate the consequences of climate change in the coming decades. This is the direction of the Paris Agreement defined in 2015, which establishes a global framework to avoid dangerous climate change by keeping the global average temperature below 2°C above pre-industrial levels and continuing efforts to limit it to 1.5°C [07]. To achieve this, a common commitment is made to reduce GHG emissions by at least 40% by 2030 compared to 1990 levels. In addition, it also highlights the key role and importance of non-signatory parties to the agreement, such as cities, national administrations, and the private sector, which should be working in the same direction and can play a more important role than it may seem at first glance.

1.1.2. Energy transition in Europe

The historic Paris Agreement signed during the XXI Climate Change Conference (COP21), by 195 member countries, was adopted at the end of 2015 and aimed to establish comprehensive measures for the reduction of Greenhouse Gas (GHG) emissions through mitigation, adaptation, and resilience of ecosystems for the purposes of global warming.

To reduce GHG emissions and mitigate the potential negative effect of climate change, the EU has set itself targets to progressively reduce its greenhouse gas emissions up to 2050. The first measures taken by the EU are included in the so-called "Climate and Energy Package"[08], which set challenges and targets such as the reduction of GHG emissions by 20% by 2020 (relative to 1990 levels), a 20% improvement in energy efficiency and a 20% contribution of total European energy from renewable energy.

The next steps taken by the EU considering the existing ambition to reduce emissions, are included in the so-called "2030 climate and energy framework"[09]. The framework includes plans and targets at EU level for the horizon 2021-2030 with the aim of extending the current legislative framework of 2020. Clarifying the goals for 2030 certainly supports progress towards a competitive economy and a secure energy system by creating greater demand for high-efficiency and low-carbon technologies. In addition, it is an incentive to stimulate research, development, and innovation, which can create new opportunities for employment and growth.

In the same terms, the EU "commits to reduce greenhouse gas emissions to 80-95% below 1990 levels by 2050 in the context of reductions required by developed countries as a group" [28]. The Commission oversees monitoring progress through the so-called 'Roadmap for moving to a competitive low carbon economy in 2050'[11], which sets out different scenarios involving major changes in carbon prices technologies and networks, energy efficiency, low nuclear, CCS[1] or the percentage penetration of RES in the energy system, are some of the examples.

[1] Carbon Capture and Storage (CCS)

On the other hand, at the end of 2019 the European Commission went further with its commitments and presented the so-called 'Green Deal'[12], an ambitious project that includes a set of proposals and objectives in terms of environmental, energy and climate policy with the important goal of achieving a carbon-neutral economy by 2050, i.e., that the total balance of emissions with the earth should be zero. In this framework, the objectives set by the EU are reaffirmed in the European Green Pact, which covers all sectors of the economy, especially transport, energy, agriculture, buildings, and industries: steel, cement, textiles, and chemicals. The minimum targets set by the EU in the different pacts or strategies are listed in Table 1.

Field	**Target 2030**		**Target 2050**
	Climate and Energy Framework[2]	*Green Deal*	*Energy Roadmap 2050*
Reduction on GHG emissions (from 1990 levels)	40%	50 - 55 %	80 – 95 %
Improvement in energy efficiency	32%	N/A	32 - 41%[3]
EU energy from renewables	32.5%	N/A	55%[4]
Electrical interconnection	15% (each EU country)	N/A	N/A

Table 1.1: Minimum targets according to "2030 Climate and Energy Framework" [09], the "Energy Roadmap 2050" [11] and the "Green Deal" [12].

To achieve all these objectives, all EU member states are required to develop country-specific strategies and long-term plans, with the aim of determining how they will achieve the greenhouse gas emissions reductions needed to meet their commitments under the EU objectives. The EU is leading the way by investing money in realistic technology solutions, empowering citizens, and aligning proposals in key areas such as industrial policy, funding and research, while ensuring social equity for a just transition for everyone. The direction is right, but acceleration is needed to enable the European Union to become the first continent to develop a carbon-free system.

[2] The objectives of renewable energy, energy efficiency and electrical interconnection may be revised upwards in 2023
[3] Compared with primary energy consumption in 2005
[4] As specified in the RES directive for the calculation of the 20% target by 2020. RES scenario

1.1.3. Energy Transition in Spain

1.1.3.1. Current situation

Spain is one of the many countries that have signed the Paris Agreement due to the seriousness of the consequences of climate change. As stated in the document "*Impacts and risks derived from Climate Change*" issued by MITECO in 2021 [13], the Spanish climate change scenarios elaborated by AEMET[5] project temperature increases of between 2ºC and 6.4ºC with an increase in hot days and longer heat waves. In addition, rainfall will tend to decrease, accompanied by changes in wind speed and a general increase in extreme events. In addition, the IPCC[6] reports point to southern Europe and the Mediterranean basin as one of the areas most exposed to the consequences of climate change, so this is an especially important issue for Spain [14].

Figure 1.2 shows the global CO_2 emissions of the world's highest emitting countries including Spain in 2019. In this year Spain was responsible for the emission of 252.68 Mt CO_2 contributing approximately 0.7 % of the total global emissions (36.44 Gt CO_2).

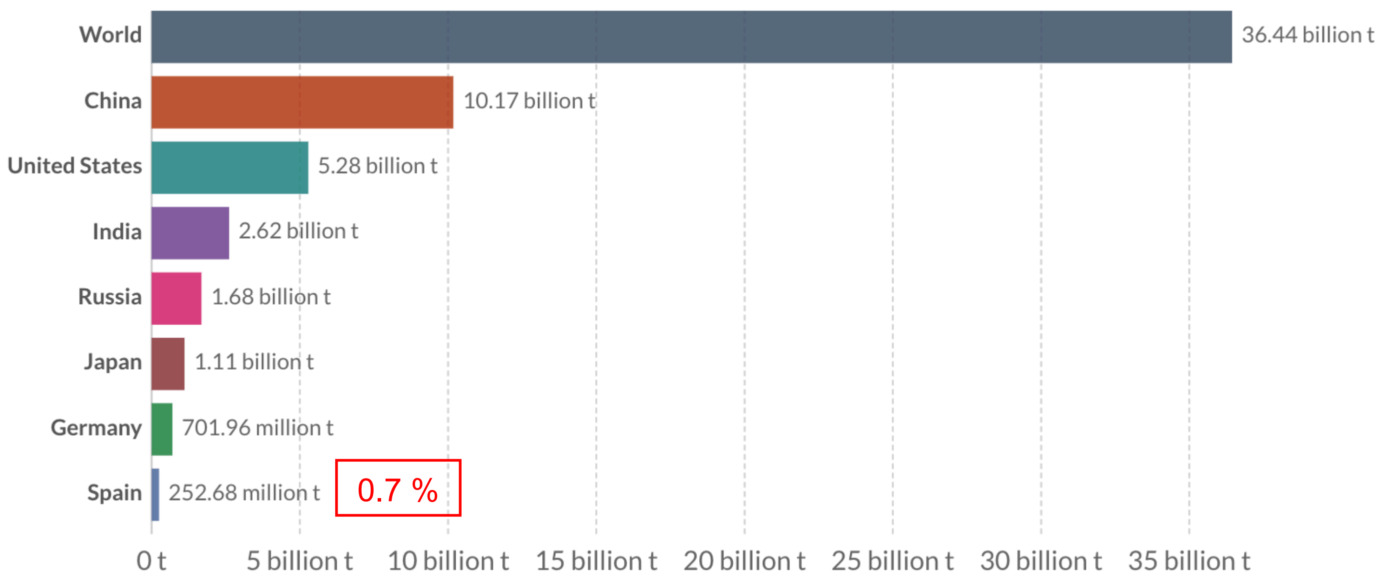

Figure 1.2: CO_2 emissions of the world in 2019. Data extracted from OECD air an GHG emissions 2019 **[15].**

5 Agencia Estatal de Meteorología

6 Intergovernmental Panel on Climate Change

Total primary energy supplied (TPES) has decreased by 5.5% in Spain over the last 10 years [16]. However, CO_2 emissions have progressively decreased over the last decades from 2009 to 2019, from 297.24 Mt to 252.68 Mt CO_2 [06]. This decrease in emissions is due to the various energy policies implemented and under development, such as increased penetration of renewable energies in the electricity sector, improvements in energy efficiency, greater interconnection with neighboring countries and an increase in the consumption of renewable resources in detriment of fossil fuels.

For this reason, Spain has already set certain targets to progressively achieve a deep decarbonisation of society in all sectors involved, as will be discussed in the following sections of this chapter. Spain has the potential to become one of the driving forces behind this necessary change, as it has one of the highest renewable resource potentials in the EU [17]. This is because it has 50 million hectares with vast territories, Mediterranean and Atlantic winds, extensive forests, a high level of irradiation and hydraulic resources, which are combined with an important business, technological and innovation network.

The following is a brief overview of the current situation in Spain in the electricity generation sector to get an overview of the Spanish energy outlook.

In relation to the current situation in Spain, taking 2019 as a reference year, the generation of electricity on the Spanish mainland stands at 247 086 GWh. The most significant variations with respect to the previous year were recorded in combined cycle generation, which rose by 93.7%, while coal and hydroelectric power fell by 69.4% and 27.6% respectively [18]. Figure 1.3 shows the structure of peninsular electricity generation.

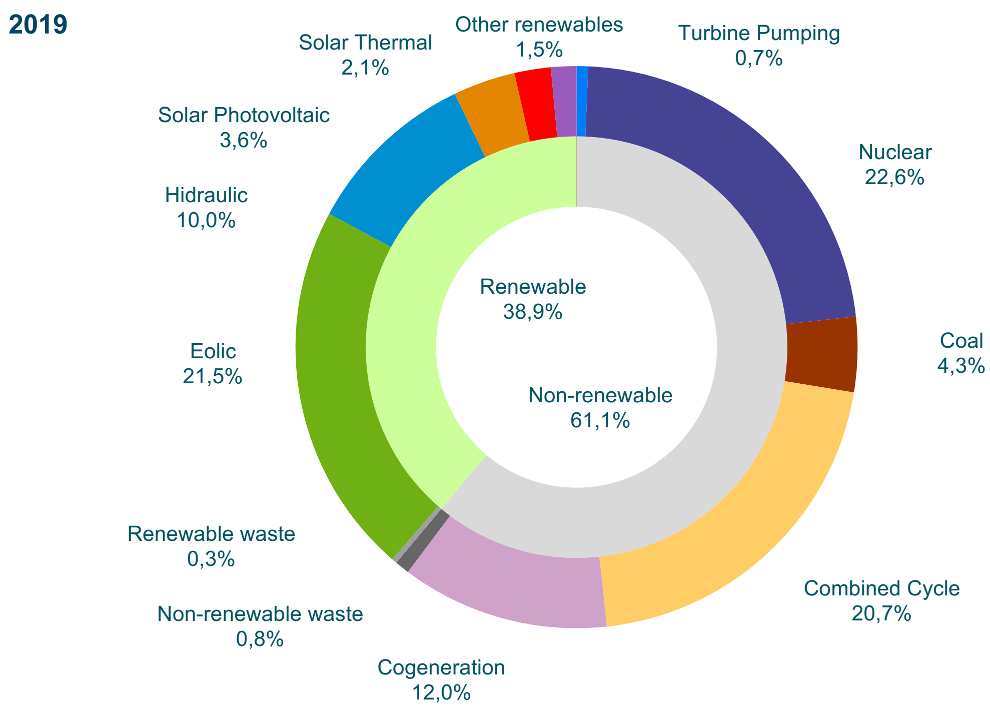

Figure 1.3: Structure of peninsular electricity generation in 2019. Data extracted from Red Eléctrica Española [19]

Non-renewable generation has reached a total of 61.1% of the total, boosted by the significant increase in electricity production in combined cycle plants, where it has doubled its weight in the structure, reaching 20.7%. On the other hand, it is worth mentioning that coal has come to represent only 4.3% of the mix and is already the lowest value on record. In terms of the generation balance, renewables have a 38.9% share of the peninsular generation structure. Figure 1.4 shows the structure of peninsular renewable electricity generation in 2019.

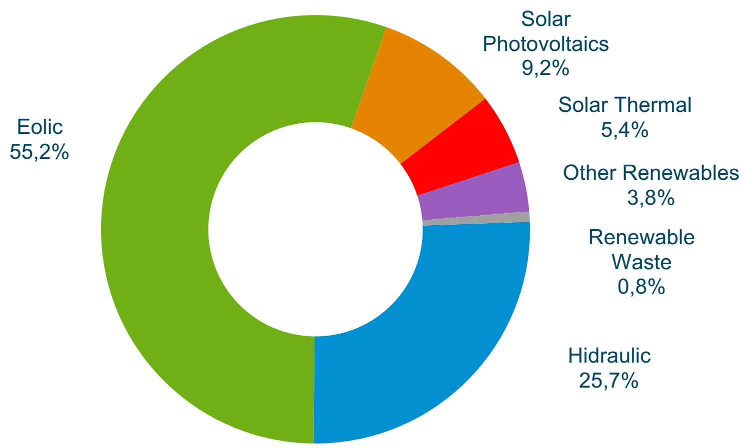

Figure 1.4: Structure of renewable peninsular electricity generation in 2019. Data extracted from Red Eléctrica Española [19]

As can be seen in the previous figure, wind, hydro, and solar photovoltaic energy have the largest shares in the energy structure. Wind energy continues to be the most important renewable technology, accounting for more than half (55.2%) of all renewables in 2019. Moreover, it has been on an upward trend in recent years and its significant contribution to the Spanish mix is worth highlighting, accounting for 21.5% of all production. Solar photovoltaic energy increased its production by 19.8% compared to the previous year, reaching a production of 8 842 GWh, which was a record annual generation with a contribution of 3.6% to the peninsular mix. Similarly, other renewables (biogas, biomass, solar thermal, marine hydro, etc.) increased their production and contribution to the energy mix.

National installed capacity reached an all-time high in 2019 with 110 376 MW installed, 6% more than the previous year. In addition, this generating park is increasingly renewable and reached 50.1% of the total installed capacity. This renewable increase is due to the significant increase in wind, solar photovoltaic and other renewable generation parks, which increased their capacity by 9.7%, 94.1% and 22.9% respectively. The following Figure 1.5 shows the structure of the installed power of the national electricity system where the relative share of each of the technologies can be seen.

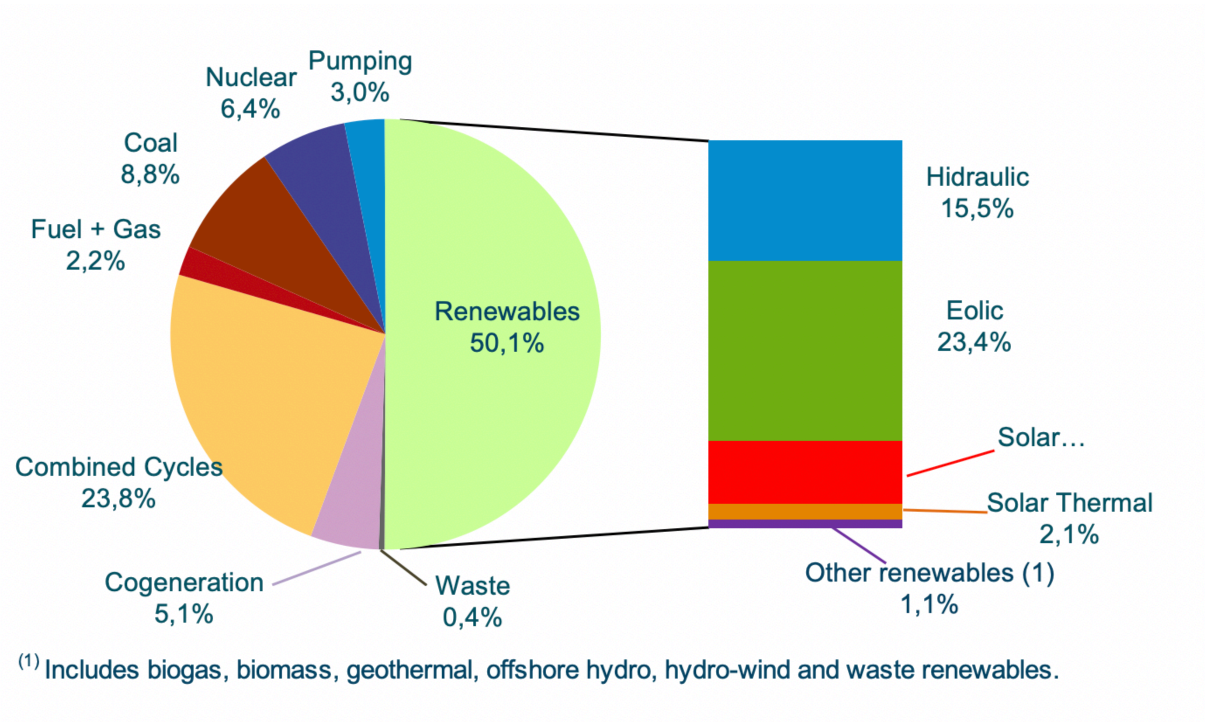

Figure 1.5: Installed power structure of the national electricity system in 2019. Data extracted from Red Eléctrica Española: "*Energías renovables en el Sistema eléctrico español*" [20]

This constant drive towards decarbonization has led to a significant decrease in CO_2 emissions associated with national electricity generation. In 2019, the lowest historical emissions since data was collected (1990) were reached, with a reduction of 23% compared to the previous year. The following figure shows the evolution of these emissions broken down by type of energy source.

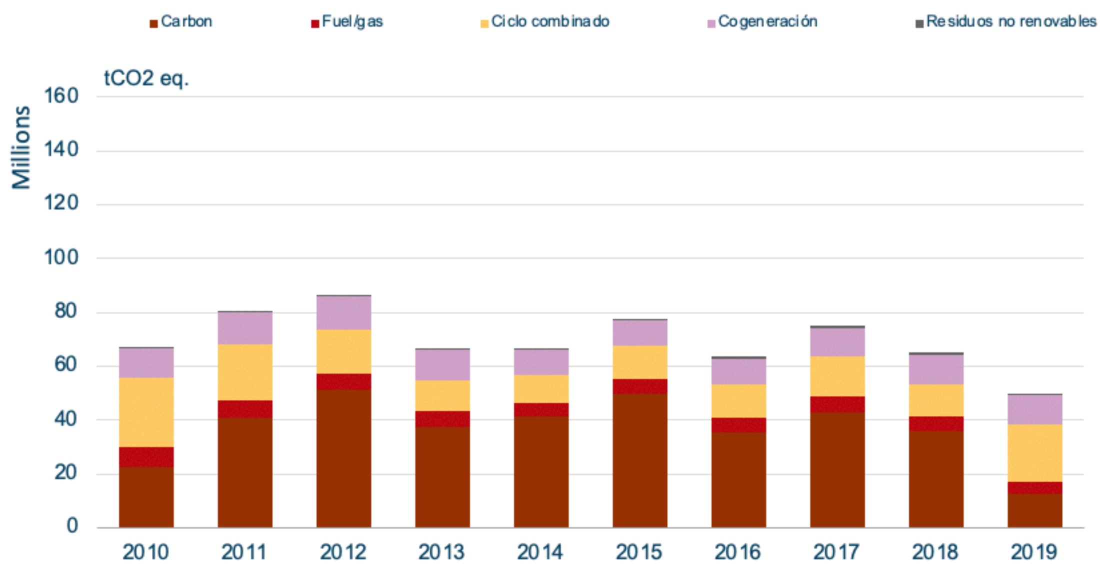

Figure 1.6: Emissions associated with national electricity generation [19]

As can be seen in the figure above, a total of 50 million tons of CO_2 were produced, 23% less than the previous year. This decrease is mainly due to the significant decrease associated with the production of coal-fired power plants which, as mentioned above, fell by 64.9% compared to the preceding year.

Regarding international electricity exchanges, Spain has been an importer since 2015. In 2019 the net balance imported was 6 862 GWh, which represents a 38% reduction in imported energy compared to 2018. Below is an annual evolution of physical exchanges with the different countries with which Spain has electricity interconnections.

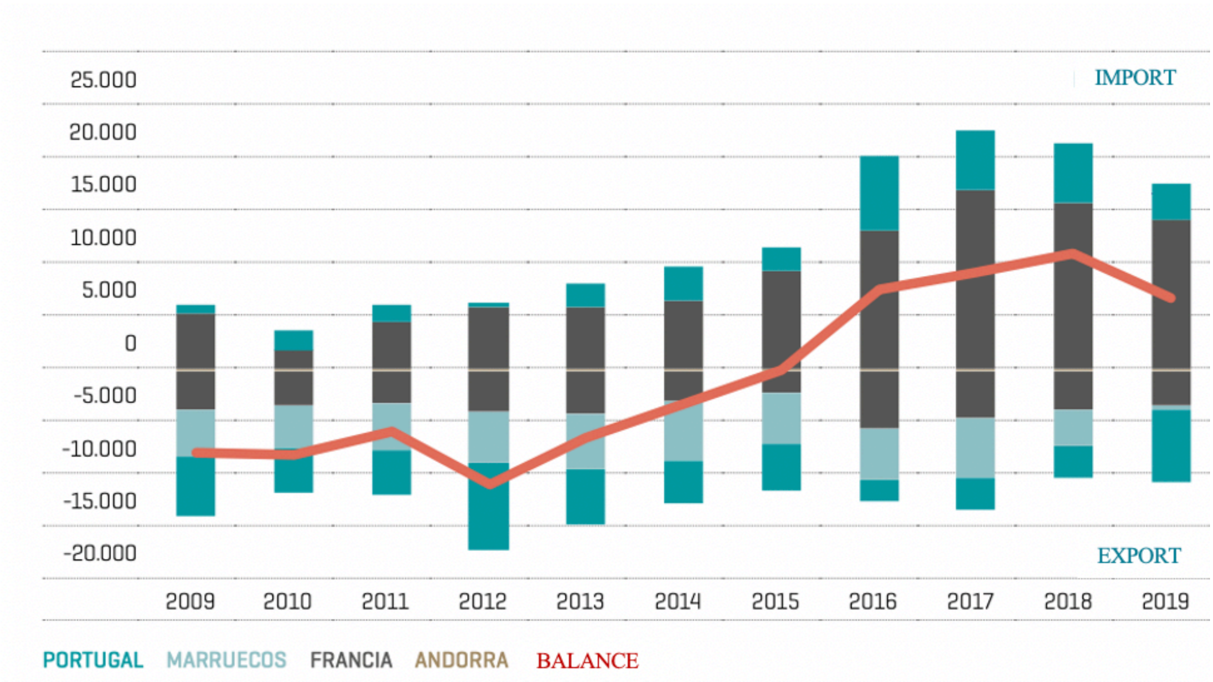

Figure 1.7: Annual evolution of physical international exchanges (GWh) [19]

Electricity interconnections with neighboring countries are key players in the energy transition, as their role is essential for a better integration of renewables, ensuring greater security of supply and advancing decarbonization. The importance of these interconnections is even greater for peripheral countries, such as Spain, for which this type of infrastructure is essential for the development of an adequate electricity system. Therefore, strengthening and increasing these interconnections is a priority in the coming years, considering that the degree of Spanish interconnection is far below the targets set by the EU of 10% and 15% for 2020 and 2030 respectively.

It is for this reason that the "*Plan Nacional Integrado de Energía y Clima*" (PNIEC) [21] proposes an increase in exchange capacity, exceeding 3 000 MW with Portugal and reaching

8 000 MW with France with the implementation of three new electricity interconnection projects.

Below is a table with a summary of the current electricity trade capacity ranges of interconnections with neighboring countries in March 2021.

Connection	***Minimum [MW]***	***Maximum [MW]***
France - Spain	3100	3300
Spain - France	2700	2800
Portugal – Spain	3000	4000
Spain - Portugal	1100	1500
Morocco - Spain	400	600
Spain - Morocco	400	900

Table 1.2: Trading capacity ranges (MW), March 2021 [22]

1.1.3.2. Future national energy plans in Spain

Spain's energy and climate policy framework are set by the European Union, which in turn depends on the aforementioned Paris Agreement to provide a coordinated response to the enormous challenge of the climate crisis. Spain ratified the Paris Agreement in 2017, which allowed it to establish its own renewed commitment to energy policy. To meet the objective of joint action by all EU member states, the EU requires each one to draw up a national plan to be able to monitor the degree of its own and joint compliance and establish actions to correct any deviations. All these actions are set out in the so-called Governance Regulation [23], which establishes certain standards to be followed by each member state. In addition to the preparation of a national plan with a 2030 horizon, it establishes guarantees beyond that horizon by requiring a longer-term strategy (2050). Finally, it stipulates that each state must submit progress reports every two years.

In this context, Spain has drafted a law called "*Proyecto de Ley de Cambio Climático y Transición Energética*" (PLCCTE) [24] which responds to the commitment made and which offers an opportunity from an economic and social point of view by facilitating the equitable distribution of resources in the decarbonisation process. This law is the constitutional framework to facilitate a correct progression of the requirements in climate action and to guarantee synergies between the different sectors to ensure coherent policies with the main objective. This law sets out the main national targets for the 2030 and 2050 horizons in terms of reducing greenhouse gas emissions, renewable energies, and energy efficiency in the Spanish economy. Two key climate and energy governance instruments have been developed in the framework of the PLCCTE, as set out in the "Regulation 2018/1999 of the European Parliament and of the Council of 11 December 2018" [25]: Plan National Integrated Energy and Climate Plan 2021-2030 (PNIEC) and the Decarbonisation Strategy to 2050.

PNIEC identifies the challenges and opportunities of the five axes set out in the aforementioned Governance Regulation: (i) Decarbonisation, (ii) Renewable energies, (iii) Energy efficiency, (iv) Internal energy market and (v) Research, competitiveness, and innovation. This plan aims to advance decarbonisation towards a neutral society and economy. It is worth mentioning in this regard that, since three out of every four tonnes of GHGs in Spain originate in the energy sector, decarbonisation is the main element of the plan. The implementation of the plan will result in greater energy self-sufficiency with an important base of efficient use of the country's renewable potential, especially wind and solar.

On the other hand, the "*Estrategia de Descarbonización a Largo Plazo 2050*" [26] (ELP) is a roadmap for moving towards climate neutrality by 2050[7], with intermediate milestones in 2030 and 2040. This strategy will also provide an energy mix that is less dependent on fossil fuels and, as a result, will make Spain more resilient to variations in international markets. Therefore, Spain is and must work on the elaboration and implementation of different plans and coherent strategies related to a multitude of sectors, especially due to the geographical area vulnerable to climate change where the country is located. Table 1.3 shows the different targets set by the different plans and strategies with different time horizons.

[7] Climate neutrality in 2050 is a scenario in which greenhouse gas emissions are completely absorbed by carbon sinks, providing zero net greenhouse gas emissions in 2050.

Topic	Target 2030		Target 2050	
	PLCCTE	PNIEC	PLCCTE	ELP
Reduction on GHG emissions (from 1990 levels)	20%	23%	100%	90%
Renewable energies as a share of total final energy consumption	35%	42%	100%	97%
Improving energy efficiency	35%[8]	39.5%	N/A	N/A
Renewable energies in electricity generation	70%	74%	N/A	100%
Reduction of foreign energy dependence to	N/A	61%[9]	N/A	13%[10]

Table 1.3: *Minimum targets according to "Proyecto de Ley de Cambio Climático y Transición Energética" [24], the* Plan National Integrated Energy and Climate Plan 2021-2030 (PNIEC) *[21] and the "Estrategia de Descarbonización a Largo Plazo" [26]. Legend: no data (N/A)*

Following these needs mentioned in Table 1.3, the expected results of the PNIEC include an annual increase of 1.7% of Gross Domestic Product (GDP) and a 3.5% annual increase in primary energy intensity[11] until 2030 due to the proposed increase in energy efficiency, a reduction in energy dependence from 74% in 2017 to 61% by 2030 due to the reduction of coal and nuclear (four of the seven reactors are planned to be retired) from the electricity generation mix and compensated by a marked increase in the penetration of renewable energies, especially wind and solar, which may increase by 55% and 88% respectively in 2030 compared to 2015 [28]. In addition, it is expected to reach 28% of renewables in transport via electrification and biofuels and an installed electricity capacity of 161 GW in 2030 compared to 107 GW in 2015 [28].

[8] Efficiency will be measured by calculating the reduction of primary energy in 2030 compared to the EU's 2007 PRIMES forecast [27].
[9] Compared to 74% in 2017.
[10] Assuming savings of 344 million euros.
[11] Energy intensity is an indicator of the energy efficiency of an economy. It is calculated as the ratio of energy demand or consumption (E) and a country's gross domestic product (GDP).

1.2. Energy System Modelling

1.2.1. Models and studies

Scenario development to model and explore low-carbon futures has been widely undertaken for a couple of decades. In an increasing number of cases, these energy models are becoming indispensable development tools that allow us to try to predict the different futures of energy systems. In addition, they provide predictions from different perspectives or a vision of possible development trajectories. As reviewed by S. Hilpert et al. [29], to capture important properties of increasingly complex energy systems, sophisticated and flexible modelling tools are needed. They are not exact forecasts but represent possible paths to different future energy situations by applying a series of hypotheses and constraints that are representative of the reality under study. The results of these models provide such valuable information that they are increasingly used by key policy makers involved in energy issues. They use this type of software to underpin and support energy policy and mitigation decisions at national and international level. So, modelling and simulation has long and well served the actors and various decision makers in the domain of energy policy. Various modelling approaches and models have been applied to address a variety of energy policy related issues [30].

In the context of the energy transition already mentioned in Section 1.1.1, ESOMs (Energy system optimization models) are used to help represent an energy system on a regional or national scale over a time horizon of up to several decades. In fact, most of the plans and documents formulated by the various organisations with energy competencies are based on scenarios and situations proposed with this type of model. Therefore, it is necessary to make a compilation of the different energy models already available to compare them according to different criteria and choose the one that could best represent the case of Spain's energy transition in a sufficiently good way.

For this purpose, a review of the literature on the different models that exist has been carried out to see which ones are most suitable for the case of Spain according to certain criteria. The work performed by Connolly et al. [31] and Limpens et al. [32] was consulted to carry out a subsequent study of the potential models suitable for the Spanish case.

1.2.1.1. State of the art in Spain and the Spanish case

A review of the different energy models applied to Spain on a national or regional scale has been carried out to have a broad view of the current state of the different scenarios with a time horizon up to 2050. To do so, the different models currently used in some of the plans issued by MITECO (Ministry for Ecological Transition) have been analysed, as well as other energy models applied to Spain carried out by other non-governmental organisations.

Firstly, a comparison has been made of the energy system models of the different models used in the National Integrated Energy and Climate Plan 2021-2030 (PNIEC) [21], already mentioned in Section 1.1.1, carried out by the department of the Directorate General for Energy Policy and Mines and for the rest of the models that have been applied in Spain.

The following table shows a comparison of the different models according to the following criteria: sector coupling or electricity only, the scale (region or country), open source and/or open use, optimisation, or simulation approach.

Tool	**Source**	**Project/ Plan**	**Sectors**		**Open**		**Scale**		**Approach**		
			Elec.	Coupl.	Use	Source	Country	Region	Optim. Cost	Optim. Emiss.	Simul.
TIMES-Sinergia	[33]	PNIEC	✓	✓	(✓)	-	✓		✓		
PLEXOS	[37],[28]	PNIEC	✓		✓	-	✓				✓
M3E	[38],[39]	PNIEC		✓	✓	-	✓		✓		
DENIO	[40],[41],[42]	PNIEC		✓	-	-	✓				✓
AIDS	[43],[44]	PNIEC		✓	✓	-	✓				✓
TM5-FASST	[45],[46]	PNIEC		✓	(✓)	-	✓				✓
JRC-EU-TIMES	[47],[48]	HRE4		✓	✓	✓	✓		✓		
ENERGY PLAN	[49]	HRE4		✓	✓	-	✓				✓
	[50]	DESIRE		✓	✓	-	✓				✓
SimRen	[51]	Solar Catalonia	✓		(✓)	-		✓			✓

Table 1.4: Comparison of Energy system models applied to Spain. Abbreviations: electricity (elec.), coupling (coupl.), optimisation (optim.), simulation (simul.), emissions (emiss.). Legend: (✓) satisfied; ((✓)) partial satisfied.

Secondly, a brief explanation of each of the models found with application to the Spanish energy or non-energy system.

The modelling of the energy system for the PNIEC has been developed with the TIMES-Sinergia (Integrated System for the Study of Energy) tool, which covers the entire energy system. Additionally, other models applied and dedicated specifically to the electricity sector have been used to cover certain characteristics that cannot be captured by the TIMES model, such as electricity generation with hourly resolution.

The main tool used in the elaboration of the PNIEC is TIMES (The Integrated MARKAL-EFOM system) [34], suitable for energy analysis and foresight. This tool was developed by the International Energy Agency within the framework of the ETSAP (Energy Technology Systems Analysis Program) for the development of energy systems. It is an evolution of the MARKAL tool [35], a generic model tailored by the input data to represent the evolution over a period of usually 40 to 50 years of a specific energy system at the national, regional, state or province, or community level [36]. TIMES has been used to model systems in more than 60 countries and is widely used at European level. In the Spanish case, TIMES-Sinergia [33] is an adaptation of TIMES-Spain. It is a bottom-up model, i.e., it starts from each of the components of the energy system to obtain data at an aggregated level. Moreover, it combines the technical and economic approaches, complementing each other.

Another model used in the development of the plan is PLEXOS [37,28]. This model, used by Red Eléctrica Española (REE), is a simplified version of the original model used for the European system in the studies carried out at ENTSO-E[12] in the development of the Ten Years Network Development Plan (TYNDP). PLEXOS is responsible for simulating the generation and guarantee of supply of the Spanish electricity system. It should be noted that the main hypothesis used by the model is governed by a perfect competition market model, i.e., the interest of generators in maximising profits is not considered. Each modelled system (supply/demand zone) is represented by a node interconnected with others and with the commercial capacity marked by the market (NTC - Net Transfer Capacity). Therefore, PLEXOS consists of optimising the cost of all generation to determine the optimal solution to cover the demand and with the restrictions of the maximum interchange capacities between nodes or zones. The major drawback is the high computational time, so this model usually only covers one sector.

In the same context, the M3E model (Modelling of mitigation measures in Spain) [39,38] allows the analysis of potentials and costs of all mitigation measures in the different sectors and the contribution of the non-energy sectors to the fulfilment of the PNIEC objectives. Its function is twofold: on the one hand, it optimises in search of the objective function of cost minimisation while complying with certain restrictions and, on the other hand, it proposes degrees of application of the measures within a range of values.

On the other hand, the DENIO model (Dynamic Neo-Keynesian Econometric Input-Output Model for Spain) [40,41,42] is a dynamic neo-Keynesian econometric model widely used to analyse the economic impact of the different measures and scenarios of the PNIEC. It is a

[12] European Network of Transmission System Operators (ENTSO-E)

disaggregated model with a wide range of inputs e.g., 74 sectors, 88 products and 16 consumption categories. For the PNIEC simulations, the DENIO model is combined with the TIMES-Sinergia model from which it uses various data such as energy mix, energy intensity and energy efficiency per sector etc.

The Almost Ideal Demand System (AIDS) [43,44] is a consumer demand model mainly used to study consumer behaviour. In the context of the PNIEC it is used to calculate the income and price elasticities of substitution for the different goods that make up a node or zone e.g., food, textiles, households etc. The main added value of this model is that it allows a first order approximation to a mainly unknown demand system.

TM5-FASST [45] is a global air quality source-receptor model (AQ-SRM) developed by the Joint Research Centre (JRC) of the European Commission in Ispra, Italy. It allows the analysis of ecosystem damage resulting from different emission scenarios or trajectories. Specifically, it uses meteorological data to analyse how emissions from a source affect different receptors in terms of particulate matter concentration, exposure, and premature deaths. A variety of studies have been conducted using this model at regional and global scales e.g., Kitous et al., 2017 [52].

Another model that is widely used in the European context is EnergyPLAN which can be used to aid in the design of systems with high penetration in renewables. Shortly, EnergyPLAN is an input/output model able to simulate the operation of regional or national energy systems including a multi sector approach and in an hourly resolution. A more detailed explanation of the model and how it works can be found in [53]. In the Spanish case, the model has been used for two different projects. Firstly, it has been used in the Heat Roadmap Europe (HRE4) project [49] carried out by the EC, which specialises in developing low-carbon heating and cooling strategies. One of the fourteen EU countries to which a heat roadmap has been modelled is Spain. The results of the Heat Roadmap Spain can be found at [54]. Secondly, the EnergyPLAN model was used in the EU-funded project DESIRE (Dissemination Strategy on Electricity Balancing for Large Scale Integration of Renewable Energy) [50]. In this case, the model was used for electricity supply considering the important role of electricity interconnections in the fluctuating electricity production and consumption especially when areas with different production systems are connected.

In the same context of Heat Roadmap Europe, the JRC-EU-TIMES model applied to fourteen EU countries, including Spain, has been used. This model is a linear optimisation bottom-up technology model that represents the EU28 energy system, with each country constituting one region of the model. The JRC-EU-TIMES is primarily an annual model that optimises the energy system over decades, although it includes time slices for smaller time intervals. The results for the Spanish case and a comparison of the results using this model or EnergyPLAN in the context of HRE4 can be found in [47, 48].

Finally, SimREN is a software that designs energy supply and demand models with a bottom-up approach. The model simulation uses real weather data for a full year with a simulation time of about 15 minutes for each step. Both supply and demand can be simulated considering the real time and weather. A detailed overview of the model is available at [55]. SimREN has been used to simulate the 100% renewable electricity sector in the region of Catalonia in Spain [51]. Once the different models applied to Spain have been analysed, several studies carried out in other EU countries with different models have been compared to conclude which models would better represent an energy system such as the one in Spain. The studies compared are cases applied to different EU countries with some of the most widely used models. The different comparison criteria for each case are: (i) Which model is used? (ii) Which country is studied? (iii) Has a multi-sector study been carried out? (iv) Which function is optimised? (Cost and/or emissions) (v) What is the resolution time-step, base year, and reference year? The Table 1.5 with the results obtained is shown below.

<table>
<tr><th rowspan="2">Tool</th><th rowspan="2">Country</th><th colspan="2">Sectors</th><th colspan="2">Objec.</th><th colspan="3">Time</th></tr>
<tr><th>Elec.</th><th>Coupl.</th><th>Cost</th><th>Emiss.</th><th>Step</th><th>Base</th><th>Target</th></tr>
<tr><td rowspan="8">MARKAL/TIMES</td><td>Sweden [56]</td><td>-</td><td>✓</td><td>✓</td><td>-</td><td>y</td><td>2000</td><td>2050</td></tr>
<tr><td>US [57]</td><td>-</td><td>✓</td><td>✓</td><td>-</td><td>5y</td><td>2005</td><td>2055</td></tr>
<tr><td>UK [58]</td><td>-</td><td>✓</td><td>✓</td><td>-</td><td>5y</td><td>2010</td><td>2050</td></tr>
<tr><td>Portugal [59]</td><td>-</td><td>✓ [b]</td><td>✓</td><td>-</td><td>5y</td><td>2005</td><td>2050</td></tr>
<tr><td>Norway [c] [60]</td><td>-</td><td>✓</td><td>✓</td><td>-</td><td>5y</td><td>2010</td><td>2050</td></tr>
<tr><td>France [65]</td><td>-</td><td>✓</td><td>✓</td><td>-</td><td>5y</td><td>2005</td><td>2050</td></tr>
<tr><td>Canada [66]</td><td>-</td><td>✓</td><td>✓</td><td>-</td><td>y</td><td>2011</td><td>2050</td></tr>
<tr><td>EU [67]</td><td>-</td><td>✓</td><td>✓</td><td>-</td><td>5y</td><td>2010</td><td>2050</td></tr>
<tr><td>PRIMES</td><td>EU [72]</td><td>-</td><td>✓</td><td>-</td><td>-</td><td>5y</td><td>2015</td><td>2050</td></tr>
<tr><td rowspan="4">EnergyPLAN</td><td>Denmark [61]</td><td>-</td><td>✓ [b]</td><td>✓</td><td>-</td><td>Snapshot [a]</td><td>2015</td><td>2035, 2050</td></tr>
<tr><td>Macedonia [62]</td><td>-</td><td>✓</td><td>✓</td><td>-</td><td>Snapshot [a]</td><td>2008</td><td>2030, 2050</td></tr>
<tr><td>Ireland [63]</td><td>-</td><td>✓</td><td>-</td><td>-</td><td>-</td><td>2007</td><td>2020 & beyond</td></tr>
<tr><td>Italy [64]</td><td>-</td><td>✓</td><td>-</td><td>✓</td><td>-</td><td>2014</td><td>2050</td></tr>
<tr><td rowspan="4">EnergyScope TD</td><td>Belgium [68]</td><td>-</td><td>✓</td><td>✓</td><td>✓</td><td>Snapshot [a]</td><td>2015</td><td>2035</td></tr>
<tr><td>Switzerland [69]</td><td>-</td><td>✓</td><td>✓</td><td>✓</td><td>Snapshot [a]</td><td>2011</td><td>2035</td></tr>
<tr><td>Italy [70]</td><td>-</td><td>✓</td><td>✓</td><td>✓</td><td>Snapshot [a]</td><td>2015</td><td>2030</td></tr>
<tr><td>EU [71]</td><td>-</td><td>✓</td><td>✓</td><td>✓</td><td>Snapshot [a]</td><td>2015</td><td>2035</td></tr>
</table>

[a] Snapshot models model the performance of the energy system over a given period of time (in this case, one year), without taking into account the pathway.
[b] Includes electricity, heating, cooling, transport and industry.
[c] Includes Norway, Sweden and Denmark

Table 1.5: Overview of national scenarios through different studies. Abbreviations: electricity (elec.), coupling (coupl.), emissions (emiss.), Objective function (Objec.). Legend: (✓) satisfied.

As mentioned above, the MARKAL/TIMES model has been used to model energy systems in more than 60 countries. As can be seen in Table 1.5, some of the studies that have been carried out refer to the complete energy system of Sweden [56], UK [57], US [58], Portugal [59] and Norway [60] among others. In a very similar context, both TIMES (JRC-EU-TIMES) and PRIMES are used at the European level where their applications can be found in [67,72], where long-term low-emission strategies are developed both at the European level and for each of the countries involved in the study. Another of the most widely used models, already mentioned above, is EnergyPLAN. This model has been used to simulate deep carbonization scenarios for Denmark [61], Macedonia [62], Ireland [63] and Italy [64] among others.

As can be seen, some of these models have already been used previously to model part or all of the Spanish energy system and to represent the different possible paths to meet the objective of decarbonising society. However, for TIMES, PRIMES and EnergyPLAN, they only have the possibility of optimizing the total cost and they are not open-source models and, therefore, it is difficult to interpret the functioning and the methodology followed in the modelling. Furthermore, some of these models, such as TIMES, are not freely available for use, as they are commercially oriented. Due to all these limitations, it can be concluded that these 3 models mentioned above are not suitable for modelling the Spanish case in the context of this work. A compilation and comparison of existing models with different criteria (open source vs. open use; operational optimization vs. investment optimization), among others, can be found in [32]

Focusing on the search for a model that is accessible and open source, we have found EnergyScope Typical Days [32]. This linear programming model allows energy planning of energy systems in a region. Unlike the models discussed above, EnergyScope TD is fast, accessible, and capable of optimising both total system cost and total emissions. In addition, it is equipped with an hourly resolution that allows it to better shape stochastic energies, as it can better adapt to the intermittency of this type of energy. A complete description of the mathematical formulation can be found at EnergyScope TD supplementary material [73]. As can be seen in Table 1.5, this model has been used in other studies applied to other EU countries, such as Belgium [68], Switzerland [69] or Italy [70].

Finally, Table 1.6 summarises the different criteria that have been followed to choose the most appropriate model to represent the Spanish case in this work, within the different models that have been introduced in this section. Considering all the literature that has been reviewed, it has been believed that EnergyScope TD is the model that best meets the different requirements (feasibility, computational time, objective function, etc.), which makes it a very interesting option for the representation of the possible future scenarios for the Spanish case.

Tool	Open Source	Open use	Sector Coupling	Optimization Investment	Optimization Operation	Comp. Time
MARKAL/TIMES	×	✓	✓	✓	×	5-35 min
PRIMES	×	✓	✓	×	×	(×)
ENERGYPLAN	×	✓	✓	×	✓	s
EnergyScope TD	✓	✓	✓	✓	✓	~1 min

Table 1.6: Final models comparison. Criteria: (✓) satisfied; (×) not satisfied; (×) no data. Abbreviations: computational (comp.)

1.3. Main objective

The main objective of this thesis is to apply an existing open-source energy model oriented to regional and national energy systems to the Spanish case. This objective focuses on identifying a set of possible low-carbon pathways towards 2030 and beyond, to offer a vision of how the well-known energy transition can be approached. The energy model chosen as a reference in Section 1.2, called Energyscope TD, is a linear programming (LP) model focused on optimisation developed by Limpens [73]. This model builds on previous work by Stefano Moret in [74]. To begin with, the focus of this work is to collect all the necessary new data from the Spanish energy system to implement them in the already defined formulation. The model resulting from the application of all these data inputs is a new version of the Energyscope TD model called *Spanish Energyscope*. The scientific literature on energy models based on the Spanish energy system is not very extensive, and the existing literature does not provide results for the different sectors of the complex Spanish energy system. The final reports of the models used for Spain are usually focused on a specific sector (electricity, heating etc.), so the *Spanish Energyscope* model offers a detailed characterisation of the Spanish energy flows. Regarding the previous formulations of the model, *Spanish Energyscope* offers different additions: new end-use demands (e.g., cold for space cooling and processes); new energy conversion technologies (e.g., motorbikes, passenger boats, plans); new resources (e.g., kerosene). Before developing the different low-carbon scenarios, the *Spanish Energyscope* model is validated with data from a past reference year (in this case 2015) to compare the results obtained and corroborate the optimal performance of the model. This simplified but sectoral complete version of the Spanish energy model is then used to run and evaluate the different scenarios for the gradual decarbonisation of the Spanish energy system. These scenarios to be modelled are based on the recent climate and energy transition plans and directives developed by the different organisations with energy competences at national and European level. The results and the evaluation of the different scenarios will give us knowledge about whether the country is able to achieve the different national and European targets defined. It will also help us to understand which are the key drivers (e.g., technologies, sectors, resources) to put more emphasis on to reach the goal of a near-zero emission system.

Chapter 2

2. The Spanish Energyscope model

As seen in chapter 1, the state of the art of the different models for energy planning comprises a wide range of models with a great diversity of functionalities. In the case to be studied in this thesis and with the goal of applying an open model to the Spanish case, as it has been concluded at the end of chapter 1, the optimal option is to try to implement the EnergyScope TD model proposed by Limpens at [32]. In this case, the viability of the mathematical formulation model to represent the Spanish case, called *Spanish Energyscope*, is studied to obtain different simulations of the functioning of the Spanish energy system and to predict its operability in the future. The entire repository with all the code information for each of the modelled scenarios can be found at the following link:

https://github.com/JosepRoselloMartinez/Spanish-EnergyTransition.git

The Spanish Energyscope model is the result of the combination of several elements that enable a proper functioning:

(i) a model that accounts for the different end-use demands considering the demand for electricity, heat (high and low temperature), cooling (both for process or cold space) and the demand for mobility (passenger and freight).

(ii) the hourly resolution of the model, which allows considering the variability of energy demand and the integration and implementation of variable renewable energies with thermal and electrical storage capacity.

(iii) the implementation of the mathematical linear programming formulation that allows a resolution with a low computational time.

(iv) The use of the so-called typical days (TD) in the mathematical formulation, which allows to represent a reference year only with several days that are the most representative of the year and that have a similar energy demand and weather conditions.

(v) a system that makes it possible to represent, within certain limits, all the energy of the system under study in the different sectors. For this purpose, a series of constraints are defined to allow the energy system to be shaped to obtain an optimal representation and results.

(vi) a model that makes it possible to simulate a version of an energy system by importing different resources, whether fossil or renewable, and by installing different technologies that guarantee the operation of the system with the possibility of optimizing either the cost or the total emissions of the system.

A detailed description of the *Spanish Energyscope* model is therefore given in this chapter. It describes the methodology adopted by the model and the different constraints considered and defined in the mathematical formulation (LP). It also describes the new parameters that have been defined only for the Spanish case to represent in a more realistic way the energy system.

2.1. Methodology

The methodology used in the case of the *Spanish Energyscope* model is a replication of that used in [32]. This methodology starts from several inputs (time series, resources, technical and economic characteristics of the energy conversion technologies, parameters defined as the shares of different technologies, etc.) that are defined to the model before performing the optimisation and represents the desired energy system by optimising either the cost or the total emissions for a reference year (past, present, or future).

As already defined in the work done by Limpens [32], this methodology consists of two steps:

STEP 1 → Optimal selection of a set of typical days that adequately represent the total of the reference year under study. This selection is independent of the use of the LP model representing the energy system.

STEP 2 → Obtaining the optimised operation and configuration of the Spanish energy system using the LP model.

The following figure shows graphically the methodology implemented in the Spanish Energyscope.

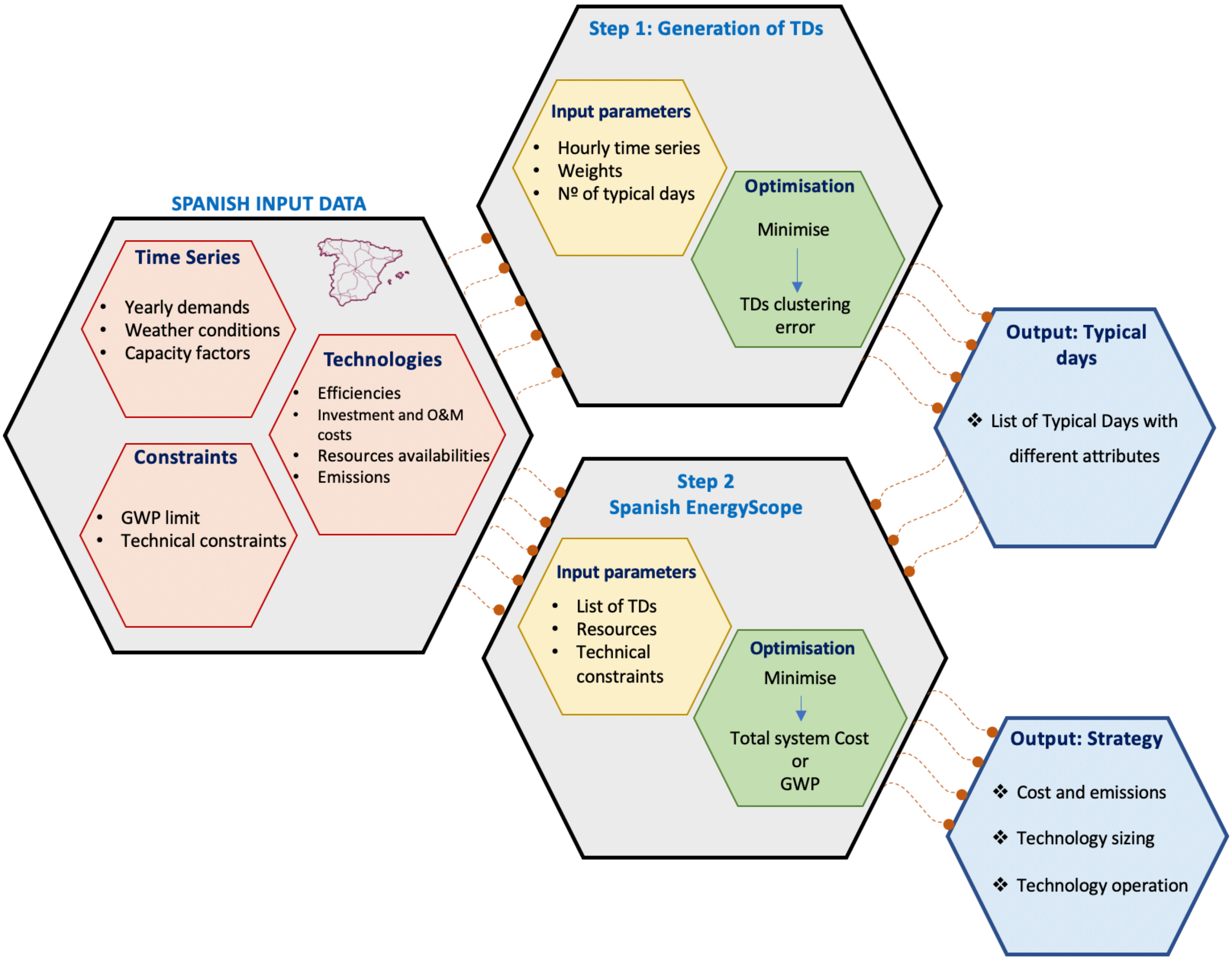

Figure 2.1: Representation of the two-step methodology for the model *Spanish Energyscope*, adapted from EnergyScope TD from [32]. Abbreviations: Typical Days (TDs), Number (Nº), Global Warming Potential (GWP).

2.1.1. Typical days

Limpens in [32] improved the existing monthly Energyscope formulation by implementing a new version of the model with hourly resolution and typical days, the Energyscope TD. These typical days are 24-hour aggregations that serve to represent specific time periods. The choice of the number of typical days to be chosen is a key point for a good energy planning by limiting the computational effort of the model. The typical days used in the *Spanish Energyscope* are 12 and are obtained using the clustering algorithm used by Limpens in [32]. The Spanish modelling considers different time series for 2015 such as electricity and heat demand, solar irradiation, wind, hydro and river production etc. These time series provide a simplified representation of intermittent demand during the year, changing weather conditions and the production of renewable energy systems. For more details on the typical day aggregation model used, reference is made to the work of Limpens in [32]. On the other hand, for more information about the Spanish time series used in the model, more information can be found in the work done by Jeroen & Jean Louis in [75].

2.1.2. Conceptual modeling framework

As already mentioned in Chapter 1, energy modelling is a very flexible and optimizable tool that allows modelling a wide variety of designs and variations of an energy system for a limited area or zone. As described by Alfonso Ippolito in [76], an energy model is "*A virtual or computerized simulation of a building or complex, realized with specific software, focusing on energy consumption, utility bills and life cycle costs of alternative energy systems to determine the most efficient design*". In this case, the proposed modelling is aimed to represent a simplified view of an energy system that considers the different energy flows within a previously defined area. The main objective is to satisfy the energy balance constraints, ensuring that all the required energy demand is met. For example, in the case of decentralized heat production in the layer (heat_low_temperature) using an electric heat pump, the FEC is the amount of electricity consumed by the heat pump while the EUD is the amount of heat generated and useful for the consumer's energy requirement. In energy modelling there are two methods for the energy approach. The so-called "pathway" can model the evolution of an energy system up to a target year and represents the whole path from the current system to a decarbonized one. On the other hand, the so-called "snapshot" model optimizes and verifies the viability of the energy system for a target year without considering the existing energy system. The Spanish case belongs to the snapshot category, as discussed in Chapter 1 and according to the classification made by Codina Gironès in [77].

Figure 2.2 shows a simplified conceptual example of the proposed structure of the *Spanish Energyscope* system at the national scale, considering three main components: Resources (renewable and non-renewable), energy conversion technologies and end-use demands. End-use demand is represented as the sum of 3 energy sectors: electricity, heating, and mobility demand. In turn, heating is divided into four end use types (EUTs): high temperature heat for industry (mainly process heating), low temperature heat for the service and residential sector (hot water and space heating), and finally for cooling there are two types of end use such as Space cooling and Process cooling. Mobility is divided into two EUTs: passenger and freight mobility.

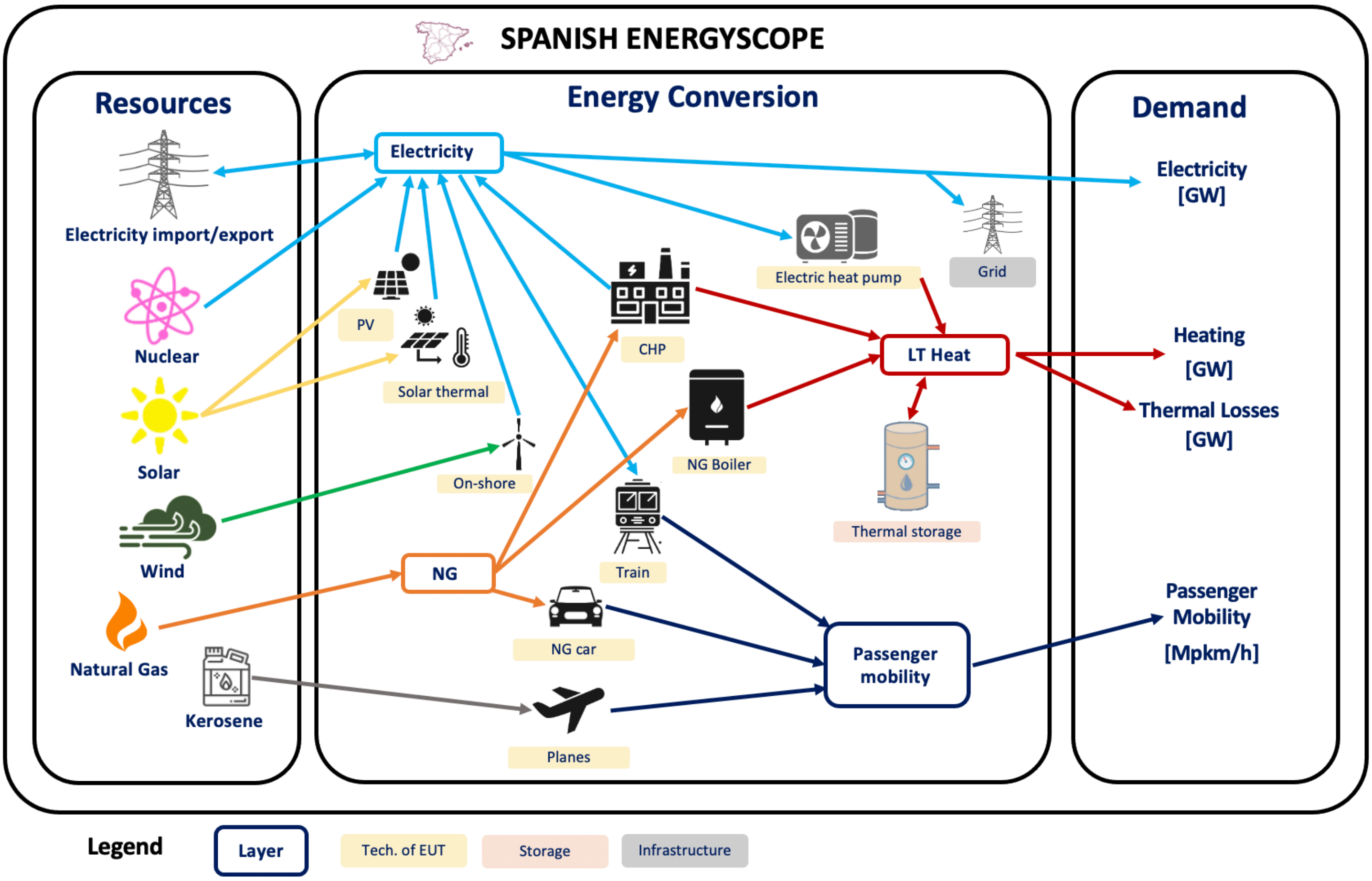

Figure 2.2: Conceptual representation of a national energy system defined with 5 resources, 11 technologies. Abbreviations: cogeneration of heat and power (CHP), photovoltaic (PV), low temperature (LT), end-use type (EUT).

As can be seen in Figure 2.2, the system is divided into three parts. The resources represented in the illustration are electricity, natural gas, uranium (nuclear), kerosene, and solar and wind energy. The different end use demands represented are electricity, heating, and passenger mobility. To meet these demands using the resources, several energy conversion technologies are needed. In this example, solar and wind energy cannot be used directly to meet the demand for electricity or heat. Therefore, technologies such as photovoltaic panels or wind turbines are used to supply the electrical demand or, on the other hand, electric heat pumps are used to supply the low temperature heat demand.

Figure 2.3 below is a schematic representation of the *Spanish Energyscope* model with a detailed illustration of all the energy vectors involved in the model. The schematic represents both the resources used in the energy system, as well as all the available energy conversion technologies and the different energy demands. The different conversion technologies are shown grouped by sector (e.g., Industrial Heat, Elec. production etc.) or by type of use (Private mobility, thermal storage etc.). Concerning the previous formulations of the different works carried out with Energyscope, certain technologies have been added with the main objective of representing the Spanish energy system in the most realistic and approximate way possible. The different novelties that have been added are illustrated in the representation by means of boxes underlined with a red line. These boxes can be coloured by different colours depending on whether these novelties are completely new and added for the exclusive Spanish case or if they are new technologies (not used in the work done for the case of Belgium in [68]), but already used in some other work as for example the one done by Marcello Borasio in [78] or the one done by Jeroen and Jean-Louis in [75].

- Boxes filled in orange: new energy technologies already used in other Energyscope models but not in the Belgium case (•).
- Boxes filled in green: new implementations specially for the Spanish case (•).

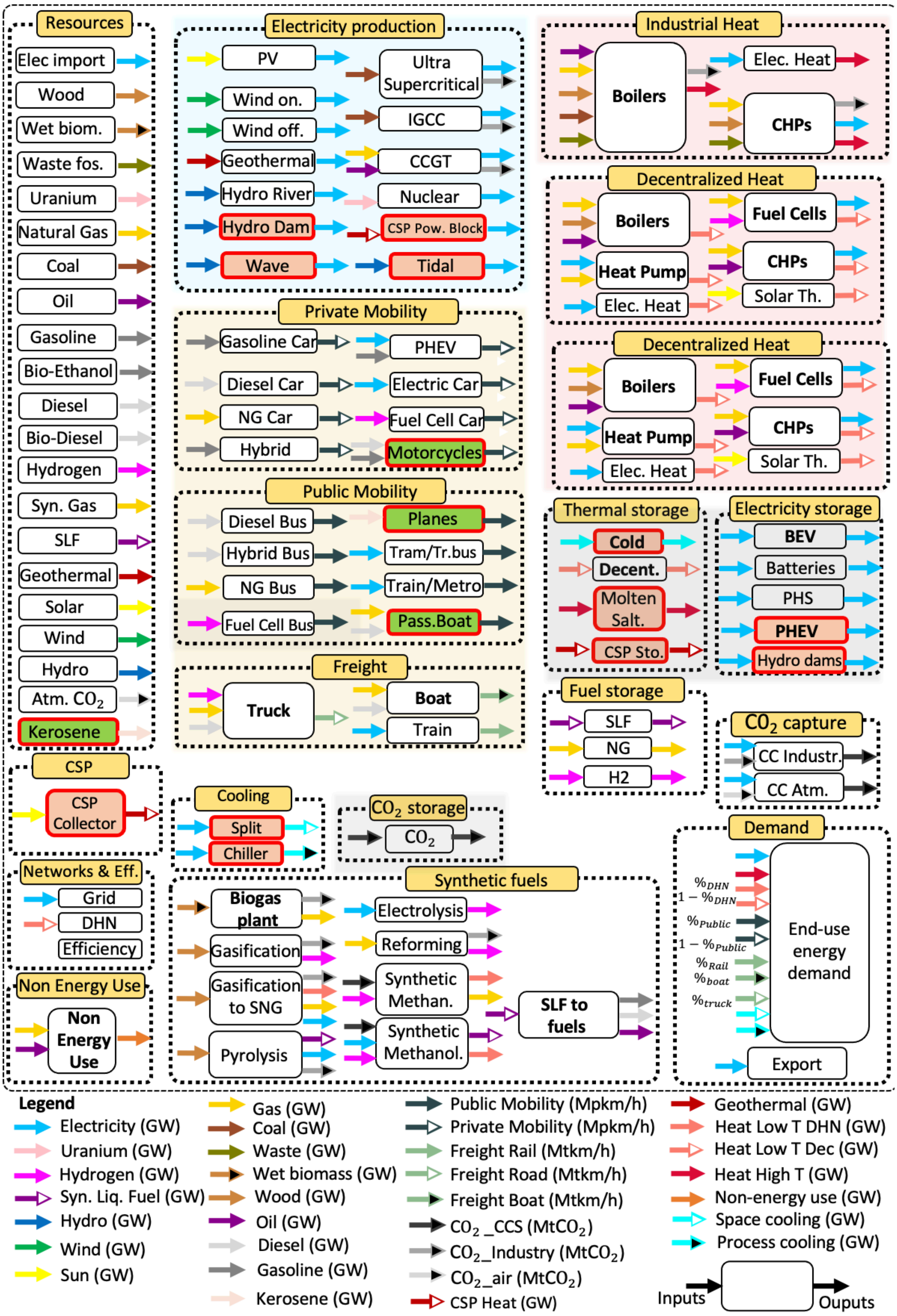

Figure 2.3: Detailed representation of the application of the LP modelling framework to the Spanish energy system. Abbreviations: natural gas (NG), synthetic natural gas (SNG), combined cycle gas turbine (CCGT), integrated gasification combined cycle (IGCC), photovoltaic (PV), plug-in hybrid electric vehicle (PHEV), cogeneration of heat and power (CHP), carbon capture (CC), synthetic liquid fuel (SLF), district heating network (DHN). Adapted from Limpens [75].

The new features that have been added are the following:

- Cold for space cooling and for industrial processes.
- New conventional technologies for mobility (e.g., motorcycles, passenger boats and planes).
- Emerging renewable technologies for electricity production: e.g., offshore wind, tidal and wave technologies, concentrated solar power (CSP).
- A new resource such as kerosene, mainly used as fuel for airplanes for passenger mobility.

In addition, several assumptions have been made for the modelling of the Spanish energy scope version that must be considered to understand the state of the art of the model and its study horizon:

- The geographical area in which the Spanish case study is framed includes both the Iberian Peninsula and the different islands (Balearic and Canary Islands). It also includes Spanish cities in African territory (Ceuta and Melilla).
- Regarding air passenger mobility, both for the validation of the model in Section 2.3 and in the different scenarios studied, only national mobility and between mainland and islands is considered, since it is the one that generates emissions in the country itself. The more detailed justification can be found in Section A.1.3 of the Appendix.
- Non-energy is not considered because it refers to consumption for non-energy uses and not for energy production.

Regarding the model operation, the program mainly considers the different end-use demands, the main technical and economic characteristics of the different energy conversion technologies and the availabilities of the different resources usable by the model. With this input data the model is able to define the optimal strategy for the use of the energy system ensuring to supply the energy demand and minimizing the desired objective function (it is possible to choose between minimizing the total annual cost of the system or the annual GHG emissions) following different constraints imposed to balance the energy balance. As for the available resources, both renewable and fossil fuels are considered, including electricity as a resource that can be both imported and exported. Local resources such as wood, wet biomass and waste have in the model a limited availability due to the reserves of the Spanish country itself. On the other hand, the other resources have been modelled with a sufficiently large availability so as not to reach the limit of use. In terms of formulation and as can be seen in Figure 2.3, the different end-use demands that are supplied are four: heat, electricity, mobility, and cooling. Each of the end-use demands is further divided into different types (EUT). Mobility can be passenger (public and private) or freight (road, rail, and sea). Heating demand is divided into high and low temperature heat, the latter is further distinguished into centralized heat and decentralized heat. Cooling is divided into industrial process cooling and space cooling. Finally, the different conversion technologies are classified into storage, infrastructure, and end-use energy technologies. On the other hand, while end-use energy technologies can convert energy from one layer to supply a demand, storage technologies are only capable of processing and converting energy always in the same layer. For example, in the case of solar thermal technology, electricity is stored to be used in the future (usually in the unlit night hours). Technologies classified as infrastructure include grid electricity, district heating and various technologies that do not directly supply an end-use demand (e.g., collectors in solar thermal plants, which capture solar energy but do not directly produce the electricity supplying the demand).

2.2. Model Formulation

The conceptual structure of the energy system described in Section 2.2 is represented as a linear programming problem. This mathematical problem is formulated by means of several components: parameters (fixed values already known); sets (groups of elements of the system); variables (unknown quantities defined with lower and upper bounds); constraints (equality or inequality equations that allow discriminating the options values of the variables); objective function (quantity to maximise or minimise as a function of the variables).

As for the detailed description of the mathematical formulation of the model, which includes sets, parameters, variables, constraints, etc., it can be found fully documented in [79] and is not expressly described in this thesis as it does not represent an essential point of research in the objective of this work.

2.3. Model Validation

2.3.1. The Spanish energy system in 2015

Figure 2.4 shows the evolution of the total primary energy supplied in Spain from 1990 to 2015 by type of source. As can be seen, after the peak achieved in 2007, Spain's TPES has decreased steadily in the following years, possibly due to certain factors present in current plans and strategies such as increased energy efficiency and an increase in the penetration of renewable energies. In addition, due to the crisis that hit Spain in those years, electricity consumption decreased significantly. The Spanish energy system is highly dependent on fossil fuels, which represented 73.1% of TPES in 2015, broken down into natural gas (20.72%), oil (41.1%) and coal (11.27%) [80].

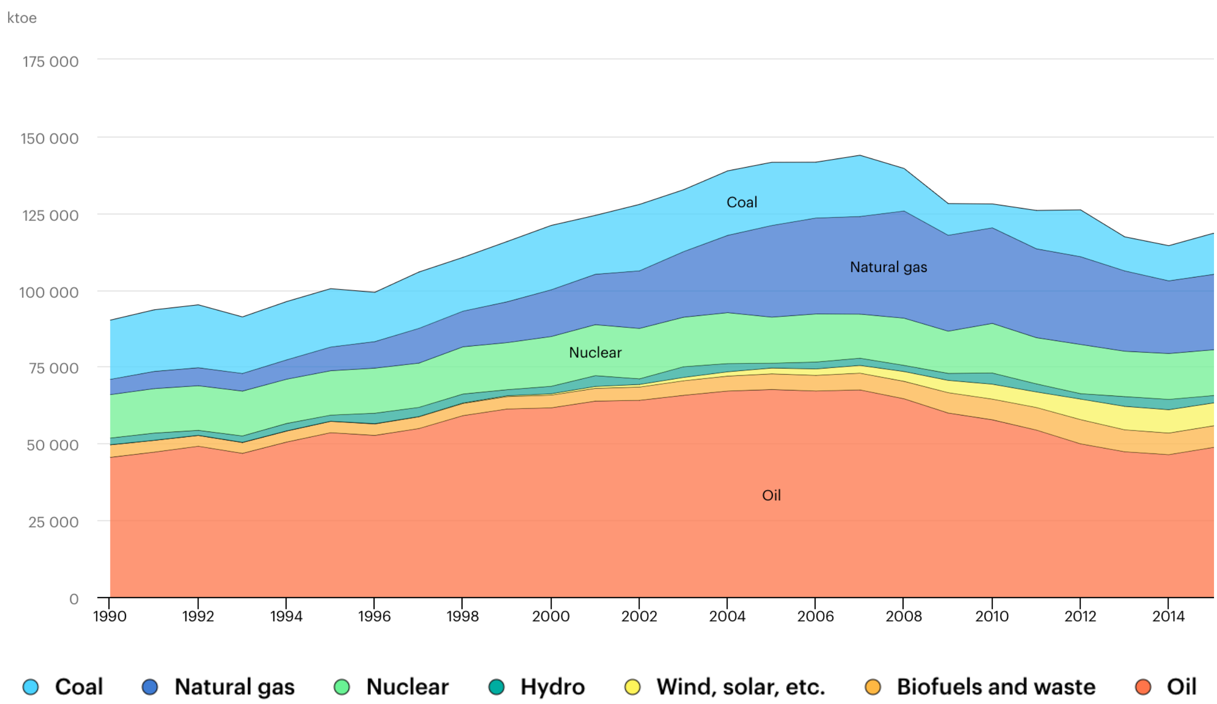

Figure 2.4: Evolution of Total Energy Supply by fuel in Spain (1990 to 2015). Data extracted from IEA. Statistics data browser [80]

Electricity generation in Spain's national system, which includes the mainland and non-mainland systems (Balearic Islands), stood at 267 584 GWh [81]. Figure 2.5 shows the important role played by non-renewable energies in electricity generation in recent years, accounting for 63.1% of the total national energy produced. This important role was reinforced by increases in coal-fired (23.8%) and combined cycle generation (18.7%) [81]. Although the share of fossil resources is still in 2015, it has a decreasing trend over the last decade starting with 83.3% in 2005 [80]. In contrast, the share of renewable energies has been gradually increasing in the energy mix, reaching 14.3% of TPES and 36.9% of the total peninsular energy produced in Spain [81], as can be seen in Figures 2.4 and 2.5 respectively.

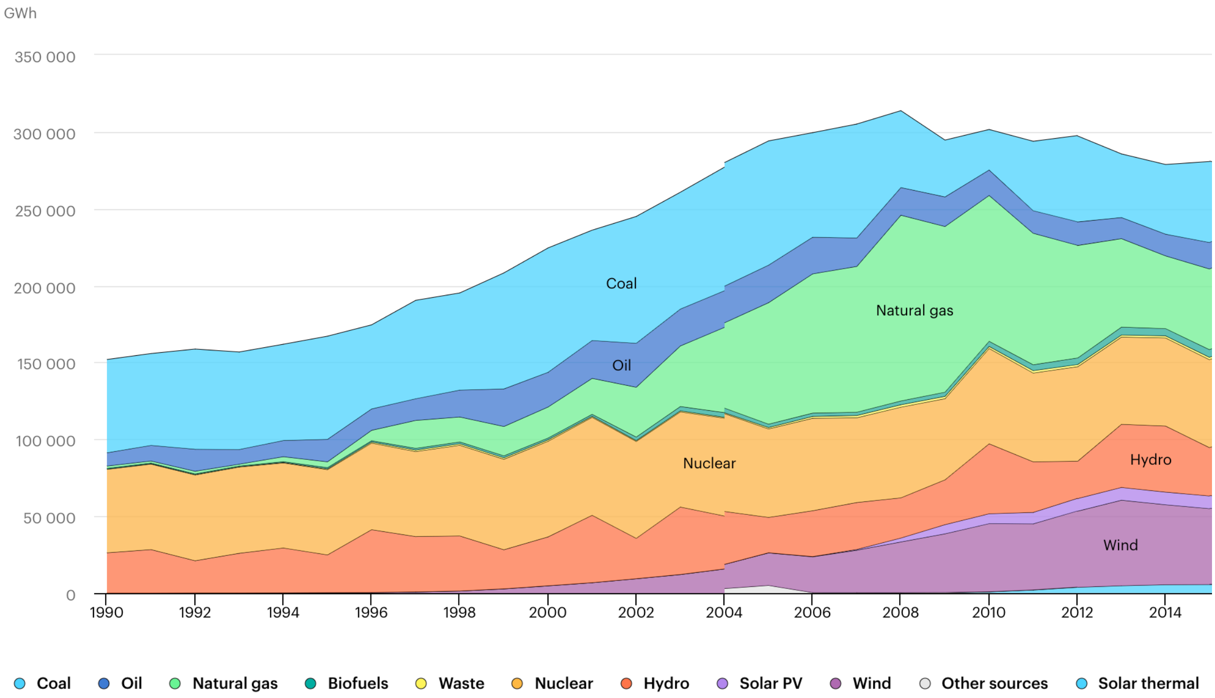

Figure 2.5: Evolution of Electricity Generation by fuel in Spain (1990 to 2015). Data extracted from IEA. Statistics data browser [102]

Table 2.1 shows the power and generation of each of the technologies contributing to the production of the renewable mix in Spain in 2015.

Renewables	Power [GW]	Net Generation [GWh]	Share [%]
Hidroelectric	20.355	30819	31.81
Hidroeolic	0.011	9	0.01
Wind[a]	23.020	48109	49.66
PV	4.664	8236	8.5
Solar Thermal	2.3	5085	5.25
Other Renewables[b]	0.747	4625	4.77

[a] only onshore wind turbines installed
[b] includes biogas, biomass, marine hydro and geothermal.

Table 2.1: Power, Net Production and share of renewable technologies in Spanish energy system in 2015 [81]

In this context, hydro and wind power generate more than 80% of the national renewable energy, followed by solar photovoltaic and solar thermal. It should be noted that the integration of wind power generation has consolidated the Spanish electricity system as one of the world leaders in renewables [82]. Although there is a general increase in the penetration of renewable energies in the energy sector, this penetration is still low in the heating sector (13%) [83].

Focusing on the Heating & Cooling sector, it is currently the largest demand for energy in Spain, comprising 41% of Spain's final energy demand as it can be seen in Figure 2.6. It is a bit lower than in most European countries, where the average is around 50% [83]. Of the total energy demand, approximately one third is used for space heating in the residential sector, in addition to process heating (mostly in industry) accounting for 40% of the total. These shares also follow an atypical line compared to most European countries where space heating generally dominates end use.

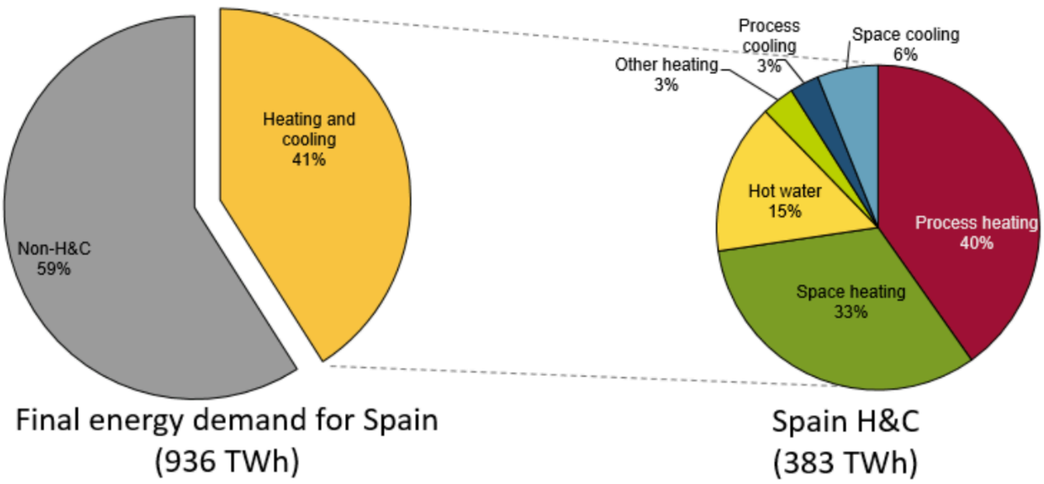

Figure 2.6: Heating and Cooling demand in Spain by end-use compared to total final energy demand in 2015 [83]

Regarding the process and space cooling, both process account in 2015 for less than 10% of heating and cooling demand, and although it is at the high end compared to other European countries, as such it does not represent a very large part of the sector or the energy system. Figure 2.7 shows the total energy demand in the H&C sector for each of the energy carriers.

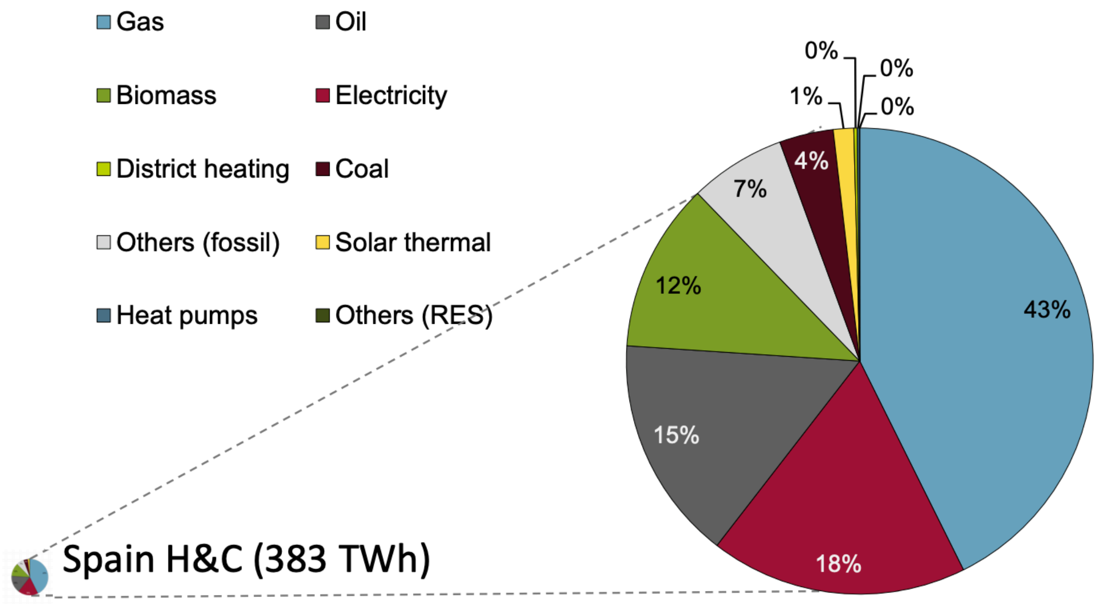

Figure 2.7: Heating & Cooling energy demand by energy carriers in 2015 [83]

It should be noted that in the Spanish energy system there is no extensive heat distribution network (DHN), covering less than 1% of total low temperature heat demand, and therefore the energy system is dominated by decentralised boilers mostly fuelled with NG, woody biomass, and oil. In fact, NG is easily accessible throughout the territory because Spain has a gas transport network with sufficient capacity to meet the needs of supply and delivery to the distribution network in the medium term [84]. Furthermore, the high diffusion of boilers is supported by a lower penetration of cleaner and more efficient technologies such as the low contribution of Heat Pumps (HPs) which cover less than 1% of the total low-temperature heat demand, as well as by a low expansion of DHN as mentioned above [83]. However, this is not due to a lack of investment as it can be the case with heat pumps, but the reasons why these types of systems are not widely spread are mainly climatic. This technology is mostly implemented in Nordic Countries where heating plays an important role in energy markets due to cold climate, and where a lot of effort has been deployed to provide heat production and consumption efficiently and with lower emissions [85]. Therefore, it should also be pointed out that the Spanish heat generation system, marked by low efficiency, is mostly based on fossil fuels (gas, coal, oil), representing more than a 60% of the total heating and cooling demand as can be seen in Figure 2.7, and consequently with considerable carbon emissions.

In terms of public and private mobility, most of the demand is basically satisfied by gasoline and diesel vehicles, while the contribution of electric means of transport is very limited. Electric mobility in Spain continues to advance slowly and inexorably. Spain may not be one of the countries that registers the most electric vehicles given its per capita income and the current lack of support for this type of vehicle. According to DGT (Dirección General de Tráfico), only 0.05% of passenger vehicles in the 2015 annual fleet use alternative fuels such as electricity [86]. The number of battery-electric (BEV) and plug-in hybrid vehicles (PHEV) on the road is still low but steadily increasing due to vehicle manufacturers have launched dedicated models to the market, grid operators are installing public charging infrastructures and governments funded multiple demonstrations and pilot projects creating a new framework condition that incentive people to purchase and use the electric vehicles [87]. Although in the PNIEC 2021-2030 Spain has challenged itself to achieve 5 million electric vehicles by 2030, it seems a very ambitious target, considering that Spain is still at the bottom of Europe in terms of electric mobility, due to the "scarce" development of charging points, with a total of 1 562 points in 2015 and currently with 8 020 points according to EAFO [88].

Figures 2.8 and 2.9 shows a breakdown of the different technologies for public and private passenger mobility. The explanation for obtaining the data represented in these two graphs can be found specified in Appendix A.1.

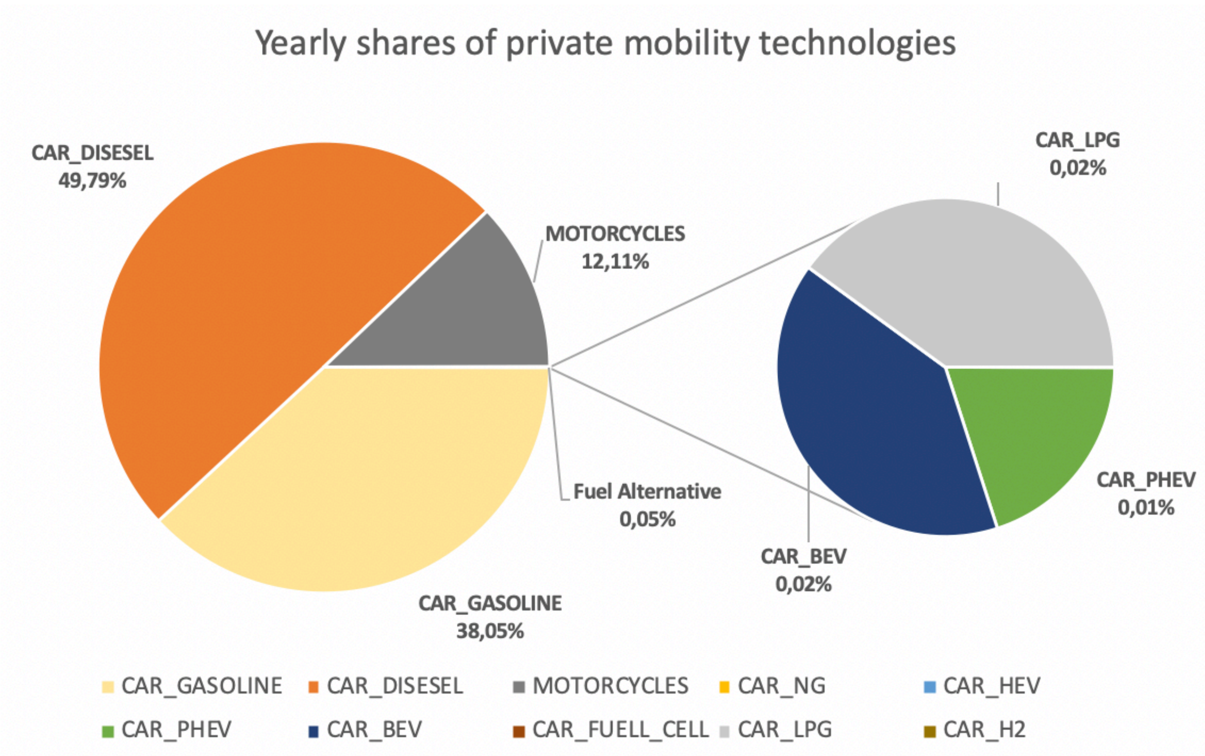

Figure 2.8: Yearly shares of private mobility technologies in Spain 2015

As can be seen in Figure 2.8, more than 80% of the demand for private mobility is supplied by fuels such as gasoline and diesel, while a very small percentage (0.05%) corresponds to the use of alternative fuels as mentioned above.

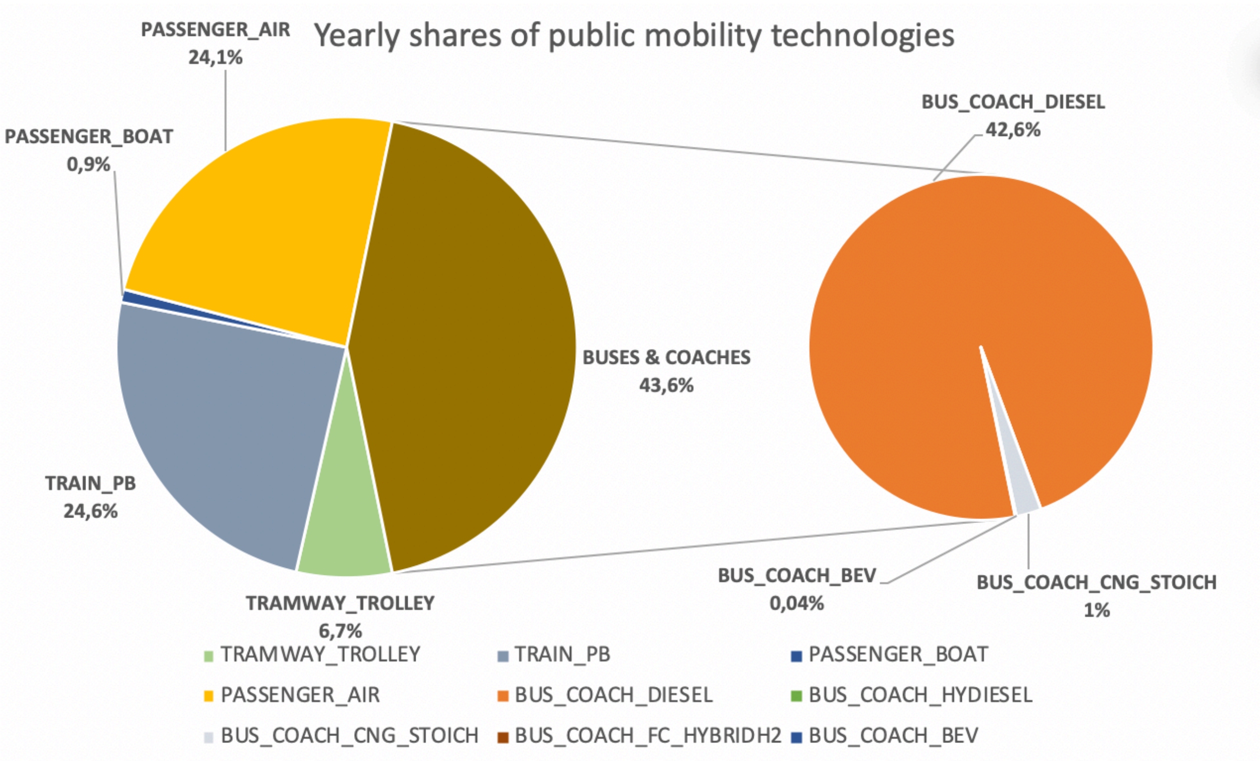

Figure 2.9: Yearly shares of public mobility technologies in Spain 2015.

As far as public mobility is concerned, as can be seen in Figure 2.9, almost all buses and coaches are fuelled with diesel. As for trains, considering that 63.6% of all lines in use in Spain are electrified [89], electric trains represent 15.6% of the total demand, a percentage slightly lower than the European average of 17.4% [90].

Regarding the freight mobility most of the demand is transported by road, largely satisfied by diesel trucks, which are more flexible and easily accessible. The remaining freight mobility is satisfied through trains, pipelines, and ships. As in passenger transport, the poor electrification of the Spanish transport network contributes to low electric penetration. These different shares of freight mobility can be seen in Figure 2.10. The collection of the data and the justification of how they have been obtained and the assumptions that have been considered can be found specifically detailed in Appendix A.1.

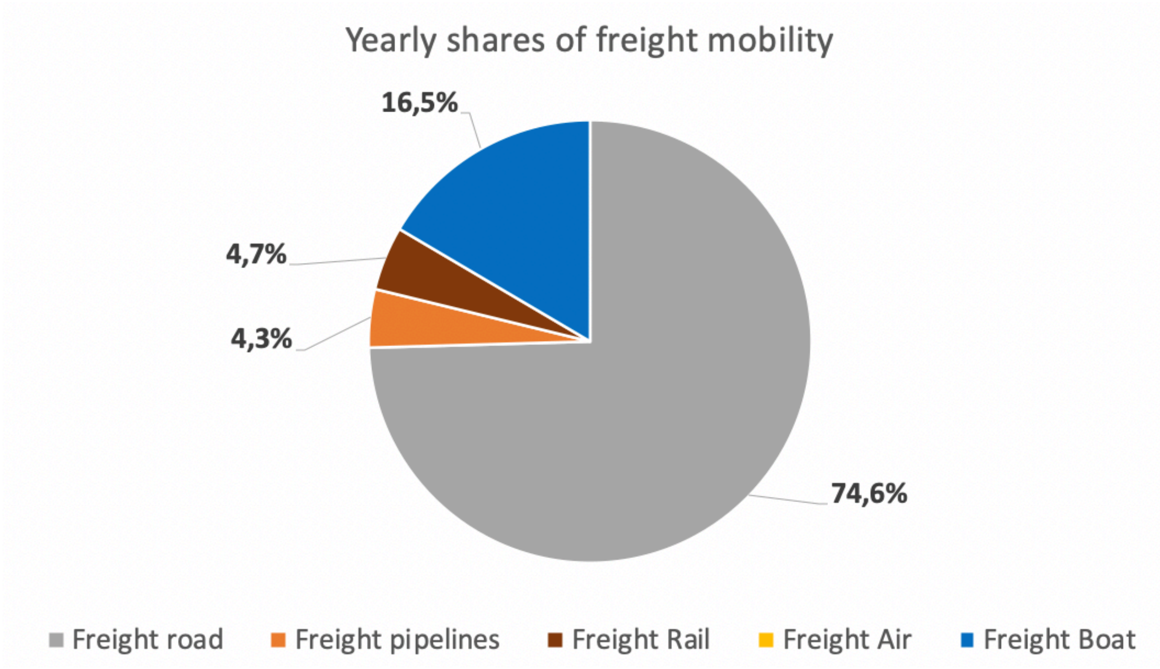

Figure 2.10: Yearly shares of freight mobility in Spain 2015

Overall, a large and effective transformation of the Spanish energy system towards a low-carbon trend is needed to reduce its environmental impact. In the near future and in a context of renewal and transition, the electrification of end-use demand will be fundamental for the diffusion of more efficient and cleaner technologies than today. The penetration of renewable energy sources must increase significantly, while the general decline of the mobility sector and fossil fuel-based heating must be overcome in favor of electric and efficient energy conversion technologies.

2.3.2. Comparison between model output and actual 2015 values

The validation of the *Spain EnergyScope* model has been carried out by adapting the one proposed by Limpens [79]. First, we start from the model and data for Spain in 2035 reported by Jean-Louis Tychon and Jeroen Dommisse in [75]. Based on the data for that year, another version of the model is made with the data necessary for the validation of the model in 2015. To obtain as a result a configuration as close as possible to the real energy system in that year, the following inputs have been introduced for the validation of the model.

- The EUD values estimated from FEC data.
- The renewable electricity production by different technologies (hydro, Solar Th., Wind, PV).
- The non-renewable electricity production by different technologies (CCGT, nuclear, coal).

- The GHG emissions (gwp_{op}) associated only to the direct emissions of CO_2 (fuel combustion) of some resources.
- The efficiencies of several of the technologies that configure the Spanish energy system in 2015.
- The share of public mobility ($\%_{Public}$), of train, road, and boat in freight ($\%_{Rail\ freight}$, $\%_{Road\ freight}$, $\%_{Boat\ freight}$) respectively, and of centralized heat production ($\%_{Dhn}$).
- The relative annual percentage of the different technologies for each type of EUD.

The outputs of the *Spain Energyscope* model for 2015 are compared with the actual values for the same year reported in [91]. To compare the real data of the Spanish energy system and those generated by the model, differences have been analyzed in:

- Primary energy consumption: global and per type of fuel
- National CO_2 emissions

In this case, the validation of the Spanish energy system model is carried out considering Spain as a single region. This decision is taken because the different data obtained for the validation are reported for Spain on a national scale. To achieve the most accurate configuration possible, a one-cell resolution is chosen.

For the validation of the model, the 12TDs generated for Spain in [75] are used using the time series of the different EUDs and of the time for the year 2035. Although these values are slightly different from year to year, it is assumed that these are constant for all years and therefore also for 2015. Regarding the computational time to solve the linear problem, this is approximately 38 seconds using the CPLEX solver on a MacBook with a 2.3 GHz Intel Core i5 processor and 8 GB of memory.

The total energy balance of the configuration in 2015 is graphically illustrated in Figure 2.11 by a Sankey diagram [81, 83, 91]. The corresponding numerical values of the Sankey diagram are presented in Table 2.2.

Appendix A summarizes in Section A.1, for the year 2015, the details of all values used for validation and the corresponding assumptions taken.

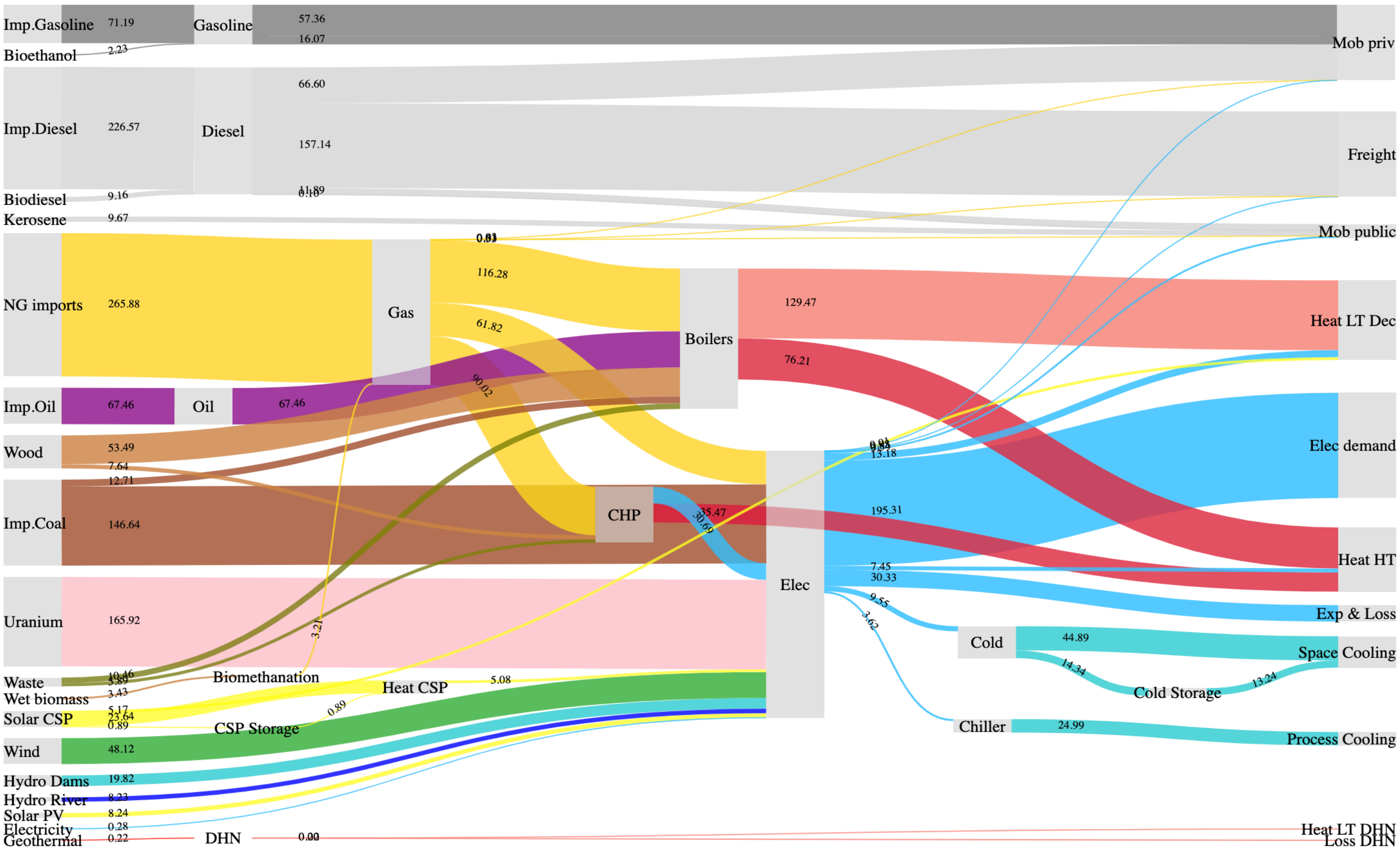

Figure 2.11: Energy flows in Spain in 2015. The left side contains the resources, and the right side contains the final energy consumption. All units are in TWh. Abbreviations: mobility (mob), private (priv), natural gas (NG), cogeneration of heat and power (CHP), concentrated solar panel (CSP), electricity (Elec), district heating network (DHN), low temperature (LT), high temperature (HT).

The overall energy balance is represented by a Sankey Diagram, as can be seen in Figure 2.11. The main conclusions that can be drawn directly from the diagram are that the Spanish energy system is based on fossil fuels, accounting for only a little more than 16% of primary energy consumed by renewable sources.[13]

Furthermore, it is observed that there is a very low electrification of transport (1.4%) and heat (7.7%) and that some of the different technologies that are increasingly expanding their use have a negligible relevance such as heat pumps (≈0%) and district heating (<1%), according to heat roadmap Spain [54]. In reference to electricity generation from renewable sources, this represents 36.4% of the total, a value very close to the 36.9% reported by the Spanish TSO in [81]. Finally, the amount of electricity imports is approximately 0. Therefore, it can be concluded that the Spanish energy system in 2015 was not an importer of electricity.

[13] Acording to IEA Energy balance database documentation [92], we include as renewable sources: geothermal, wind, hydro, solar PV, solar CSP, wave, biofuels, wood and biogas

Table 2.2: Model validation: outputs vs real 2015 data for Spanish energy system. Real values are extracted from [91] otherwise stated. Abbreviations: electricity imports (Elec.imp.), solar thermal (Solar Th), total renewables (Total RE.).

		2015	ESTD	Δ	Δrel	Units
Primary energy consumption	Gasoline		71.19			TWh
	Diesel		226.57			TWh
	Kerosene	65.56	9.67	-55.89		TWh
	Oil for Mobility	324.97	307.43	-17.54	-5.40%	TWh
	Oil	70.17	67.46	-2.71	-3.86%	TWh
	Total Oil	**395.14**	**374.89**	**-20.25**	**-5.12%**	TWh
	Total Gas	**251.05**	**260.42**	**9.37**	**3.73%**	TWh
	Total Coal	**153.94**	**159.35**	**5.41**	**3.51%**	TWh
	Uranium	**171.91**	**165.92**	**-5.99**	**-3.48%**	TWh
	Elec.imp.	**-0.12**	**0.28**	**0.4**	-	TWh
	Solar PV	8.269	8.24	-0.03	-0.35%	TWh
	Solar Th	28.77	29.71	0.94	3.27%	TWh
	Wind	49.32	48.12	-1.20	-2.44%	TWh
	Hydro	28.14	28.05	-0.09	-0.32%	TWh
	Geothermal	0.22[a]	0.22	0	0.41%	TWh
	Wood	61.17	61.13	-0.04	-0.07%	TWh
	Biogas	3.05	3.21	0.16	5.35%	TWh
	Biofuels	11.40	11.39	-0.01	-0.09%	TWh
	Total RE	**190.34**	**190.07**	**-0.27**	**-0.14%**	TWh
	RE.	2.93				TWh
	non RE.	2.93				TWh
	Total Waste	**5.86**	**19.04**	13.18		TWh
	Total Energy	**1168.12**	**1169.97**	**1.85**	**0.16%**	TWh
GHG emissions		**250.51**	**243.77**	**-6.74**	**-2.69%**	[Mt CO_2-eq]

[a] From "Cuadro 8.2" in [93]

In terms of energy consumed, the model provides a reasonably good approximation of the Spanish energy system in 2015, as described in Section 2.3.1. Some differences can be appreciated between some of the compared resources, which are due to certain assumptions or approximations.

Firstly, the total amount of kerosene is underestimated since the Spanish Energyscope model, unlike the energy balance reported by Eurostat, does not consider the international air demand[14] since it does not emit in the Spanish national territory, as explained in Section A.1.1.3 of appendix A. Therefore, only air passenger demand within the Spanish territory is considered, on a national scale (inland + Balearic and Canary Islands). Consequently, the value of kerosene consumption in the model is much lower than the real value of consumption (this represents 15% of the total). This percentage is meaningful considering that the proportion of the number of passengers transported by aviation within the national territory in 2015 represents 17% with respect to the total number of passengers transported nationally plus internationally [94].

The use of both uranium and oil is a bit underestimated, probably due to a slightly higher efficiency than the real one. Coal use is slightly overestimated due to slightly lower efficiency than the real in 2015. Regarding natural gas and waste, their total values are overestimated compared to actual values. This is due to:

- Waste: In the heat roadmap Spain [54] the value of energy supplied for the industrial sector by the energy carrier "other(fossil)[15] (14% out of the total) is assumed as fully waste.
- Waste: In the data reported by Eurostat on fuel used in the different CHP plants in Spain [95], used to know the different relative shares of the cogeneration technologies, the vector "other (fuels)[16] is assumed totally as waste.
- Gas & Waste: In the data reported by Eurostat on fuel used in the different CHP plants in Spain [95], only the fuels NG and Waste have been considered because biomass only represents 2.2 % and oil is not implemented as a cogeneration technology in the model. Therefore, this percentage belonging to oil and biomass has been distributed proportionally to its use in NG and waste. Consequently, the total value of gas and waste consumed is slightly higher than expected because of an overestimation of their consumptions.

Regarding the environmental impact of the Spanish energy system configuration, the total energy related[17] GHG emissions from fuel combustion in 2015 were 250.511 Mt$CO_2 - eq$ (OECD [97] and EC [98]). This value reported by the two sources mentioned above only

[14] Includes the international demand in the U.E Schengen and outside the UE

[15] Heat roadmap in the Profile of Heating and Cooling demand in 2015 [96], define others (fossil) as: mainly fuels used in industry including waste, stack gas, etc.

[16] Eurostat in the CHP data 2005-20018 [95], in the category other (fuels) includes among others industrial wastes and coal gases

[17] Excluding the agriculture, international aviation, Land use, land-use change and forestry (LULUCF)

considers the direct emissions from the combustion of the different fuels. This value does not include fugitive emissions[18] from fuels, because the configuration of the industrial energy demand in the model does not include these eventual emissions due to possible leaks in industrial processes.

On the other hand, the gwp_{op} values of the different resources used in the model include the indirect[19] emissions in addition to the ones related with the combustion of the fuel. For this reason, to perform an accurate environmental comparison, only the direct emissions of each one of the resources have been used in the model. Therefore, for those resources that have associated direct emissions, the gwp_{direct} values, extracted from [99], are used and for those that do not, value of gwp_{op} is assumed as 0.

The model results in direct emissions of 243.77 Mt$CO_2 - eq$ This lower environmental impact is a consequence of the slight differences in some of the resource consumptions. Mainly because oil consumption (slightly lower than actual) is linked to a lower gwp_{op} than emissions related to gas consumption (consumption slightly higher than actual). Therefore, the modeled emissions are lower than the real ones.

Finally, the proposed model aims to provide a representation of the country's energy balance. The results obtained in the validation confirm that the model can support the orders of magnitude of the capacities installed by the different technologies. Although the modeling resolution is of one cell, considering the country as a single region, the validation of this model demonstrates the consistency of the results provided and corroborates its reliability as an energy planning model.

[18] The IPCC defines fugitive emissions as "emissions that are not produced intentionally by a stack or vent and include leaks from industrial plants and pipelines". In the fossil fuel sector, fugitive emissions are sometimes broadly defined as any emissions unrelated to the end use of the fuel [100]

[19] Indirect emissions are related with the extraction, production, and transportation of these resources

Chapter 3

3. Decarbonization Pathways

Energy modelling helps policy makers, scientists, and politicians to find the best set of possible pathways towards low-carbon national energy system configurations. In this context, it has already been demonstrated in Chapter 2 that the proposed *Spanish Energyscope* energy model is suitable to be a reference in the search for different future scenarios in the Spanish case.

Starting from the Spanish energy system described in Section 2.3.1, this Chapter 3 defines the future Spanish energy transition, highlighting the sectors on which efforts should be focused to achieve the objective. Then, an explanation is provided of the different data needed and the methodology followed for the optimal development of the different scenarios to be modeled. Finally, an analysis is carried out with the aim of defining the different decarbonization pathways with a 2030 horizon and beyond. These different pathways are classified into reference scenarios and policy scenarios. Throughout the chapter, each of the scenarios is explained in detail, specifying all the assumptions and considerations considered in each of them.

3.1. Case study: the Spanish energy system in 2030

As described in Section 1.1.3, both the European Union and the Spanish state itself have defined ambitious new measures with the aim of implementing policies that help Spanish society to achieve a decarbonized energy system. The key points of these policies, defined in the "Proyecto de Ley de Cambio Climático y Transición Energética" [24] and in the "Plan Nacional Integrado de Energía y Clima" [21], are based on the following points: (i) decarbonization of the energy system, especially the electricity generation sector; (ii) improvement of energy efficiency; (iii) increased penetration of renewables in energy end-use; (iv) increased electrification of the transport and mobility sectors. It is within this framework that, as in the case of national and European directives, the year 2030 has been considered as a reference to compare and check the consistency of the results proposed through the different energy scenarios proposed to be modelled.

With the main objective of achieving the different targets proposed by the EU and by Spain itself, and to guarantee a gradual shift towards a significant electrification of the energy sector, Spain has already defined several actions to partially decarbonize the energy system. To begin with, a global phase-out of existing coal-fired power plants in the electricity sector is scheduled for 2030 [21,101]. As can be seen in Figure 2.5, coal-fired plants represent 19% of the total electricity produced [102], accounting for a significant share of generation. On the other hand, existing coal-fired plants throughout the peninsula are also scheduled for partial closure. In particular, 4 of the 7 nuclear reactors are scheduled to close by 2030 [103]. Therefore, the various planned phase-outs must be achieved with a parallel effort to find alternative solutions for electricity generation that are able to compensate for the electricity lost by the phase-out itself. In this context, the electricity system in the coming years will certainly be characterized by a strong increase in RES penetration in power generation. This increase will occur both in technologies already established in the country (e.g., PV, Concentrated Solar Power (CSP), wind onshore, hydro etc.) and in newer technologies that are in their pilot or expansion phase (e.g., wave energy, tidal, geothermal etc.). In addition, this technological transition will also be enhanced by a gradual reduction in the investment and maintenance costs of these renewable technologies. This reduction will help not only to reduce the environmental impact but also to make these technologies more suitable for use. At the same time, the increased availability of renewable resources is also leading to increased electrification of the mobility and heat sectors, through the widespread use of efficient technologies such as electric vehicles and heat pumps respectively.

The energy transition of the Spanish energy system by 2030 will be influenced by the following factors:

- national availability and price of fossil resources.
- the modernization of the electricity grid in terms of security and guarantee of supply, to adapt to the increased penetration of intermittent RES technologies.
- modernization of existing energy conversion technologies to achieve more electrified and efficient sectors.
- final demand from the different end-use sectors

Therefore, the future development of the Spanish energy system towards a low-carbon system is numerous, difficult, and highly dependent on strong economic and technological investments. In this framework, the *Spanish Energyscope* energy model described in Section 2.2 can be used as a support tool for the identification of the most interesting and optimal possible paths and strategies to follow in economic and environmental terms. Therefore, this model will be applied to the Spanish energy system over a 15-year horizon, starting from the validation of the model in the reference year 2015 explained in Section 2.3 and ending in 2030.

However, identifying all these alternative strategies accurately and with high reliability requires further investigation of the Spanish energy system in terms of resource availability, efficiency of the different conversion technologies, energy demand and production capacities of renewable technologies.

3.2. Scenarios definition

The Spanish energy system faces a major challenge towards a deep decarbonization that can overcome the different barriers and uncertainties as to whether Spain can achieve carbon neutrality. To solve this challenge, multiple scenarios of the Spanish energy system can be useful to identify the most robust and effective options in aiming to reach a low or carbon neutral system by 2030. For this purpose, the LP formulation described in Chapter 2 has been applied to perform the different decarbonization scenarios of the *Spain EnergyScope* model. The different scenarios have been carried out with a time horizon up to 2030 and considering Spain as a single region (considering the Spanish mainland and the Balearic and Canary Islands). For the realization of the different scenarios, the different critical parameters in the model, such as the prices of the different fuels and resources, the end-use demands, and the technical situation of the different conversion technologies, are considered to be those corresponding to the last horizon year (in this case 2030). The modeling of a scenario requires that the input data agree with the technical and economic projections in the target year. Therefore, since the snapshot version of the EnergyScope TD [74] model has been used, the evolution of the energy system in the time horizon prior to the year under investigation is not considered.

In this case, we have started from the work done by Jeroen Dommisse and Jean-Louis in [75], where they collected data for Spain in 2035. Some data independent of the scenario under investigation have been modified to obtain the most consistent and realistic scenarios possible, such as:

- Investment and maintenance prices of some technologies (CSP technologies, H_2 electrolysis, biomethanation etc.).
- The end-use demand for passenger and freight mobility has been adopted for the year 2030 according to [98] since the data previously defined corresponds to 2035. For details of the data collected, please refer to Section A.2.1 of Appendix A.

Figure 3.1 shows a schematic representation of the methodology adopted for the modelling of the different decarbonization scenarios. Based on the modelling of the *Spanish Energyscope* explained in Chapter 2, a set of specific constraints for each scenario are added for the definition and configuration of the different scenarios. Some of these constraints consist of setting the production/capacity/share of some technologies or resources of the Spanish energy system, such as for example: relative percentages of passenger and freight mobility, penetration of certain technologies (nuclear, PV, etc.), penetration of certain technologies (DHN, HP's) etc. It is also possible to activate or deactivate the use of certain technologies to simulate a phase-out of a certain technology. Depending on the use of the technologies, availability of resources and uses, the specific primary consumptions of each of the resources vary and consequently the total cost and emissions of the system.

Then, for each of the scenarios under study, the optimal model solution is defined to minimize either the emissions (in terms of gwp_{tot}) or the total system cost (in terms of C_{tot}). In the case of minimizing emissions, the model directly discards the less efficient solutions or configurations and therefore the optimization of the energy system is maximized and opts for the cleanest and more efficient technologies.

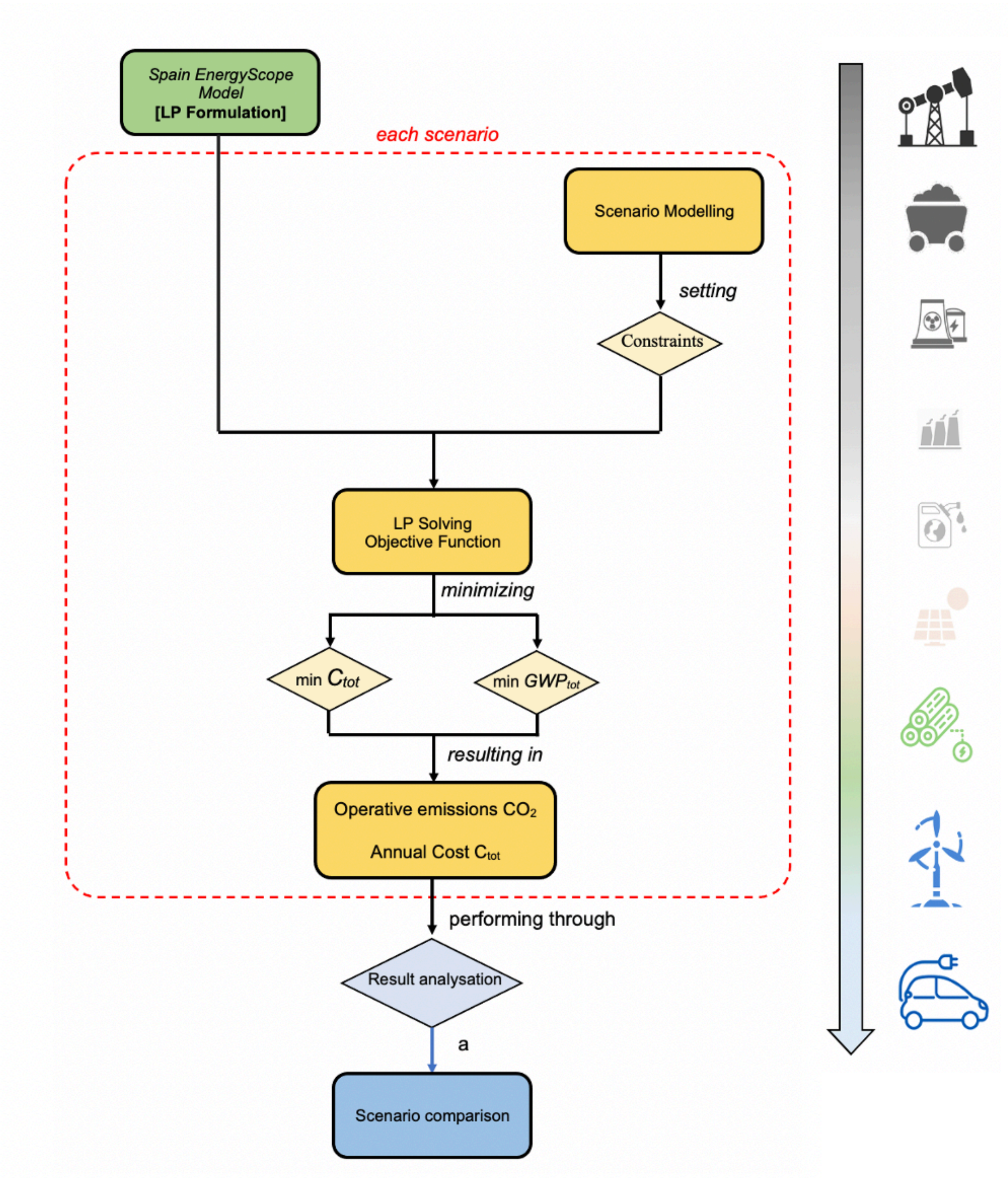

Figure 3.1 Methodology for the realization and evaluation of the different decarbonization scenarios.

In a very similar way to the model validation described in Section 2.3, the different data inputs for the different scenarios have been defined. For each scenario, the following inputs are introduced for the year 2030:

- EUD values extracted from the work done by Jeroen Dommisse and Jean-Louis in [75]. See Section A.2.1 in Appendix A.
- The national availability of the different resources.
- The maximum installable capacity of renewable-based technologies at the national scale.
- The different shares of passenger and freight mobility in addition to the share of centralized heat production.
- The fuel efficiencies of the different energy conversion technologies. We start from the efficiencies reported for Spain in 2035 in [75] considering that they are equal in 2030.

In reference to the previous points, some characteristic constraints are also added for each scenario to differentiate it from the others (e.g., if we want to simulate a phase-out of the nuclear plants, the uranium availability is limited to 0; if we want to simulate an increase in efficiency with respect to another scenario for a specific technology, this efficiency is modified by its new value). The results of the scenario modelling are analysed to see if they are in line with the different targets set by the different national and European energy organisations [24, 21,09,12] explained in Section 1.1.2 and 1.1.3. The main targets set by the different agencies at national and European level are focused on: (i) reduction of GHG emissions compared to 1990 levels, (ii) improvement in energy efficiency, (iii) penetration of renewables in final energy consumption.

Table 3.1 below shows a list of the different scenarios proposed for the analysis of the different decarbonisation pathways of the Spanish energy system in the defined time horizon. Three reference scenarios are defined, which are those that represent the evolution of the energy system in accordance with current policies and trends or those defined by already validated plans and studies. On the other hand, a police scenario is defined, which allows the system itself to choose the most optimized version of the model, seeking the optimal cost to subsequently carry out a study of the evolution of the system as the system's emissions are limited.

Type	Name	Description
Reference	*ESP30_S1*	Business as Usual (BaU) scenario, no development
Reference	*ESP30_TEND*	Scenario coherent with PNIEC "Tendential" [21]
Reference	*ESP30_OBJ*	Scenario coherent with PNIEC "Objective"[21]
Policy	*ESP30_P1*	Cost-optimum scenario of the Spanish energy system

Table 3.1: List of the different scenarios developed with the Spanish Energyscope model for the target year 2030.

The main points to be evaluated in the analysis of these scenarios are:

- The reduction of operational CO_2 emissions to be able to compare it with the different national and European reduction targets.

- The identification of the most efficient and cleanest technologies and infrastructures in which to invest to achieve a more decarbonised system.

- The economic and environmental quantification of the different policies applied in each scenario in terms of costs, penetration of fossil fuels, energy dependence, energy consumed, etc.

3.2.1. Reference Scenarios

The *Spanish Energyscope* model is used to define and simulate three different reference scenarios. These scenarios represent those pathways that describe the evolution of the energy system considering the different targets, trends or development policies defined by the different national, European, or global organizations. In this case, Table 3.2 summarizes the main characteristics of the three scenarios evaluated by the model for the year 2030 and according to the targets and forecasts taken from the "National Energy and Climate Plan 2021-2030" [21] and the "Climate and Energy Framework 2030" of the European Commission [09].

Sector	Technology	Scenario		
		ESP30_S1	*ESP30_TEND*	*ESP30_OBJ*
Power	Coal Phase-out	✗	Partial[a]	Total[b]
	Nuclear Phase-out	✗	✗	Partial
	Typical RES[c] maturity	✗	PNIEC[d]	PNIEC[d]
	Offshore wind	✗	✗	✗
	CSP	✓	✓	✓
	Wave	✓	✓	✓
	Geothermal	✗	✗	✗
Mobility	% Fr.rail	0.049	0.1	0.1
	% Fr.boat	0.173	Same as 2015	Same as 2015
	% Public	0.251	0.4	0.5
	Share of electric cars[e]	0.01	0.05	0.1
Heating	DHN development	✗	5% increase[f]	5% increase[f]
	HP's penetration[g]	✗	30%	40%

[a] a partial phase-out is planned by 2030 in the power sector in 2030, as described in scenario "Tendential" in PNIEC proposed in [21, 78].

[b] total phase-out of coal for power generation by 2030, as described in scenario "Objective" in PNIEC proposed in [21].

[c] development of PV, onshore wind, hydropower, biomass electricity production technologies.

[d] according to the different scenario forecasts proposed by [21].

[e] it refers to the sum of battery electric cars (BEV) and hybrid electric cars (HEV).

[f] with respect to 2015 centralized heat production.

[g] maximum share of heat pumps in decentralized heat production

Table 3.2: Reference scenarios assumptions in the Spanish Energyscope model to the Spanish energy system in 2030. Abbreviations: Concentrated Solar Power (CSP), Plan Nacional de Energía y Clima 2021-2030 (PNIEC), Renewable energy systems (RES), freight (Fr.), Heat pump (HP), District Heating Network (DHN). Legend: technology available ✓; technology not available **X**.

The Business-as-Usual scenario, hereafter ESP30_S1, describes a configuration in which a strategy is followed to leave the same energy structure as in 2015 and therefore not to develop or implement the use of any new technology. Therefore, the percentage of use of electricity generation technologies (i.e., PV, wind onshore, hydro dam, etc.) as well as the percentage of annual production of the different technologies for each EUD is considered to remain at the same values in 2030 as in 2015. As stated in the current national plans in [21] in the following years the Spanish energy system will be transformed towards greater energy self-sufficiency based on efficiently exploiting the country's renewable potential, particularly solar and wind. Moreover, this transformation will have a decisive impact on national energy security by significantly reducing the dependence on fossil fuels that consequently affects the high economic bill. Therefore, this scenario, which maintains the same structure as in 2015, does not seem the most realistic and optimistic possible. However, although the structure remains the same, some modifications are made to obtain a scenario that is as realistic as possible. As mentioned above, new EUD values have been taken for 2030 since the forecasts show an increase in population, an increase in the number of households and changes in consumption habits [21].

In addition, as suggested by the different national and European energy plans, a substantial increase in the energy efficiency of the different conversion technologies is needed. Therefore, it is interesting to quantify this increase in energy efficiency compared to 2015. An example of this is the energy efficiency of a coal-fired plant which, according to Richard Martin in [104], can achieve an efficiency of 49% by 2030 compared to the efficiency of 36% in 2015. Similarly, the efficiency of a nuclear plant can reach 37% by 2030, according to [75], as opposed to 33% for nuclear plants in 2015. In this case, this first scenario has therefore been divided into two sub-scenarios. The difference between the two is that although in both cases the same structure of the energy system is maintained, the first does not consider this increase in the energy efficiency of the different technologies, while the second does. Table 3.3 below shows a comparison of the two versions of the scenario to observe the environmental and economic impact of the aforementioned increase in energy efficiency.

Scenario	Environmental Impact			Total Cost
	Operating emissions[a]	Variation vs 2015[b]	Variation vs BaU	
	[Mt CO_2/y]	[%]		[B€/y]
Validation 2015	243.77			150.15
BaU_ESP1[c]	251.14	3.1		182.66
BaU_ESP2[d]	231.56	- 5	- 7.8	175,62

[a] only accounted the direct emissions from the total operating ones.
[b] values directly used from the model validation in 2015
[c] values from the different energy conversion technologies in 2015 are used. See Appendix A.1.6. **Also called ESP30_S1A**
[d] values from the different energy conversion technologies in 2030 are used. Values directly extracted from the work done by Jeroen and Jean-Louis in [75]. **Also called ESP30_S1**

Table 3.3: Comparison of the two sub-scenarios of the Business-as-Usual case considering or not an increase in the energy efficiency of certain conversion technologies in 2030.

Analyzing the results, it can be seen firstly that keeping the same structure in 2030 increases both emissions and total system cost. It makes sense due to the increase in final energy demand and a constant maintenance of both energy production and efficiency. On the other hand, it can be observed that the increase in efficiency of the technologies in Spain in 2030 leads to a significant decrease in operational CO_2 emissions of 7.8% compared to the version where no technical improvements are applied in the different technologies. This analysis reveals the potential for operational emission reductions only by acting on the efficiency of certain conversion technologies. These improvements in energy efficiency are in line with the development of the MCI[20], which is responsible for developing R&D policy in the energy sector and coordinating all the stakeholders involved in the energy sector [21].

The *ESP30_TEND* and *ESP30_OBJ* scenarios have been carried out using the Spanish Energyscope model in the framework of Spain's "*National Energy and Climate Plan 2021-2030*". This plan suggests different forecasts and policies for the development of the entire energy system based on two different situations.

The *ESP30_TEND* scenario is defined based on the first scenario of the PNIEC, which represents an energy system where no additional policies and measures are implemented in addition to those already defined today. A constant development trend is considered for some RES technologies and a more conservative scenario is adopted. In this case the Spanish energy system is still heavily dependent on the different fossil fuels representing an important part of all primary energy consumed. The different assumptions taken for this decarbonization scenario are summarized in Table 3.4. The penetration of renewables in the Spanish electricity system is defined by the different forecasts of installed capacity in this tendential scenario [21]: The largest growth in installed capacity corresponds to PV (289% higher than in 2015), followed by wind onshore (66% higher vs 2015). The installed capacities of CSP, hydro and marine remain constant without any development. Nuclear technology is assumed constant without any phase-out in this scenario. Unlike nuclear, coal is assumed to have an 80% reduction in installed capacity for electricity generation due to the Spanish government's target to close coal plants that have not invested in the short term by the end of 2025 because of European regulations [105]. Innovative offshore wind technology has not been included in the model because the PNIEC plan does not mention specific targets for this technology, although it does refer to the high potential of this technology in Spain. As for biomethanation technology for biogas production, biogas production has been set as a target in the "*Ruta por el biogás*" plan defined by the Ministry of Ecological Transition and the Demographic Challenge of the

[20] Department of the General State Administration in charge of executing the policy on scientific research, technological development and innovation in all sectors.

Spanish government. This plan sets a target of 3.8 times more biogas production in 2030 than that estimated in 2020 [106].

As for the heating sector, a share of the district heating network (DHN) of 0.5% of the total demand for heating and cooling is assumed, as specified in [107]. This value is one of the lowest in comparison to all European countries, mainly due to the high temperatures in the country and the fact that the development of these systems is more developed in countries with a colder climate. As for the development of heat pumps in the decentralized heat sector, a maximum share of 30 % of the total decentralized heat demand has been assumed. This value is slightly lower than European forecasts which suggest that 40% of all residential and service buildings will be heated by electricity [108]. This slight difference is due to the tendency of this scenario to be more conservative and not to make such ambitious assumptions.

As for the mobility sector, the composition of private cars based on fossil fuels has been set according to the forecasts made by Cepsa in its Energy Outlook 2030 in [109]. On the other hand, the share of motorbikes in 2030 has been defined considering the forecasts of the "Strategy for the decarbonization of Land Transport in Spain" in [110]. As for the share of electric vehicles[21] in the total private road passenger demand, a 5% has been considered as defined by the "*Instituto de Investigación Tecnológica IIT_ICAI*" in [111]. The share is lower than the one defined by IIT-ICAI because this scenario tends to be more conservative and that is why a lower percentage has been defined. Finally, as for hydrogen cars, the forecast for 2030 is only about 8000 passenger cars [112] and therefore this technology has been excluded from the model. Finally, in terms of freight mobility, it has been established that 10% of the total freight demand is by rail, as set out in the target for Spain in [113]. This share is higher compared to the 5% established in the validation of the model in 2015. The modal shift is assumed to be from road to rail and therefore the boat share is considered to be the same as in 2015.

[21] Including battery electric cars (BEV) and hybrid electric cars (HEV).

Assumptions		
	Subject	**Description**
Power	Coal	Partial phase-out in the power sector: 80 % reduction of the installed capacity in the power sector vs 2015 [21]. Remain in the industrial sector: same consumption [21].
	Nuclear	No phase-out: Constant installed capacity vs 2015.
	Renewables	PV installed capacity :Increase of 289% of PV capacity in 2030 vs 2015 (19GW) [21]. Wind onshore installed capacity: Increase of 66% of wind on capacity in 2030 vs 2015 (38 GW) [21]. Wind offshore installed capacity: Not available → Not specific objectives for offshore technology in Spain [21]. CSP installed capacity : Same installed capacity of CSP in 2030 (2,3 GW of 2015) [21]. Wave: → Available Biogas: Bio-methanation conversion available [106]. Hydro: Not increasing forecasts [21].
Mobility	Passenger	Public: share of public passenger mobility ($\%_{Pass.}$) equal to 40 % Private: car fleet in 2030 according to different sources [130,131]
	Freight	Share of train freight mobility ($\%_{Fr.\ Rail}$) equal to 10% [113]. Share of boat freight mobility ($\%_{Fr.\ Boat}$) equal to 17,3%
Heating	DHN	DHN development: Centralised heat production: 0,5 % [107].
	HP's	HPs penetration: 30% upper bound of decentralised heat production [108].

Table 3.4: Summary of the main assumptions made for the definition of the ESP30_TEND scenario. All assumptions are based on reasonable bases, unless explicitly stated otherwise.

On the other hand, the ESP30_OBJ scenario is aligned with the policies and objectives set out in the PNIEC [21], which establishes the framework on which the Spanish energy system should focus in order to achieve the decarbonisation objective and to establish a solid basis for achieving climate neutrality in the economy and society by 2050. In this case the different assumptions taken for the modelling of this scenario can be seen listed in Table 3.5.

This scenario is mainly characterized by a strong decarbonization of the power generation, transport, and heat sectors. In the context of the power sector and with reference to the policies defined in the PNIEC for this scenario, a large increase in both established and innovative RES technologies is assumed [21].

The installed capacity of PV is set to eight times higher than the installed capacity in 2015, reaching approximately 39 GW in 2030. The wind onshore capacity is set to more than double the installed capacity in 2015, reaching approximately 50 GW in 2030. Innovative offshore wind technology has not been included again in the model because the PNIEC plan does not mention specific targets for this technology. In this case, nuclear energy suffers a partial phase-out since the Spanish government has established a plan for the orderly and staggered closure of the nuclear fleet over the decade between 2025 and 2035. However, in the period 2021-2030, the installed capacity of nuclear power plants is expected to fall by more than 4 GW (corresponding to four reactors out of the seven currently in operation) [103]. Regarding coal, it is foreseen that power generation from coal-fired plants that continue to operate beyond 2020 (a maximum of five or six of the 15 currently in operation) will be phased out by 2030 at the latest [103]. However, some coal consumption is maintained for the heating sector. CSP technologies undergo a significant increase in installed capacity. In the framework of this scenario and as indicated by Spain's National Energy and Climate Programme (PNIEC), the development and construction of CSP projects that have been silent for more than 5 years will restart, with up to 5GW of new CSP installed capacity to be added to the local energy matrix from 2020 to 2030 [103]. These increases in RES technologies compensate for the electricity that is no longer generated due to the closure of nuclear and coal-fired plants. Regarding biomethanation technology for biogas production, an increase in biogas production of 3.8 times more in 2030 than estimated in 2020 has been established as in the ESP30_TEND scenario. [106].

Regarding the heating sector, a share of the district heating network (DHN) of 0.5% of the total demand for heating and cooling is again assumed, as specified in [107]. In this case it is also considered that the share of DHN remains constant compared to the ESP30_TEND scenario as the development of this technology is not a factor on which Spanish policies are focused mainly due to the high temperatures in the country and therefore it has been decided to keep the same share. As for the development of heat pumps in the decentralized heat sector, a maximum share of 40 % of the total decentralized heat demand has been assumed. This value is aligned to the European forecasts which suggest that 40% of all residential and service buildings will be heated by electricity [108].

As for the mobility sector, the composition of private cars and motorbikes has also been fixed based on the forecasts made in [130,131]. As for the share of electric vehicles[22] in the total private road passenger demand, 10% has been considered as defined by the "Instituto de Investigación Tecnológica IIT_ICAI" in [111]. Finally, as for hydrogen cars, the same forecast for 2030 of only about 8000 passenger cars is considered [112] and therefore this technology has also been excluded from the model.

[22] Including battery electric cars (BEV) and hybrid electric cars (HEV).

Finally, in terms of freight mobility, it has been established that 10% of the total freight demand is by rail, as set out in the target for Spain in [113]. This share is the same as in the tendential scenario since no additional policy is established for rail freight transport and it has been decided to set the same share in both scenarios. The modal shift is also assumed to be from road to rail and therefore the boat share is the same as in 2015.

Assumptions		
	Subject	**Description**
Power	Coal	Total phase-out in the power sector: 100 % reduction of the installed capacity in the power sector vs 2015 [103]. Remain in the industrial sector: same consumption [21].
	Nuclear	Partial phase-out: 57 % reduction of the installed capacity: 4 out of 7 reactors will be closed before 2030 [103].
	Renewables	PV installed capacity :Increase of 707% of PV capacity in 2030 vs 2015 (39GW) [21]. Wind onshore installed capacity: Increase of 120% of wind on capacity in 2030 vs 2015 (50,33 GW) [21]. Wind offshore installed capacity: Not available → Not specific objectives for offshore in Spain [21]. CSP installed capacity : Increase of 217,5% of CSP capacity in 2030 (7,3 GW vs los 2,3 de 2015) [21]. Wave:→ Available Biogas: Bio-methanation conversion available [106]. Hydro: Not increasing forecasts
Mobility	Passenger	Public: share of public passenger mobility ($\%_{Pass.}$) equal to 50 % Private: car fleet in 2030 according to different sources [130,131].
	Freight	Share of train freight mobility ($\%_{Fr.\ Rail}$) equal to 10% [113]. Share of boat freight mobility ($\%_{Fr.\ Boat}$) equal to 17,3%
Heating	DHN	DHN development: Centralised heat production: 0,5% [107].
	HP's	HPs penetration: 40% upper-bound of dec. heat production [108]

Table 3.5: Summary of the main assumptions made for the definition of the ESP30_OBJ scenario. All assumptions are based on reasonable bases, unless explicitly stated otherwise.

For the different constraints (upper and lower bounds) of the different technologies of the different EUTs, please refer to Appendix A.2.3.

3.2.2. Policy Scenario: Cost-optimum

In addition to the reference scenarios already explained, the *Spanish Energyscope* model is used to model a policy scenario using 2030 demand and efficiencies. In this case, the model tries to identify which cost-optimal scenario can represent a possible future decarbonization trajectory of the Spanish energy system. Although the results of this scenario are unlikely to be achieved in 2030, due to economic and technical limitations, its development is interesting as it can suggest which are the key technologies in terms of efficiency, cost, and availability, which should play a very important role in the achievement of national and European targets beyond 2030.

Table 3.6 summarizes the main assumptions made to define the policy scenario evaluated with the Spanish Energyscope model.

Assumptions		
	Subject	**Description**
Power	Coal Nuclear	Total coal phase-out: allowed Total nuclear phase-out: allowed
	Renewables	Maximum PV capacity fixed according to [75] Maximum wind onshore capacity fixed according to [114] CSP maximum capacity equal to the forecast done by PNIEC [21] Hydro[a] maximum capacity is constant Biomethanation: Allowed at its maximum Wave: allowed
Mobility	Passenger	Public: share of public passenger mobility (% Pass.) equal to 40 % Private: Maximum capacity of all the private mobility technologies allowed.
	Freight	Minimum share of road[b] freight mobility (% road) equal to 50%. Share of boat[c] freight mobility (% boat) equal to 17,3%
Heating	DHN HP's	DHN[d] development between 5% and 30% HPs development maximum of 40%

[a] the maximum capacity of hydro technologies has remained constant, as it is considered that the hydro potential is already well exploited in the country. As evidence of this, there has been no increase in installed capacity in recent years and there are no plans to do so [81].
[b] this minimum is set because a minimum of road freight transport is required, for example to reach locations that can only be reached by road.
[c] this share is fixed, in this case the same as in 2015, as a minimum of goods transport by sea is required to make the connection with the different islands of the country.
[d] a maximum DHN development of 30% is set, considering that by 2050 a development of 68% is expected according to [54].

Table 3.6: Summary of the main assumptions made for the definition of the ESP30_P1 scenario. All assumptions are based on reasonable bases, unless explicitly stated otherwise.

In particular, the ESP30_P1 scenario analyses a possible cost-optimal strategy that significantly decarbonizes the Spanish energy system and meets the European emission reduction target beyond 2030. Basically, the objective of this scenario is to investigate a possible version of the energy system that includes a very high-RES penetration maximizing its potential and considers a significant electrification of the mobility and heating sectors. To do so, for those conversion technologies that do not have a physical or logical limitation to supply the full demand of their layer, the parameters $f_{min,\%}$ and $f_{max,\%}$ are set to 0 and 1 respectively. To understand this with an example, this means that the private passenger demand could theoretically be supplied only by electric vehicles ($f_{max,\%}$ [CAR_BEV] =1) or for example by fuel cell vehicles ($f_{max,\%}$ [CAR_FUEL_CELL] =1), which are efficient technologies and are characterized by zero CO_2 emissions. On the other hand, conversion technologies that do have a physical or logical limitation, the $f_{max,\%}$ parameter of these is set according to this limitation. An example of this is the TRAIN_PUB technology, where it is not possible for all public passenger mobility to be carried out by train, as the infrastructure does not allow access by this type of transport to all locations in the country. In this case, all limited $f_{max,\%}$ values for this scenario can be found in Appendix A.2.3

Chapter 4

4. Results and Discussion

This chapter presents the results obtained in the different scenarios developed in the previous chapter. All these scenarios have been carried out following the methodology described in Section 3.2. A complete and detailed comparison of the different outputs obtained in the modelling of the different scenarios is shown below to be able to quantify the economic and environmental impact of the different alternatives for decarbonizing the Spanish energy system in 2030. Finally, the chapter focuses on a detailed study of the ESP30_P1 scenario that obtains the cost-optimal scenario with no policy or trend-based constraints, only physical constraints (infrastructure, maximum capacities, etc.).

4.1. Scenarios Comparison

This section provides a detailed comparison of the different configurations of the Spanish energy system generated by the different scenarios. The validation of the model in 2015 is also added to have a reference point to know the starting conditions. In this case, this detailed comparison is based on: environmental impact through CO_2 emissions from fuel combustion, total primary energy supply by energy source, specific analysis for the electricity, transport and heating sectors and economic analysis and necessary investments.

4.1.1. Summary of the main results

This section summarizes the main results obtained from the scenario analysis. Table 4.1 highlights the main differences between the different scenarios developed in terms of emissions, primary energy supply, electricity generation, RES penetration in the electricity sector, electrification etc. The results are specifically compared and evaluated throughout chapter 4 and the graphical representations of each scenario, represented by Sankey diagrams, can be found in Appendix B.

Subject	Units	Transport TPES				
		Model Validation	ESP30_S1	ESP30_TEND	ESP30_OBJ	ESP30_P1
2030 Emissions Target [EU]		✗	✗	✗	✓	✓
2030 Emissions Target [PNIEC][a]		✗	✗	✓	✓	✓
TPES	[TWh]	1173.0	1152.5	1032.3	990.6	793.1
RES over TPES	[%]	17.6	19.4	32.9	47.9	99.1
Elec. Generation	[TWh]	265.0	280.4	292.3	314.1	492.7
RES over Elec. Generation	[%]	36.42	36.15	52.26	73.80	100
2030 RES over Elec. Gen target [EU]		✗	✗	✗	✓	✓
2030 RES over Elec. Gen target [PNIEC][a]		✗	✗	✗	✓	✓
HPs heat	[TWh]	0	0	67.39	95.61	96.57
Electrification of LT heat[b]	[%]	8.9	9	28.8	49.17	64.66
Electrification of mobility[c]	[%]	6.7	6.9	20	29.5	18.87[d]
Total annual cost	[B€/year]	150.1	175.6	151.6	153.0	89.11

[a] target of the "*Plan Nacional Integrado de Energía y Clima*"

[b] including both centralized and decentralized low temperature heat generation

[c] including both passenger and freight mobility

[d] in this case the entire electrification of mobility is slightly lower as private mobility is completely supplied by hydrogen, which does not count as electric.

Table 4.1: Main results among the different scenarios performed with Spanish Energyscope model. Legend: ✓satisfied; **✗** not satisfied.

In more detail, the summary of these results introduces a layout of the different scenarios developed with the model and, above all, gives a vision and a focus on which are a priori the main technologies on which a decarbonised energy system should be based. As an example, the ESP30_OBJ scenario represents a highly decarbonised electricity system characterised by a high penetration of RES with approximately 74 % of the total electricity generated.

A comparative analysis of the different scenarios shows a progressive growth in the electrification of both mobility and low-temperature heat generation, thus limiting the demand related to fossil fuels and limiting the related environmental impact. Finally, it can be seen that a significant reduction in emissions is achieved, as the ESP30_OBJ scenario meets the national and European emission targets. The detailed explanation of each of these results is explained throughout this chapter.

4.1.2. Emissions

Table 4.3 summarizes the emission reduction target values in the different European directives such as "Climate and Energy Framework 2030" [09], "Green Deal" [12], "Energy Roadmap 2050" [11] and PNIEC 2021-2030 [21]. The values reported in the directives indicate the overall percentage of emission reductions expected for the EU compared to 1990. However, individual targets are specified for each European Member State in [115]. These national targets usually include a distinction between the Emission Trading System (ETS) sectors, which include energy-intensive installations such as power industries, large industrial installations, and aviation, and the non-ETS sectors, i.e., medium-sized industry, transport, and waste [115]. For example, focusing on the non-ETS sectors, Spain targets a GHG emission reduction of 26% by 2030, compared to 2005 levels. Nevertheless, since it is not possible to differentiate specifically between ETS and non-ETS sectors in the Spanish Energyscope modelling, the overall European targets indicated in Table 4.2 have been used as a reference for the comparison of the results of the different scenarios.

In addition, the above-mentioned European targets consider the emissions of all energy and non-energy sectors, whereas the *Spanish Energyscope* model formulation considers only the operational emissions of each resource (gwp_{op}) in terms of CO_2-eq emissions for the energy sector. Therefore, it is assumed that for the comparison of results the emission reduction targets are the same.

Field	**Target 2030**			**Target 2050**
	Climate and Energy Framework	Green Deal	*PNIEC*	*Energy Roadmap 2050*
Reduction on GHG emissions[a]	40%	55 %	32%[b]	80 – 95 %

[a] *compared to 1990 levels*
[b] considering only energy sectors

Table 4.2: Targets of emissions reduction for 2030 and 2050 according to "Climate and Energy Framework 2030" [09], "Green Deal" [12] and "Energy Roadmap 2050" [11] directives and PNIEC [21].

Table 4.3 shows the total operational CO_2 emissions and the percentage reduction compared to the 1990 and 2015 values for each of the pathways developed with the *Spanish Energyscope* model. The 2015 emissions value is the one from the 2015 model validation (see Section 2.3), which has been added to give a clearer picture of the environmental trend in recent years. The emissions value for 1990 is taken from the OECD database and corresponds to 209.48 Mt CO_2-eq[23] [97].

In addition, Figure 4.1 represents graphically for each scenario the total CO_2 emissions from fuel combustion (left y-axis). It also shows the percentage reduction of emissions compared to the 1990 level (right y-axis) represented by an orange trend line. The emission reduction target limits listed in Table 4.2 are also represented by dashed lines.

Scenario	Total emissions [Mt CO_2-eq/y]	Reduction vs 1990	vs 2015
2015 Validation	243.77	16.4%	-
ESP30-S1	231.56	10.5%	-5%
ESP30_TEND	142.51	-32%	-41.5%
ESP30_OBJ	118.88	-43.2%	-51.2%
ESP30_P1	9.93	-95.3%	-95.9%

Table 4.3: Total CO_2 emissions and percentage reduction compared to 1990 and 2015 values for each scenario.

[23] The value extracted from the database follows the same methodology as explained in Section 2.3 of the model validation.

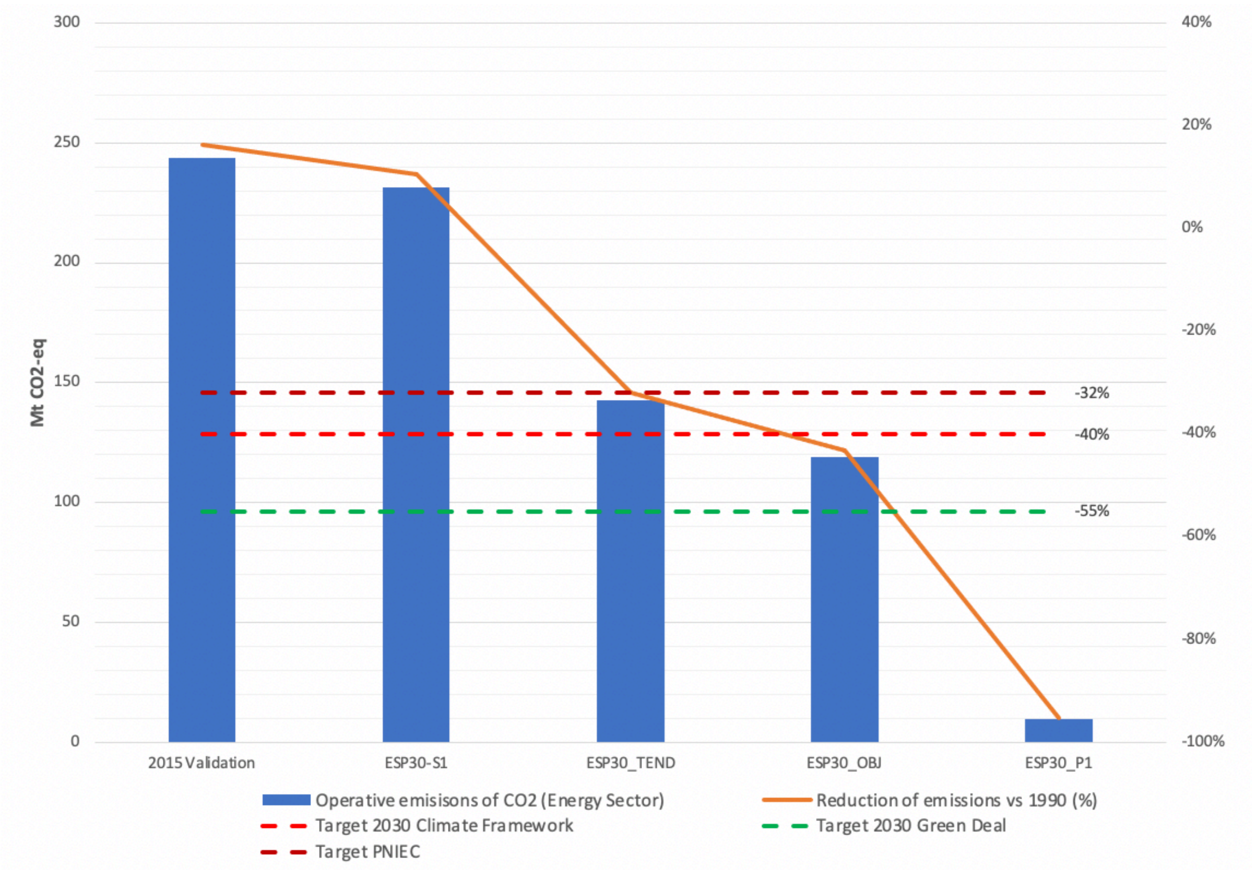

Figure 4.1: Representation of total energy related CO_2 emissions and percentage reduction compared to 1990 levels for each scenario.

As can be seen in Figure 4.1 and as could be predicted, the strategy of leaving the energy system undeveloped beyond what is in existence in 2015 (ESP30_S1), despite improving efficiencies, offers a system with almost no reduction in environmental impact. This system offers a small reduction of 5 % compared to the model in 2015, which is far from meeting national and European targets. The ESP30_TEND scenario also fails to meet the European emission target as it achieves a 32% reduction compared to 1990 levels. However, this scenario does achieve the emission reduction percentage of 32% set in the PNIEC [21]. It is also necessary to make greater efforts to develop more efficient technologies to achieve a deeper decarbonisation to meet the European targets. For this purpose, the ESP30_OBJ scenario offers a version of the Spanish energy system in accordance with the most ambitious and recent national guidelines that with some certainty meet the decarbonisation targets set by the European Union. Therefore, of the different reference scenarios only ESP30_OBJ reaches and exceeds the target set by the European Commission for 2030 in [09] with a 43.2 % reduction of CO_2 emissions. This scenario also meets the emission reduction target set by the PNIEC. As can be seen, none of the reference scenarios reaches the European Green Deal target of 55% emission reduction, so more efforts in the same direction are needed in the coming years.

Finally, the ESP30_P1 scenario modelled with the aim of representing a cost-optimal system characterised by deep decarbonisation, pushes the Spanish energy system also below the 40% reduction limit in 2030. Rather, the scenario shows a near zero emission system achieving a 95.3 % reduction. This policy scenario demonstrates that deep decarbonisation is possible if enormous efforts are made to extend the use of cleaner and more efficient technologies. These technologies plus a broad sectoral electrification and a higher RES penetration could help to reduce the environmental impact of the Spanish energy system by 2030.

4.1.3. Primary energy supply

The total primary energy supplied, and the related emissions depend on the different fuels and technologies that are used to convert energy to supply the entire energy demand. As the energy sector decarbonises and therefore uses a higher share of renewable energies and cleaner and more efficient conversion technologies, the total primary energy supply is reduced. As can be seen in Figure 4.2, as the Spanish system decarbonises under the different scenarios, total primary energy decreases.

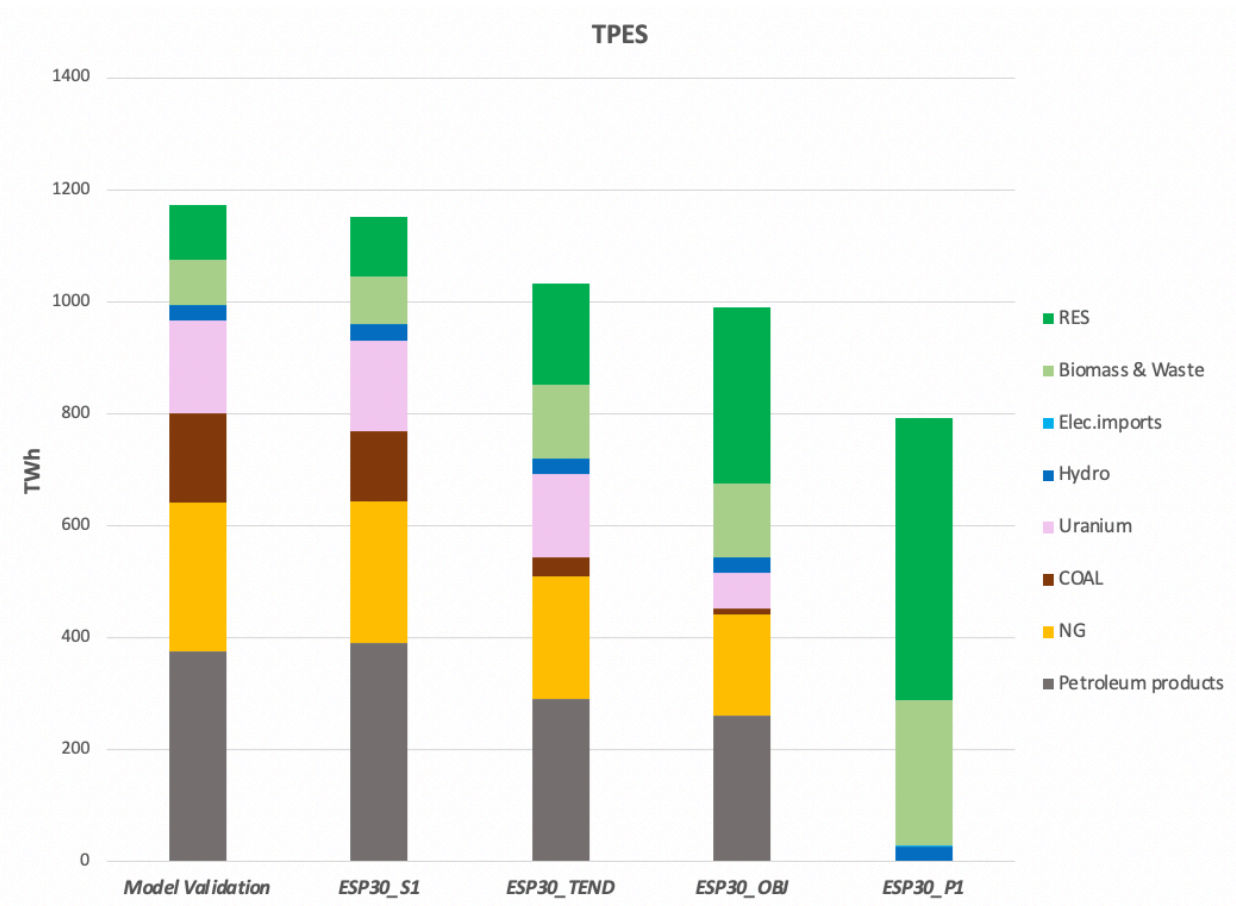

Figure 4.2 Total primary energy supply (TPES) in each scenario by energy source

As can be seen in Figure 4.2, in all modelled scenarios primary energy demand is continuously reduced compared to the 2015 energy system, achieving a reduction of 15.5% in the ESP30_OBJ scenario and up to a 32.4% maximum decrease in the ESP30_P1 scenario. This steady reduction is mainly due to improvements in energy efficiency and the increased penetration of renewable energies, which should be the key driver and factor in decarbonisation until 2030 and beyond. The modal shift towards electric vehicles in transport and fuel switching from fossil fuels to cleaner and renewable sources guarantees significant energy savings and consequently lower emissions. As can be seen in the different scenarios, there is a continued increase in the penetration of renewable energies, reaching 34.7% of the total TPES in the ESP30_OBJ scenario, while at the same time there is a gradual phase-out of certain fossil fuels (coal) and uranium. Renewable resources cover up to 67% in the ESP30_P1 scenario. Limiting and reducing the penetration of fossil fuels in the energy system is key not only to diversify and expand clean energy sources but also to increase energy security. Spain's energy dependence reached 74% in 2017 and aims to reach 61% by 2030 **[21].** Therefore, it is vital to significantly increase indigenous energy sources and the shift towards more innovative and renewable technologies strongly increases the chances of achieving it.

4.1.4. Electricity generation sector

One of the key points of the Spanish "*National Energy and Climate Plan*" is the progressive decarbonisation of the electricity generation sector with the aim of reducing the environmental impact of the Spanish electricity system. In this context, the "*Climate Change and Energy Transition Law*" (PLCCTE) sets a target of 70% of electricity generation to be based on renewable energy sources [24]. Furthermore, the PNIEC itself achieves in its target scenario 74% of electricity generation based on renewable sources [21]. Table 4.4 confirms the fulfilment of the target in the ESP30_OBJ scenario, reaching a renewable electricity generation of 73.8%, which is assumed to meet the targets of the two plans. Furthermore, the table shows how through the different scenarios renewable electricity generation is increasing, reaching an increase of 18.5% in the ESP30_OBJ scenario and up to 85.8% in the ESP30_P1 scenario compared with 2015 values.

Scenario	Elec. Production		RES		Target 2030: % RES in Elec. Gen.	
	[TWh]	Variation vs 2015	[TWh]	%	PLCCTE [70%]	PNIEC [74%]
2015 Validation	265.05	-	96.54	36.42%	✗	✗
ESP30-S1	280.44	5.81%	101.39	36.15%	✗	✗
ESP30_TEND	292.25	10.26%	152.75	52.26%	✗	✗
ESP30_OBJ	314.06	18.49%	231.77	73.80%	✓	✓
ESP30_P1	492.68	85.88%	492.68	100%	✓	✓

Table 4.4 Spanish power generating sector in terms of electricity and percentage of electricity generation based on renewable energy sources

Figure 4.3 shows the electricity generation of the Spanish system by generation technology. Furthermore, Figure 4.4 shows the percentage of electricity generation based on renewable sources in each scenario. The generation structure can be seen to be changing significantly by focusing electricity generation on renewable energy sources. To begin with, a key point towards the decarbonisation of the electricity system is the national phase-out of coal as a generation source, either partially or totally, as proposed by the PNIEC in [21] and modelled in the ESP30_TEND and ESP30_OBJ scenarios. In addition, another important point is the partial phase-out of nuclear power plants which is defined in [21] and modelled in the ESP30_OBJ scenario. On the other hand, as mentioned above, RES penetration is set to increase through a growing share of electricity production, from 96.54 TWh in 2015 to 231.77 TWh in 2030 in the ESP30_OBJ. In this scenario, the main actors in this increase are PV technology, which goes from generating 8.23 TWh in 2015 to 66.91 TWh in 2030, and wind onshore, which goes from generating 48.12 TWh in 2015 to 110.63 TWh in 2030. Hydro generation remains constant at 28.05 TWh, which assumes that the potential is already exploited today. As already mentioned, the ESP30_OBJ scenario reaches a generation of 73.8% based on renewables, reaching the targets listed in [24,21]. The contribution of intermittent RES grows more rapidly in the policy scenario ESP30_P1, accounting for 492.68 TWh.

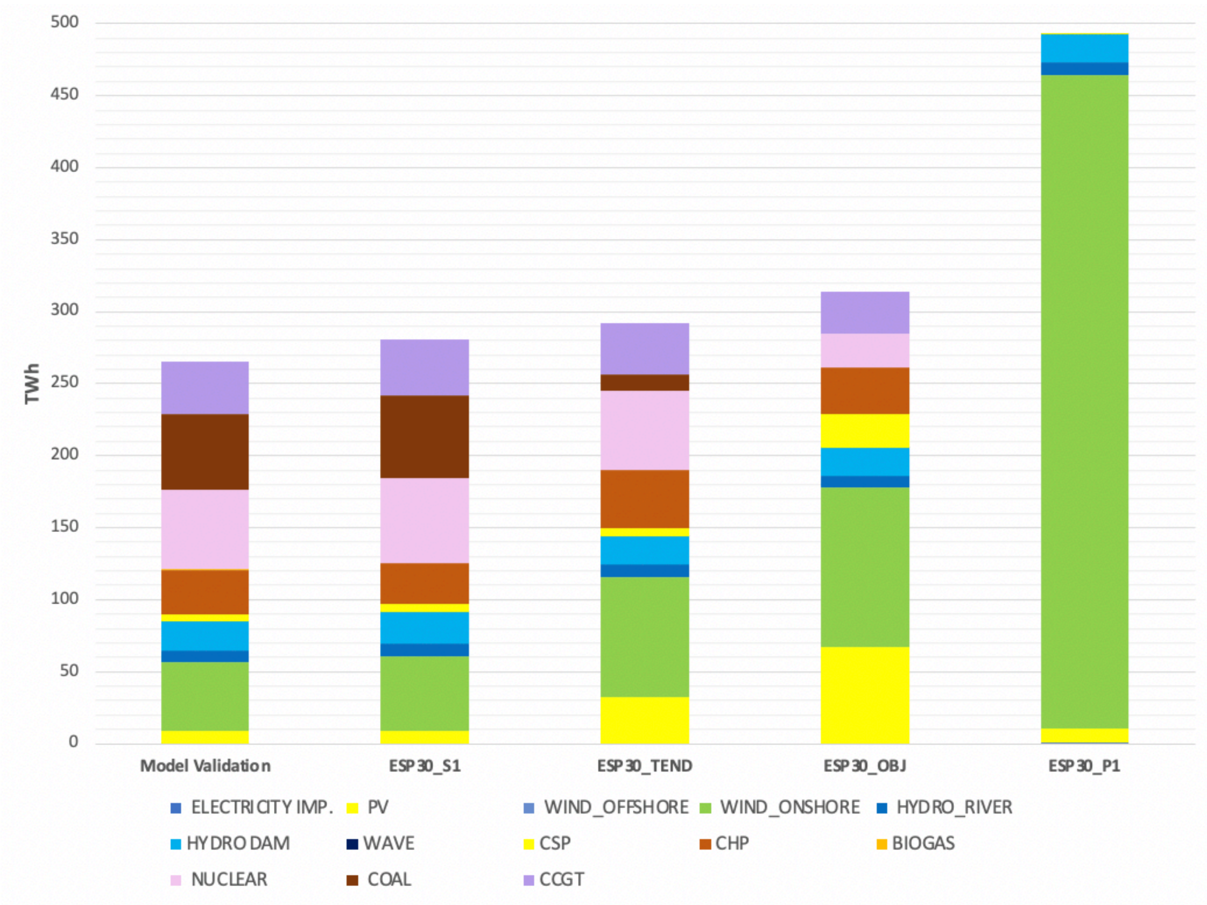

Figure 4.3 Electricity production in all scenarios by type of technology used. Abbreviations: combined Heat and Power (CHP), photovoltaic (PV), concentrated solar power (CSP), combined cycle gas turbine (CCGT).

It is worth mentioning that this increased renewable electrification is in line with the objective of reducing primary energy supply described in Section 4.1.3, since fossil-based technologies have lower efficiencies than renewables and therefore increase total consumption. Furthermore, as also discussed in Section 4.1.3, reducing the total consumption of fossil fuels consequently reduces the country's energy dependence.

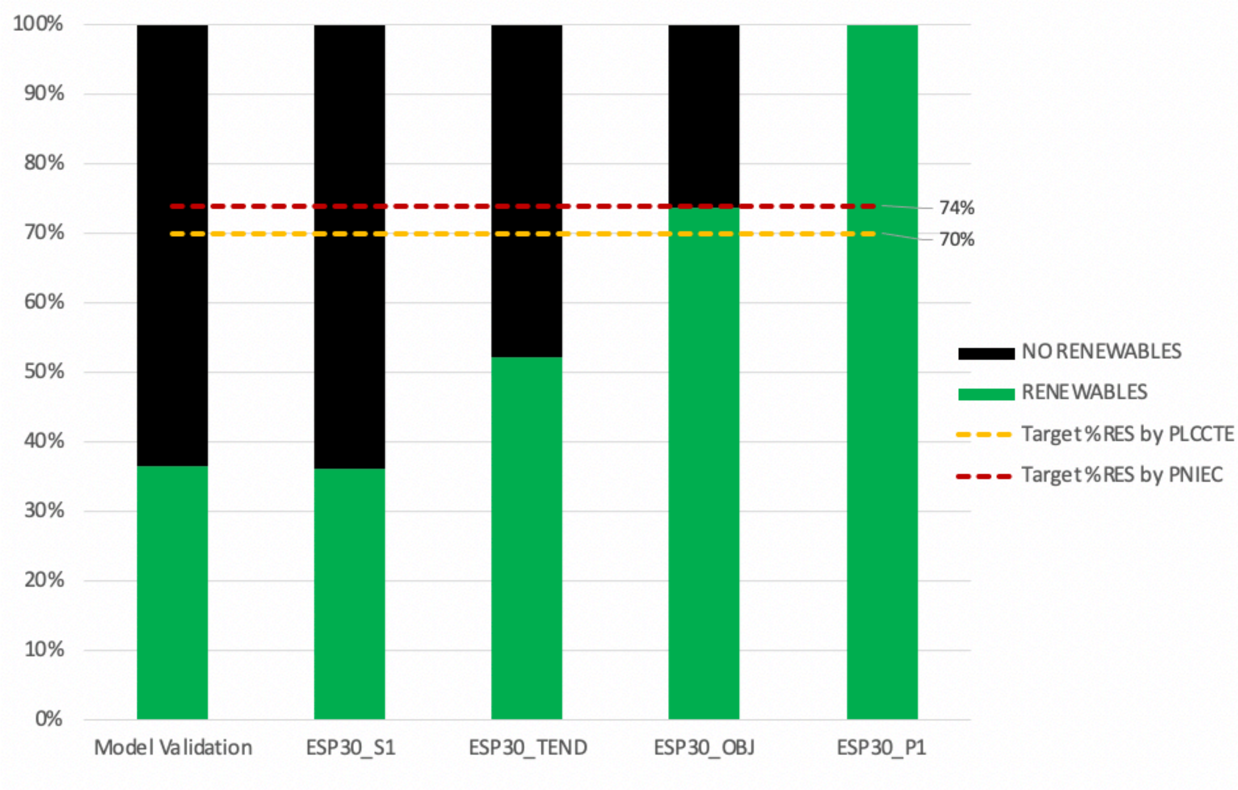

Figure 4.4: Percentage of electricity generation based on renewable energy sources. Renewable energy sources are divided in PV, wind, hydro, wave, CSP, biogas, CHP by waste & wood and elec. Imports. Abbreviations: “Plan Nacional de Energía y Clima” (PNIEC), “Proyecto de Ley de Cambio Climático y Transición Energética (PLCCTE).

4.1.5. Transport sector

The transport sector is the largest emitter in the case of model validation with 39% of total emissions. Therefore, decarbonising the transport sector will certainly contribute to mitigating the environmental impact of the Spanish energy system. Gradually eradicating traditional fuels in the automotive sector, such as diesel and petrol, is key to achieving a significant reduction in both emissions and pollution produced in areas of pollution such as cities. Figure 4.5 shows the total private passenger demand by type of transport. As can be seen, there is a gradual shift from traditional fossil fuels to an increased use of efficient electric vehicles and natural gas vehicles. This increase, which is essential to decarbonise the transport sector, is starting to be reflected in the ESP30_OBJ scenario, where these innovative cars cover 13% of the total private passenger mobility demand. Furthermore, in this same scenario, the development of new infrastructures for electric vehicles (e.g., charging stations, electric storage etc.) is very important to ensure that the efficiency of these vehicles can be increased and help these technologies to stabilise in the current market. This development of electric infrastructure is also essential to match and stabilise these vehicles to the grid, especially during peak production from RES. In addition, the same graph shows that in the reduction of fossil fuels there is a shift from diesel to petrol, mainly due to the fear of bans, the various restrictions, and the proliferation of alternatives such as hybrid cars [116]. In contrast to the ESP30_OBJ scenario, in ESP30_P1 all private passenger demand is satisfied by fuel cell cars only. In addition, the demand for road freight mobility is also only satisfied by fuel cell trucks. This gives us an idea of the importance that vehicles based on this technology should have, although it does not represent a realistic view of what Spain can or will achieve in terms of private and freight mobility.

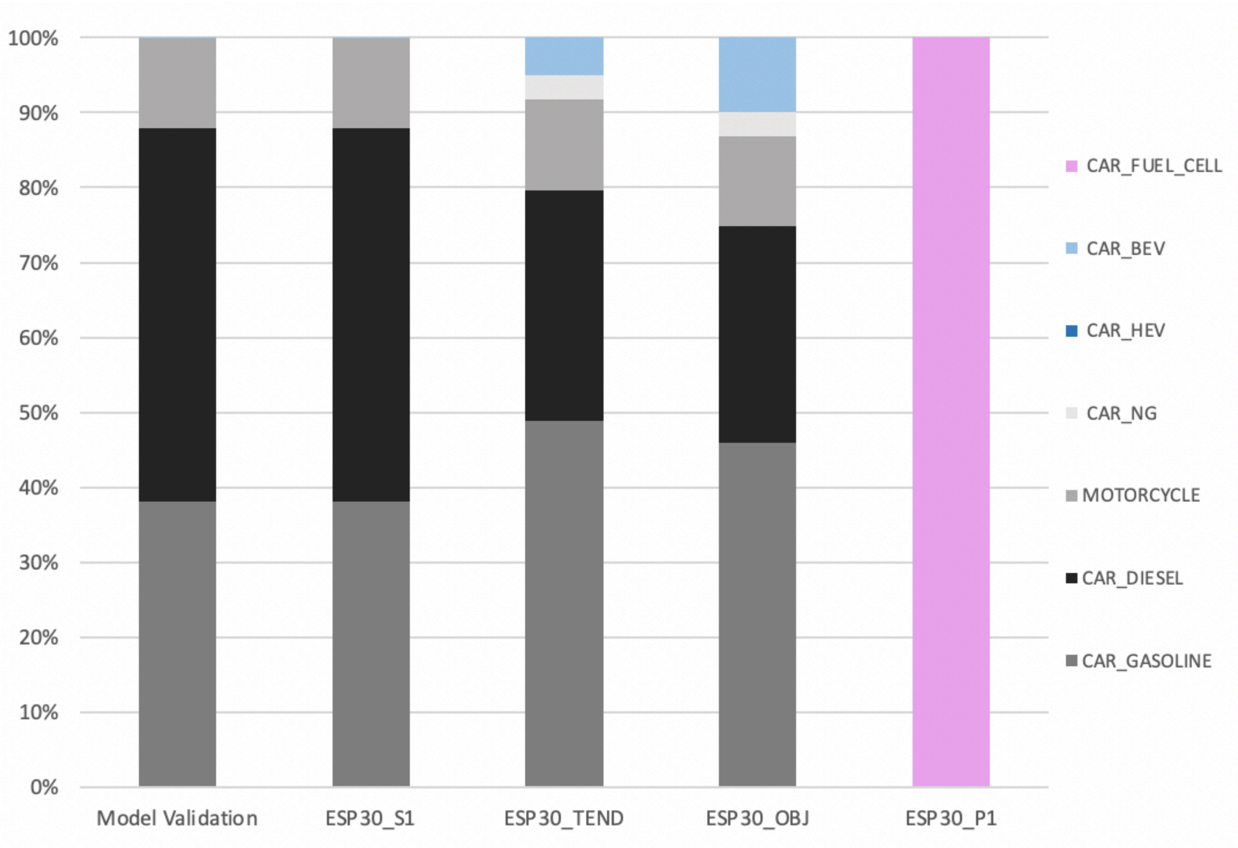

Figure 4.5: Demand for private passenger mobility by type of technology. Abbreviations: Hybrid electric vehicle (HEV), Battery electric vehicle (BEV).

Finally, Figure 4.6 shows that both the gradual shift from fossil fuels to electric vehicles, plus a shift from road to rail mobility and a significant increase in public mobility, leads to a reduction of the total primary energy supplied by the transport sector compared to 2015 values (18 % in ESP30_OBJ). This shift is also due to the higher efficiency of electric vehicles compared to traditional vehicles. As an example, a fuel cell car is assumed to have 0.1794 kWh/pkm efficiency in 2030 while a gasoline car has an efficiency of 0.4297 kWh/pkm, as reported in [75].

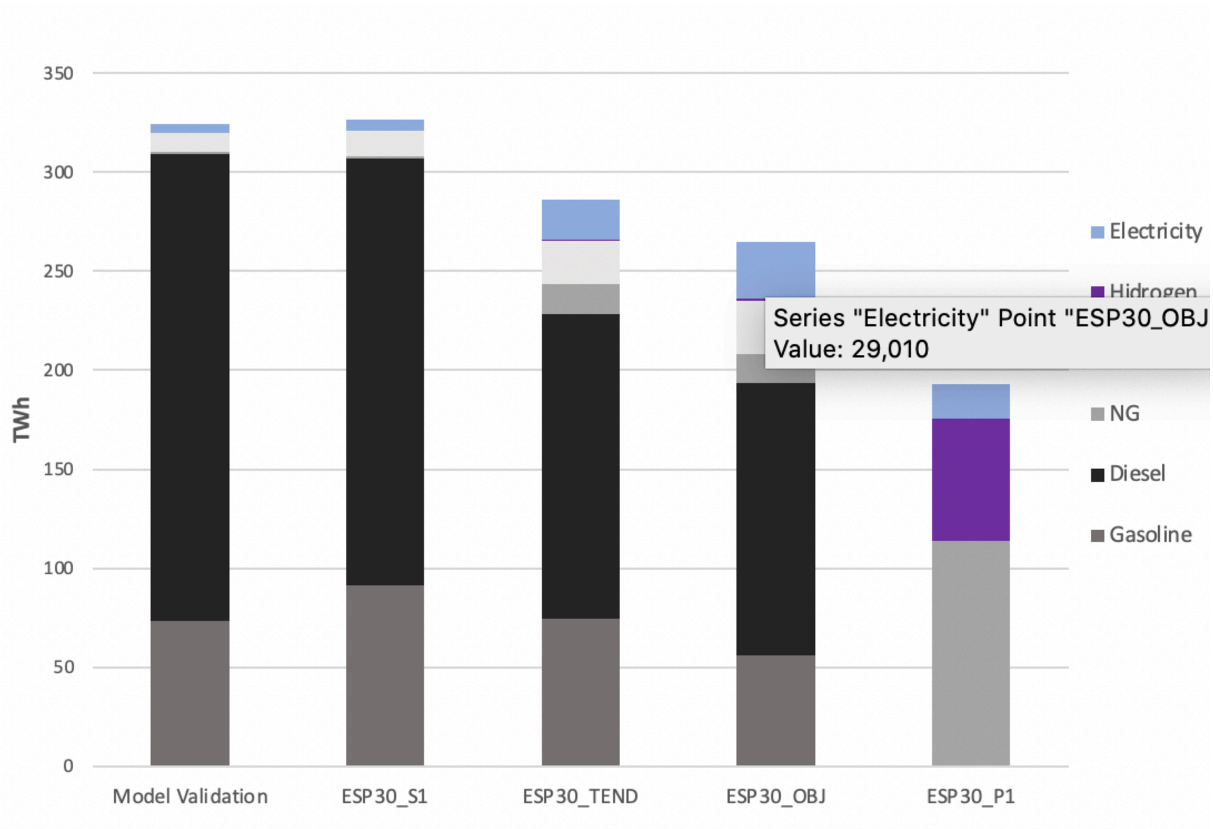

Figure 4.6: Primary energy supply by energy source for each scenario in transport sector.

4.1.6. Heating sector

The CO_2 emissions related to low and high temperature heat generation in space heating and hot water for low temperature applications and industrial processes for high temperature applications can be seen in Table 4.5 below. At present, the heating sector is not the largest emitter, as it corresponds to the transport sector. In any case, the heating sector in the Spanish energy system contributes 33.2 % of the national emissions in the validation case. In more detail, low temperature applications account for 43% of the total emissions of the sector. This environmental impact of the sector is due to the use of different fossil fuels in low efficiency technologies (boilers) and the low electrification of the heat demand.

Scenario	Emissions		
	Low T Heat [Mt CO_2-eq/y]	**High T Heat** [Mt CO_2-eq/y]	**Total** [Mt CO_2-eq/y]
2015 Validation	34.41	46.31	80.71
ESP30-S1	48.65	30.86	79.51
ESP30_TEND	23.32	31.55	54.87
ESP30_OBJ	19.48	26.22	45.70
ESP30_P1	0	9.93	9.93

Table 4.5: Operational CO_2 emissions for each scenario in the Spanish heat generation sector

The scenario analysis shows that in the ESP30_S1 scenario, emissions from LT heat generation increase compared to the model validation in 2015, mainly due to the significant increase in low-temperature heat demand in 2030 compared to 2015. This increase is in turn mitigated by the increase in energy efficiency of traditional boilers. In the same framework, it can be observed that in the ESP30_TEND and ESP30_OBJ scenarios the emissions related to low-temperature heat generation are significantly reduced. This phenomenon, which can be seen in Figure 4.7, is mainly due to the gradual shift from low efficiency fossil boilers to a more important penetration of decentralised heat pumps and solar thermal panels, which have much less weight in the scenarios with the 2015 energy system.

Regarding high temperature heat demand, it is usually supplied by CHP plants fuelled with NG and waste, fossil (gas, coal, oil) and biomass boilers, and electricity. In this case, the penetration of heat pumps and solar thermal panels faces a difficult barrier due to the high temperatures of the industrial processes characteristic of this sector. The decrease in emissions in high-temperature heat generation is due to a slight reduction in demand in 2030 compared to the value in 2015 and on the other hand due to a shift caused by the phase-out of coal in industrial boilers mainly in the ESP30_TEND and ESP30_OBJ scenarios.

For the ESP30_P1 scenario, all emissions are produced by the high-temperature heat generation sector. This is since there are no emissions in the power generation sector with 100% renewable penetration and the transport sector is mainly hydrogen based (as discussed in Section 4.1.5). As for the low temperature heating sector, all the gas used comes from the biomethanation process and therefore the model does not account for its emissions as it is not an imported resource.

Figure 4.7 can be seen below and graphically represents the evolution of high and low temperature heat demand. This demand is represented by the relative share of each type of technology used to supply this demand.

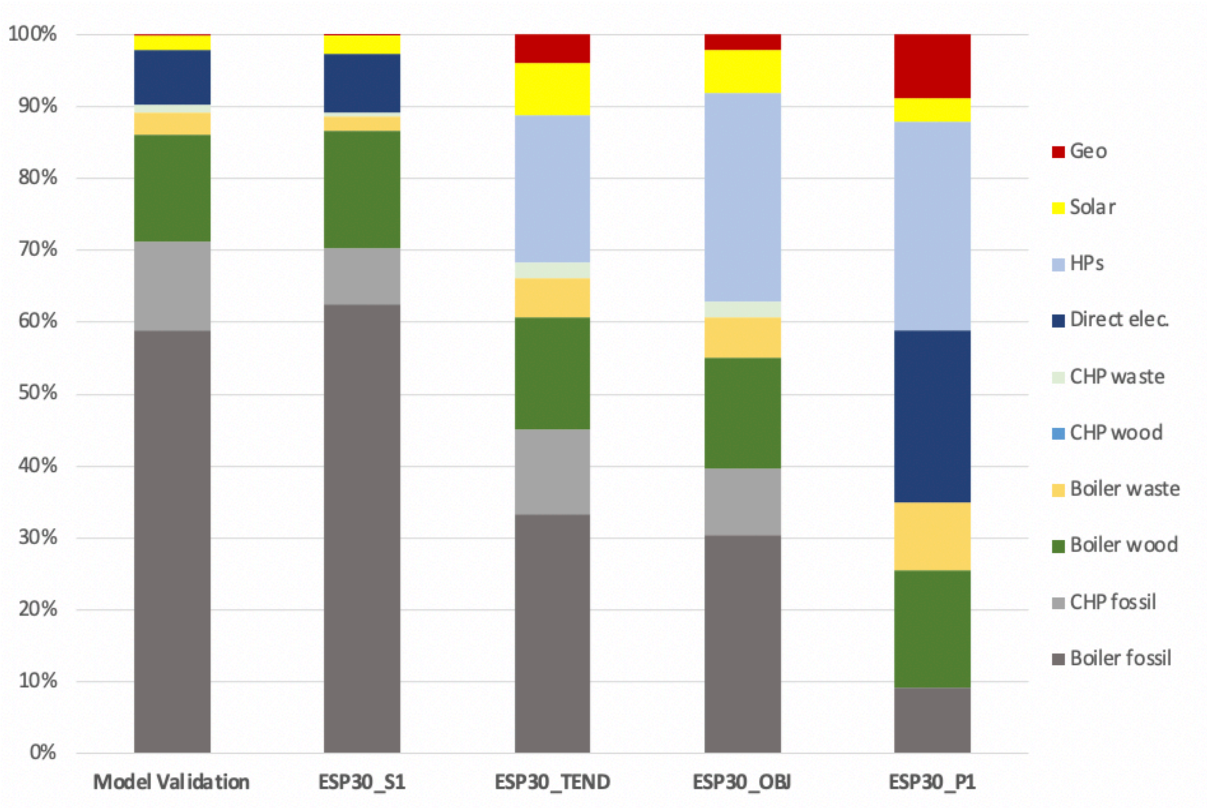

Figure 4.7: High and low temperature heat demand (centralized and decentralized) by type of technology.

The continued transition from traditional fossil fuel boilers to other technologies such as heat pumps and RES leads to increased electrification of these heat systems. As a consequence, these technologies (heat pumps, solar, geo, boiler wood and direct elec.) reach a penetration of 53% in the ESP30_OBJ scenario and up to 81% in the ESP30_P1 scenario.

In conclusion, this analysis demonstrates that a decarbonisation of the heat generation sector can be achieved through electrification of these systems. This electrification should be based on the use of heat pumps and technologies based on renewable sources (geo, solar thermal panels, biomass boilers etc.), although in the high temperature sector this is more difficult due to the complexity of its processes.

4.1.7. Cost and investments

The different strategies designed to try to achieve a profound decarbonisation of the Spanish energy system not only require efforts to develop new and better clean technologies but must also go hand in hand with the economic aspect. Table 4.6 shows a list of the total annual system cost ($\mathbf{C_{tot}}$) for each scenario developed. This total cost is further broken down into investment costs ($\mathbf{C_{inv}}$), maintenance costs ($\mathbf{C_{maint}}$) and operational costs of the different resources ($\mathbf{C_{op}}$). As can be seen in Table 4.8, the annual cost of the modelled energy system does not decrease despite the increased penetration of renewable energies and improved energy efficiencies of the technologies. Furthermore, although total CO_2 emissions are on a decreasing trend, the annual cost of the system does not decrease. This phenomenon gives us an idea that a deep decarbonisation of the Spanish energy system requires large economic investments to try to reverse the fossil fuel-based system. In detail, the cost analysis shows that in the low-carbon strategy, in the ESP30_TEND and ESP30_OBJ scenarios, there is an economic shift from operational costs to more infrastructure-related costs. This shift, mainly due to the reduction in fossil fuel penetration and the increase of RES technologies, results in lower emissions due to the consumption of fewer fossil resources.

In this analysis, in terms of electricity generated, only the investment and maintenance costs of the different generating technologies and operational costs are included. Therefore, the total annual cost does not include the cost of transmission and distribution of electricity to the different consumption locations. Furthermore, the cost of emitting CO_2, which is stipulated in the European Directive of 2003 (Directive 2003/87/EC) [117] and which aims to correct the externality of GHG emissions, is also not included. On the other hand, investments in the electricity grid due to the increased penetration of renewable technologies are accounted for. In scenarios characterized by a high penetration of intermittent renewable energies and a considerable increase in the electrification of the energy system, specific investments are required for the modernization, adaptation, and security of the electricity grid. This ensures that the grid is able to capture the full renewable electricity potential while guaranteeing security and quality of supply.

Scenario	Costs review			
	Cinv [B€/y]	Cmaint [B€/y]	Cop [B€/y]	Total [B€/y]
2015 Validation	72.95	32.34	44.86	150.15
ESP30-S1	89.56	41.39	44.67	175.62
ESP30_TEND	81.30	36.51	33.83	151.64
ESP30_OBJ	87.32	36.76	28.88	152.97
ESP30_P1	76.03	10.59	2.49	89.11

Table 4.6: Review of the total annual costs of the Spanish energy system for each developed scenario

Figure 4.8 shows the total annual costs per category type for each scenario. The graph shows the costs of imported fossil and renewable resources, mobility technologies, heating, storage & infrastructure, and fossil & RES electricity generation technologies.

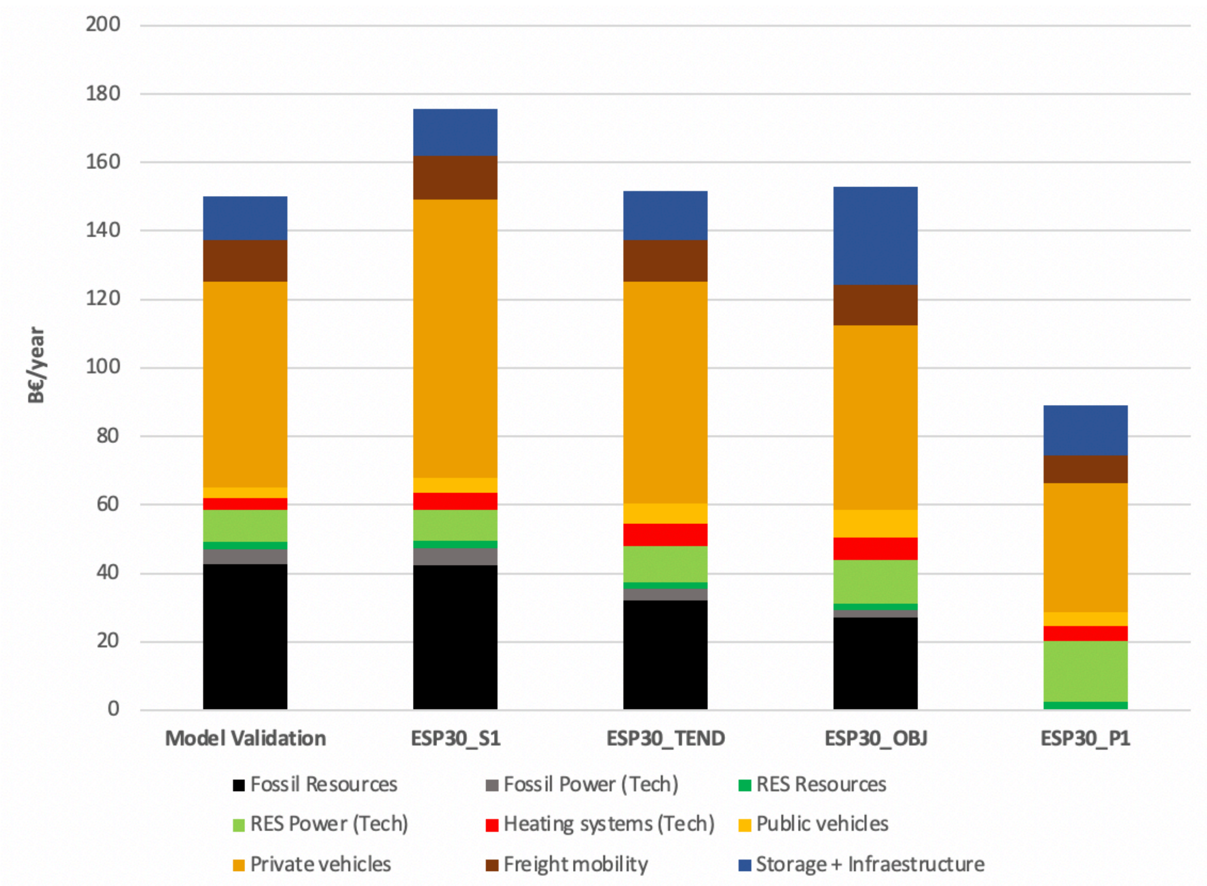

Figure 4.8: Total annual costs by type of category for each developed scenario.

In this context, it can be observed that going through the different scenarios, more emphasis is placed on gradually shifting the costs of fossil resources towards costs more related to renewable electricity generation capacity (infrastructure, storage etc.) and cleaner and more efficient electricity technologies. This is partly driven by the gradual phase-out that occurs for example in coal and nuclear plants, as already discussed in Section 3.2.1. This gradual shift contributes to a cut in the total national TPES as already seen in Figure 4.2. The increase in annual cost in the ESP30_S1 scenario is associated with a significant increase in mobility demand and as can be seen in the graph, this cost increase is mainly reflected in the costs related to private vehicle mobility. This increase represents 17% compared to 2015. In the other two scenarios (ESP30_TEND and ESP30_OBJ) this increase in demand in 2030 also occurs, but in this case the costs of private mobility are not as high due to the higher share of public mobility and the shift from the use of traditional fossil fuels in cars to a greater use of natural gas and electric vehicles. It should therefore be noted that the private mobility sector is key to the financing of the energy transition of the Spanish system, as it corresponds to a high percentage of the total cost in all scenarios developed. Finally, a significant decrease in the total annual cost (40.6%) of the ESP30_P1 scenario compared to 2015 should be noted. This scenario, which represents the optimal cost scenario, suffers this cost decrease due to the low operational cost (C_{op}) of the different resources used. As mentioned above, this scenario is characterised by a very high penetration of RES in the total TPES, therefore the operational cost of renewable resources is much lower compared to the other scenarios.

As a conclusion, it can be said that looking for a cost reduction in the national electricity generation sector is apparently feasible by seeking a higher RES penetration, while looking for this reduction in the private mobility sector is not so easy. As has been seen, the reduction in the use of traditional vehicles for further electrification does not lead to cost reductions. Therefore, strong sector-specific investment is needed in this sector either through private capital or public investment. Therefore, to achieve the goal of deep decarbonisation, it is not only necessary to create plans and strategies, as their achievement and success depend directly on appropriate financing. Companies, organizations and mainly the population as an entity itself, need this funding to enable them to be key players and help achieve the goal of this challenging challenge.

Chapter 5

5. Conclusions

Through this thesis, an energy model called Energyscope TD has been implemented to make it acceptable to Spanish applications with the intention of identifying different low-carbon scenarios to help national energy planning for the year 2030 and beyond. The entire repository with all the code information for each of the modelled scenarios can be found at the following link: *https://github.com/JosepRoselloMartinez/Spanish-EnergyTransition.git*

With respect to previous work done with the Energyscope TD model, the model proposed in this thesis as a solution, called *Spanish Energyscope*, presents some additions such as new conversion technologies and new resources to define the Spanish energy system. Once the Spanish energy system framework has been defined (Chapter 2), and using the mathematical formulation of previous works, the *Spanish Energyscope* model has been applied in real conditions of Spain in 2015. This year has been chosen because it is a past reference year and therefore it has been possible to compare the real results with those obtained in the model to validate the model and corroborate the consistency of its results. Then, the validated model has been used to implement multiple low-carbon scenarios for the Spanish energy transition until 2030 (Chapter 3). The development and analysis of these scenarios aims at trying to find out whether the different policies defined by the current national plans and directives (the so-called reference scenarios) could achieve the different European targets in terms of emission reductions or RES penetration. In addition, it also serves to evaluate configurations that represent a deep decarbonization (the so-called policy scenario). The results of the analysis of the different scenarios are discussed and compared in Chapter 4.

The comparison of scenarios has demonstrated that for the coming years profound modifications and investments are required to significantly reduce emissions and increase RES penetration in the Spanish energy system. Following a no-action trend in the system, the impact of the Spanish energy system is bound to increase because of increasing energy demand. Furthermore, the energy strategy of keeping with the same trends (ESP30_TEND) turns out not to be sufficient to cut emissions. However, the ESP30_OBJ scenario, which contains the most ambitious but realistic national policies, can reach the European targets, leading the energy system to reduce CO_2 emissions by more than 40% compared to 1990 levels. This same scenario allows to reduce the TPES by 15.5 % and thus the dependence on resources from other countries. This reduction is mainly based on: the total phase-out of coal and partial phase-out of nuclear plants in electricity generation; the increase of energy efficiency; a high electrification of the energy system through a higher penetration of RES in the electricity system and heat pumps and electric vehicles in the heating and mobility sectors respectively. The results of the ESP30_OBJ scenario show that the progressive decarbonization of the Spanish energy system requires considerable economic investments. The total annual cost of the energy system does not decrease even though there is a reduction in CO_2 emissions. This is due to an increase in RES penetration in the electricity sector and the increased use of HPs and electric vehicles. Considering that the private sector is the costliest sector, without specific strategies for this sector it is very difficult for the decarbonization of the Spanish energy system to be economically viable.

In addition, a scenario characterized by a deep decarbonization of the energy system has been analysed. To achieve this, in addition to decarbonizing the electricity system, it is necessary to focus efforts on electrifying the heating and transport sectors. In this context, this ESP30_P1 scenario leads the energy system to an enormous reduction in emissions (95.3% compared to 1990 levels) and TPES (32.4%). This ambitious scenario could represent an interesting line of research for energy policy makers to help them understand which technologies should play a major role in the future. Even if some of the results are not feasible either for technical or economic reasons (e.g., widespread use of hydrogen in private passenger mobility), a very low emission configuration has proven to be achievable especially in the power generation sector.

The *Spanish Energyscope* model has proven to be a valuable tool capable of quickly representing future decarbonization scenarios for the Spanish energy system. This intuitive tool can help future researchers, energy policy makers and in general students and people interested in the energy transition of the country to evaluate future configurations of the Spanish system. In the future, the Spanish energy system could be evaluated by dividing the Spanish territory into several regions, to obtain more accurate results. In addition, the possibility of considering imports and exports of resources (e.g., hydrogen) with neighbouring countries could be incorporated into the model to broaden the scope of the energy system. Clearly, these improvements would increase the computational time of the model, but on the other hand, they would provide more accurate results that would offer greater certainty for energy policy makers.

Appendix A

A. Spanish Energy System data

A.1. Real data in 2015 for model verification

This appendix details how all the data necessary to model and implement the real energy system for the past 2015 has been collected. Therefore, the following paragraphs detail more specifically what actual data has been collected, what methodology has been followed to obtain it and from which sources it has been obtained.

Therefore, this section details the data of the Spanish energy system in 2015 used to validate the LP model. The different data inputs used for the validation of the model are:

i) The yearly EUD ($endUses_{year}$) values in the different sectors (Households, Services, Industry, Transportation)

ii) Data for the electricity production technologies in the Spanish energy system.

iii) The relative annual production shares of the different heating, cooling and cogeneration technologies.

iv) The shares of public mobility (***%public***), the different shares of passenger and freight mobility and the share of centralised heat production (%***Dhn***).

v) The relative annual shares of the different public and private technologies.

All other data not specified in this appendix, such as technology prices, energy conversion technology efficiencies, lifetime, emission factor etc. are assumed to be the same values as those defined in the Spanish case in the work done by Jeroen and Jean Louis in [75]. In this appendix only the values that have been varied compared to the values already defined in that work are specified.

A.1.1. Energy Demand

The data for the EUDs in Spain for heating, cooling, electricity, and mobility in 2015 in this chapter are the result of a data collection and elaboration process from different accessible sources. To obtain the different EUD data, a set of assumptions have been considered to present a simplified configuration of the Spanish energy system and suitable for the validation of the model. The EUD data in Spain 2015 are listed in Table A.1:

	Units	Households	Services	Industry	Transportation
Electricity (other)	[GWh]	66130	55513	74107	0
Lighting	[GWh]	8893	21589	7329	0
Heat High T	[GWh]	0	4440	114682	0
Heat Low T (SH)	[GWh]	49218	28793	22270	0
Heat Low T (HW)	[GWh]	43325	4423	0	0
Cold Process	[GWh]	0	9552	15439	0
Cold Space	[GWh]	11951	34488	11687	0
Mobility passanger	[Mpkm]	0	0	0	418901
Mobility freight	[Mtkm]	0	0	0	263912

Table A.1: End-uses demand in Spain($endUses_{year}$) in 2015

Specific details on how the EUD data for Heating & Cooling, Mobility, Electricity (not related with heating) and Lighting have been obtained are detailed in different sections below.

A.1.1.1. Heating and Cooling

2015

The different EUD data for the households, services, and industry sectors in the Spanish energy system in 2015 have been calculated using data obtained from the "Heat Roadmap Europe" [118]. Furthermore, it is shown which are the different resources (e.g., fuels, RES, direct electricity etc.) used to satisfy the demand in each of the sectors.

In the heating and cooling demand profiles provided by Heat Roadmap Europe, the FEC values for each of the different types of heat (space heating, space cooling, process heating, process cooling, hot water) can be found separated by the different carriers (e.g., oil, gas, coal, RES etc.) responsible for supplying that consumption. Table A.3 shows the final calculated data for the detailed final energy consumptions with the different carriers used and the result of the different values for the heating and cooling EUDs. The data for the different EUDs have been obtained from the FEC data by type of heat use, which are available in [118]. The average efficiencies used for each type of end-use technology to pass from FEC to EUD are shown in Table A.2.

	COP [-]	Efficiency [%]
Households Boilers		0.81
Services Boilers		0.86
Industries Boilers (LT Heat)		0.90
Industries Boilers (HT Heat)		0.77
Elec.Direct Heating (LT Heat)		0.95
Elec.Direct Heating (HT Heat)		0.84
Decentralised HPs	2.7	
Elec. Space Cooling	2.4	
Elec. Process Cooling	2.2	

Table A.2: Average efficiency/COP of different technology categories used to satisfy the cooling and heating demand in Spain in 2015

These efficiencies are not taken directly from the Heat Roadmap, but are calculated as the average of different efficiencies (e.g., the efficiency of boilers in the household sector has been calculated as the average between the efficiencies of space heating ($\frac{EUD_{space\ heating}}{FEC_{space\ heating}}$) and hot water($\frac{EUD_{hot\ water}}{FEC_{hot\ water}}$) or the COP in space cooling is obtained as the average between the COP in space cooling in the three different sectors).

	Heat Roadmap Spain **[118]**				
	EUD type	**Technology/source**	**Households** [GWh/y]	**Industry** [GWh/y]	**Services** [GWh/y]
FEC	Space heating		62684	24784	32392
	Space cooling		5426	4675	13265
	Hot water		52133	0	5332
	Process heating		0	149095	4876
	Process cooling		0	6421	4776
FEC[1]	Space heating	Fuels	62075	24714	29756
		RES	362	70	2457
		Elec.heat pumps	247	0	179
		Elec.direct heating	13315	548	2576
	Space cooling	Fuels	0	0	0
		RES	0	0	0
		Elec.heat pumps	0	0	0
		Elec.direct heating	5426	4675	13265
	Hot water	Fuels	46363	0	4493
		RES	2086	0	432
		Elec.heat pumps	146	0	29
		Elec.direct heating	3538	0	379
	Process heating	Fuels	0	140636	0
		RES	0	0	0
		Elec.heat pumps	0	0	0
		Elec.direct heating	0	8459	4876
	Process cooling	Fuels	0	0	0
		RES	0	0	0
		Elec.heat pumps	0	0	0
		Elec.direct heating	0	6421	4776
EUD[1]	Space heating		49218	22270	28793
	Space cooling		11951	11687	34488
	Hot water		43325	0	4423
	Process heating		0	114682	4440
	Process cooling		0	15439	9552
EUD[1]	Heat LT		92543	22270	33215
	Heat HT		0	114682	4440
	Cold HT		11951	11687	34488
	Cold LT		0	15439	9552

[1]*Calculated values*

Table A.3: FEC and EUD data for households, industry, and services in Spain in 2015. Abbreviations: Low Temperature (LT), High Temperature (HT).

The recorded FEC values result from the sum of the fuel consumed either in boilers or in CHP plants, the electricity consumption for direct heating/cooling, the electricity consumption for HPs and the energy provided by renewable resources (e.g., solar thermal). Table A.4 below shows a summary of the energy carriers classified in the Heat Roadmap Europe and which have been merged into different categories as seen in Table A.3.

Category	ID Energy Carriers	Technology/Source
Fuels	3	Oil
	5	Coal
	2	Gas
	4	Biomass
	16	Other (fossil)
	8 + 9	Micro CHP
RES	10	Solar Thermal
	15	Other (RES)
Elec.Heat Pumps	11	Heat pumps total (electric)
Elec. Direct heating	6	Electric Heating

Table A.4: Relations between ID energy carriers from [118] and the different categories used to represent each technology/source in Table A.3

Thus, the EUD for heating accounts for the heat supplied by traditional boilers, the heat supplied by micro-CHP plants, the heat supplied by HPs and RES and the heat provided by direct electric heating system. Regarding the EUD for cooling (space cooling and process cooling) is only supplied by electric cooling system. Because there is a clear distinction between low and high temperature in the EnergyScope model formulation, it is necessary and required to make a more specific classification to fit the model. Therefore, HT heat includes only the demand for process heating and LT heat includes the EUD of space heating and hot water. On the other hand, as far as cooling is concerned, LT cold considers process cooling for industry and services and HT cold covers space cooling demand for all three sectors.

A.1.1.2. Electricity & Lighting

This section explains how the non-heat electricity demand data for Spain in 2015 has been obtained for the three sectors previously considered in the End-uses demand matrix. The overall electricity demand (FEC_{elec}) is taken from the Monthly hourly Load Profile from Spain available in [119].

This electricity demand has been compared with the FEC data for electricity (given in black) reported for Spain in the Eurostat Energy Balance, available in [120], to check that the two values reported by the two sources match. However, only the final energy consumption (FEC) is given by sectors, so it is assumed for electricity that the values of EUD and FEC are the same.

There is a difference between the two values of final electricity consumption (FEC_{elec}) which is related to distribution network losses, which must also be considered. Even considering the distribution losses, there is a relative difference of 3% which is considered not significant.

In this case it has been decided to take the total FEC_{elec} value provided by ENTSO-e in the time series of electricity demand as a reference. As the FEC values by sector is only reported by Eurostat and there is a relative difference of 3 % between the two sources, as mentioned above, the FEC values of each sector must be corrected so that the total FEC_{elec} is the one taken as a reference. For this purpose, the ratio of electricity consumed in each sector with respect to the total electricity consumed has been calculated. This ratio of electricity consumed is 32.8 %, 30.2 % and 31 % for industry, households, and services respectively. Considering these ratios constant and having the total energy consumed, the adjusted FEC_{elec} for each sector can be calculated. Table A.5 shows the data collected from Eurostat and Table A.6 shows the FEC_{elec} values adjusted.

	EUROSTAT [ktoe]		
	FEC	$FEC_{elec,sector}$	Ratio ($FEC_{elec,sector}$ / FEC_{elec}) [%][a]
Industry	18915	6539	32.8
Households	14876	6024	30.2
Services	10037	6191	31

[a] *Calculated value*

Table A.5: FEC values by sector extracted from [119]

	ENTSOE Hourly Profile [ktoe]		
	FEC_{elec}.	Ratio ($FEC_{elec,sector}$ / FEC_{elec}) [%]	FEC_{elec}.[a]
	21365		
Industry	-	32.8	7002
Households	-	30.2	6451
Services	-	31	6630

[a] *Calculated value*

Table A.6: Adjusted FEC values by sector with FEC electricity value from [120] as a reference

A part of the electricity is assumed to be a fixed demand, such as freezers in the residential and services sector, while another part of the electricity such as lighting demand is variable. Knowing the percentage of electricity used for lighting in each of the sectors, the electricity demand can be divided between lighting demand and other electricity demand. In the residential sector, 4.8% of the energy demand was spent on lighting in 2015 [121], which corresponds to 12% of the total electricity demand. For the industrial and services sectors, the same values as Italy in 2015 specified in [122] have been taken, assuming that Spain and Italy are similar countries in terms of climatology and that therefore the share of lighting demand is similar. Tables A.7 and A.8 report the electricity demands for each sector and divided into lighting demand and the rest of electricity demand.

	FEC_{elec} [ktoe]	% lighting	Lighting [ktoe]	Electricity (others) [ktoe]
Industry	7002	9	630	6372
Households	6451	12	765	5686
Services	6630	28	1856	4773

Table A.7: FEC_{elec} values by sector in Spain 2015

	Lighting [GWh]	Electricity (others) [GWh]
Industry	7329	74107
Households	8893	66130
Services	21589	55513

Table A.8: Electricity demand not related to heating by sector in 2015

A.1.1.3. Mobility

The annual passenger mobility demand for Spain in 2015 is estimated to be 418,901 million passenger kilometres (Mpkm) from Tables 1-6 of [123]. The annual demand for freight mobility is estimated to be 263,912 million tonnes kilometres (Mtkm) from Tables 11, 20 and 25 of [123] and Table 1.1.13 of [124]. For both passenger and freight mobility, due to the difficulty of finding mobility data at the international level, the national level has been defined as the boundary and only mobility that generates emissions within the national territory is considered, in a similar way to what has been done in the case of Belgium by Limpens [04]. Thus, all mobility that generates emissions outside the limits of Spanish territory has not been considered.

State organisations when reporting the GHG emissions of the country normally do not take into account the emissions generated by international transport, as is the case in Table 3 of [125] where 299712.29 thousand tonnes of CO_2 equivalent (Mt$CO_2-eq.$) are reported, while in other statistical organisations when reporting the total number of GHG emissions of the country they do specify the emissions generated by international mobility (maritime and air), as is the case in [126], with a total of 33812.29 kt CO_2-eq. The difference between the two emission results reported in the two sources is specifically the emissions generated by international maritime and air mobility (38.400 kt CO_2-eq) reported in Figure A.1.

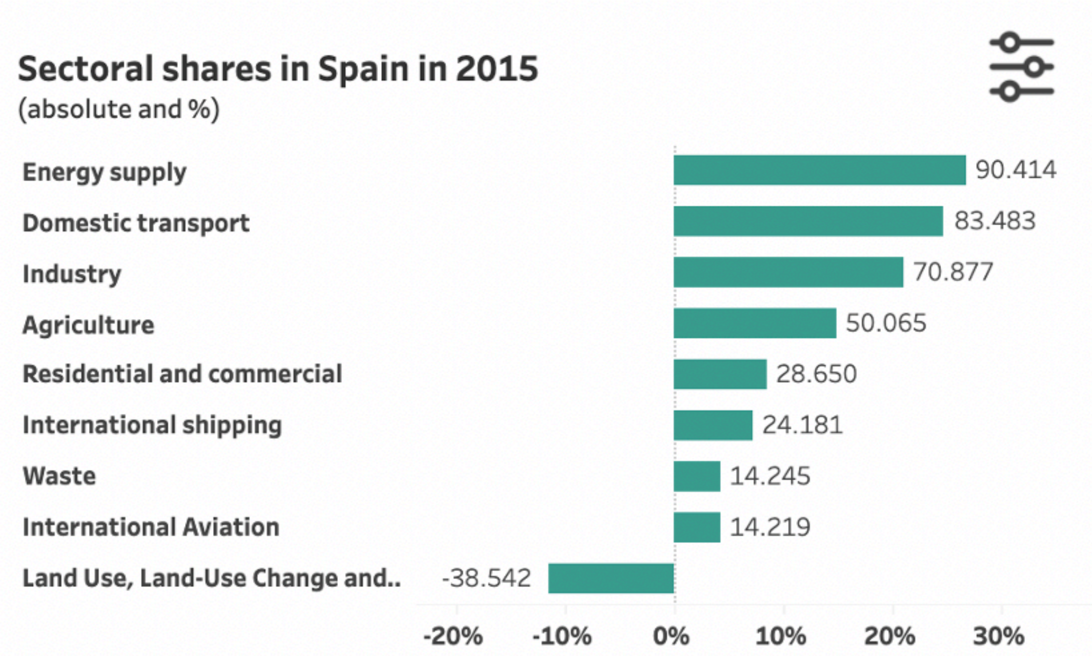

Figure A.1: Sectoral emissions shares in Spain 2015

Therefore, international passenger and freight demand outside Spanish territory is not quantified in the total demand.

Both total passenger and freight demand is divided into four modes of transport: road, rail, air and maritime and the scope of the Spanish territory includes mobility within the mainland, mobility between the mainland and the different islands (Balearic Islands & Canary Islands), mobility between the mainland and the cities of Ceuta and Melilla and inter-island mobility. Table A.9 shows the total interior demand for passenger and freight mobility classified by mode of transport.

	Units	Mode	Mainland and islands
Mobility passenger	[Mpkm]	Road	366092
		Train	26452
		Air	25392
		Maritime	965
		Total	**418901**
Mobility freight	[Mtkm]	Road	209386
		Train	10882
		Air[1]	63.835
		Maritime[2]	43580
		Total	**263912**

[1] *no data from private or regional airports have been considered.*
[2] *includes traffic with island provinces*

Table A.9: Total demand for passenger & freight mobility in Spain 2015. Abbreviations: Million passengers' kilometre [Mpkm], Million tonnes kilometre [Mtkm] [123,124]

A.1.2 Electricity production

In the case of electricity generation, electricity generation from the different technologies present in the Spanish electricity system has been used to validate the model. Table A.10 below shows the electricity generation imposed in the validation of the model for each of the generating technologies.

Elec prod [F_t]	[GWh]	Source
NUCLEAR	54755	[127]
CCGT[a]	35854	[127]
COAL US	52789	[127]
COAL IGCC[b]	0	[128]
PV	8236	[127]
Wiind onshore	48109	[127]
Wind offshore	0	[127]
Hydroriver[c]	8234	[127]
Hydrodam[c]	19823	[129]
Pump hydro storage[c]	2762	[129]
Geothermal	0	
Wave	0.25	[130]
Parabolic Trough	4904.75	[131,132,133]
Solar Tower	178	[131,132,133]
Stirling Dish	2.25	[131,132,133]
Biomass	3818	[134]
Waste	1766	[134]
Biogas	1174	[134]
CHP	25108	[127]

[a] CCGT + Fuel/gas plants. Gas turbines and ICE are used in islands with little loads. These machines can vary a lot but have a lower efficiency. The overall capacity is 0.918 GW of CCGT and 1.6 GW of ICE, GT and steam turbine. As it represents a small fraction (compared to the rest of the techno implemented in Spain), fuel & gas is assimilated as CCGT.
[b] IGGC Plant in Puertollano - CLOSED in 2015
[c] the percentages for each hydro technology from ENTSOE 2016 have been applied and then these shares have been applied to the Monthly Domestic Values 2015-2019 data.

Table A.10: Electricity generation by different technologies in 2015 for the Spanish electricity system.

A.1.3. Heating & Cooling & CHP Technologies

For the calculation of the different shares of each of the technologies used for industrial, centralised, and decentralised heat generation, we have used the data obtained by Heat Roadmap Europe in [118]. These different shares for each technology (CHP, boilers, solar thermal, etc.) could not be obtained directly from the source consulted, but different calculations had to be carried out to obtain the desired results. First, it has started from the percentage distribution of all the energy demand for Heating & Cooling in Spain by end use type (see Figure A.2) and from the same distribution by energy carriers and by end use type but classified according to the different end-use sectors (see Figure A.3).

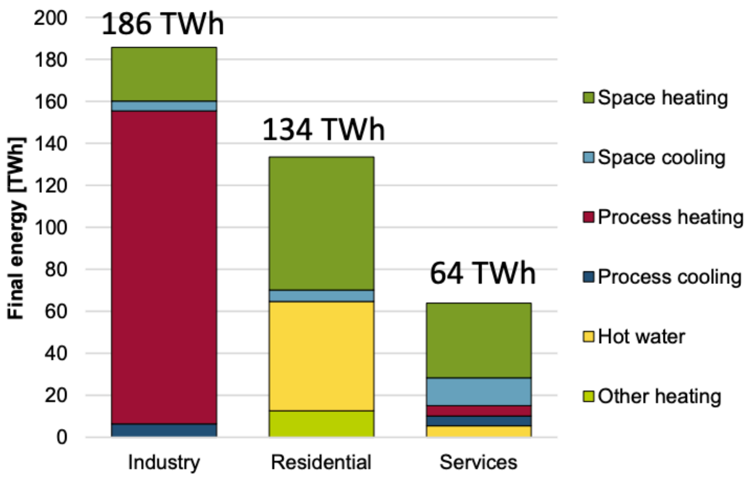

Figure A.2: Energy demand for Heating and Cooling by sectors and end-use types in Spain 2015 [118]

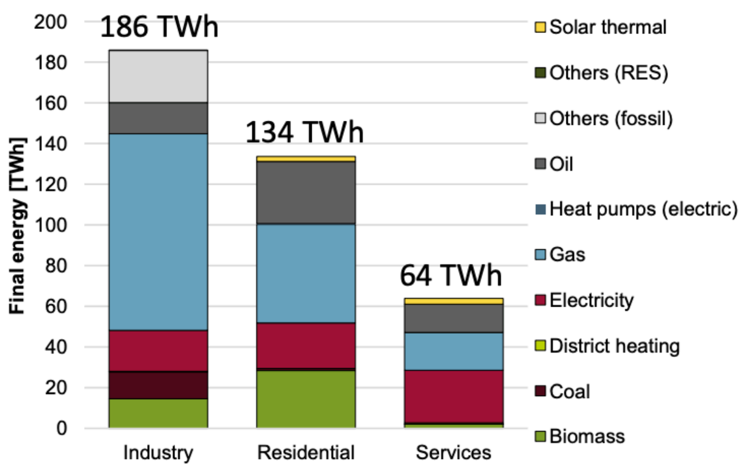

Figure A.3: Energy demand for Heating and Cooling by sectors and energy carriers in Spain 2015 [118]

As can be seen in Figure A.3, the share of District Heating (DHN) and Heat Pumps can be considered negligible as their contribution is almost 0. Therefore, for industrial heat generation (IND) the industrial sector data will be used, while the residential and service sectors will be counted for decentralised heat generation. Below is an explanation of how these data have been collected for both industrial heat generation and decentralized heat generation (DEC), taking in consideration that in Spain the penetration of DHN is not yet significant and therefore it is not considered in the validation of the model.

A.1.3.1. Industrial Technologies

As mentioned above, the objective is to know how much of each energy carrier (e.g., gas) is used for each end-use type (e.g., process heating). As these values are not published directly in the Heat Roadmap Spain, they have been extracted from Figures A.4 and A.5 shown below.

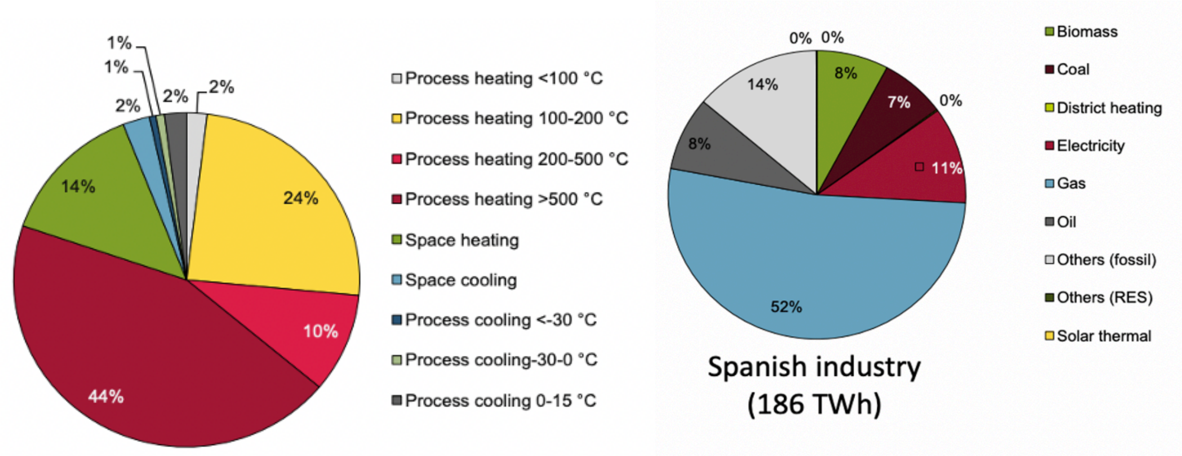

Figure A.4: Energy demand for Spanish Industry by energy carriers & EUT in % [118]

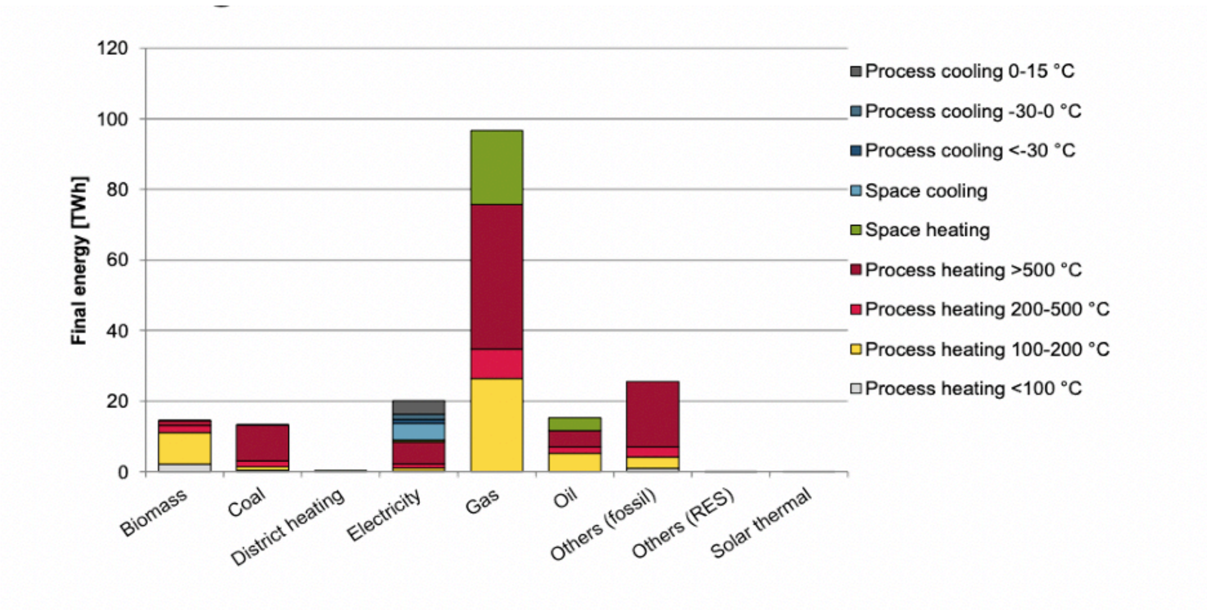

Figure A.5: Energy demand for Spanish Industry by energy carriers & EUT in 2015 [118]

As can be seen in Figure A.5, the amount of energy of each of the energy carriers destined for each of the EUTs is shown. In addition, knowing the percentages with respect to the total energy demand of the industrial sector shown in Figure A.4, it is possible to calculate the different TWh used by each energy carrier, which are reported in Table A.11.

INDUSTRY (186TWh)	**%**	**TWh**	Pr.cooling 4 7.44	Pr.heating 8 148.8	S.heating 14 26.04	S.cooling 2 3.72	**Available for heating** [a]
Biomass	8	14,88	0	14.88	0	0	**14.88**
Coal	7	13,02	0	13.02	0	0	**13.02**
Others (fossil)[b]	14	26,04	0	26.04	0	0	**26.04**
Oil	8	14,88	0	10.56	4.32	0	**10.56**
Electricity	11	20,46	7.44	9.3	0	3.72	**9.3**
Gas	52	96,72	0	75	21.72	0	**75**

[a] *own calculation*
[b] *others fossil → waste*

Table A.11: Energy available for High Heat Temperature in the industrial sector by energy carrier [118]

In the model, the industrial sector is identified with the Heat High Temperature end-use and therefore, to calculate how much energy from each of the energy carriers is destined for this EUT, it has been considered:

- The demand for industrial cooling is supplied entirely by electricity.
- The total demand of the industrial sector (IND) in the model will be the respective one for Process Heating.

To determine how much gas, wood, waste, oil, and coal is used in boilers and how much in CHP plants to supply this demand, the different percentages of fuel used in CHP plants in Spain have been used, available in [95]. With these percentages it can be known how much of each energy carrier is used by CHP plants and therefore the rest is used as fuel in boilers. Thus, knowing the energy demanded by each energy carrier with respect to the total available heating energy and the percentages of fuel used in CHP plants, it is possible to calculate the different shares of each technology for the industrial sector.

	Share Heat [%]
Boiler Wood	10 %
Boiler Coal	8.8 %
Boiler Oil	7.1 %
Boiler Waste	11 %
Boiler Gas	3.3 %
Direct Elec.	6.3 %
CHP Waste	6.5 %
CHP Wood	0 %
CHP Gas	47.1 %

Table A.12: Yearly shares of industrial high temperature heat & CHP technologies for the Spanish energy system, in 2015.

A.1.3.2. Decentralised Technologies

As in the industrial sector, for the service and residential sectors, the objective is to know the final demand of each energy carrier for each EUD type. As mentioned above, the percentage of District Heating in Spain is practically zero, and therefore its contribution is not significant in the Spanish model. Therefore, the demand of the residential and service sectors is assimilated to decentralized systems (DEC). In this case, in a similarly way as for the industrial sector, the energy demand matrix by carrier and EUD in the service sector has been calculated first, starting from Figures A.6 and A.7.

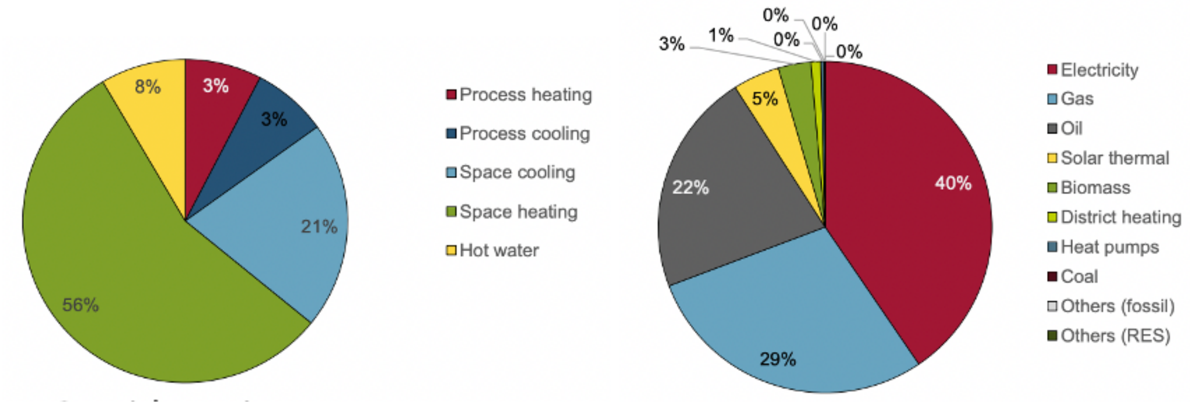

Figure A.6: Energy demand for Spanish Services sector by energy carriers & EUT in % [118]

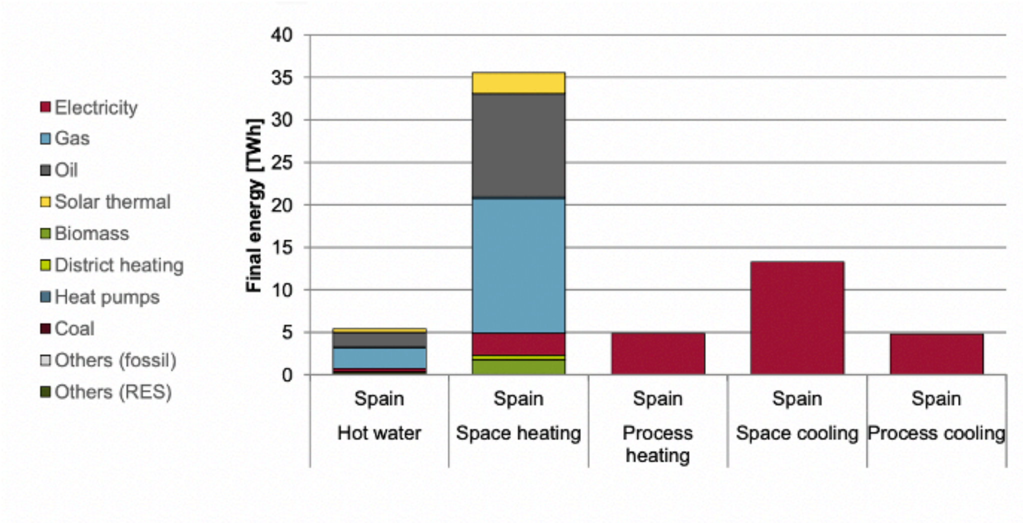

Figure A.7: Energy demand for Spanish Services sector by energy carriers & EUT in 2015 [118]

Table A.13 shows the demand of each of the energy carriers for each type of EUT. For instance, as can be seen in Figure A.7, all the energy demand provided by biomass (in green) has been destined to supply space heating demand.

SERVICES			Pr. cooling	Pr. heating	S.heating	S.cooling	H.water	**Available for heating[a] [TWh]**
(64 TWh)	**%**		3	3	56	21	8	
		TWh	1.92	1.92	35.84	13.44	5.12	
D.heating	1	0.64	0	0	0.64	0	0	**0.64**
Biomass	3	1.92	0	0	1.92	0	0	**1.92**
Solar thermal	5	3.2	0	0	2.9	0	0.3	**3.2**
Oil	22	14.08	0	0	12	0	2.08	**14.08**
Electricity	4	25.6	4.8	4.8	2.38	13.44	0.18	**2.56**
Gas	29	18.56	0	0	16	0	2.56	**18.56**

[a]*Own calculation*

Table A.13: Energy available for Heat Low Temperature in the services sector by energy carrier [118]

In this case, in contrast to the case of the industrial sector, for the calculation of the available demand for heating has been considered:

- The demand for services cooling is supplied entirely by electricity.
- The total demand of the Service sector in the model will be the respective one for Space Heating and Hot Water.

Analogously, in the case of the residential sector, the above-mentioned matrix has been calculated based on Figure A.8.

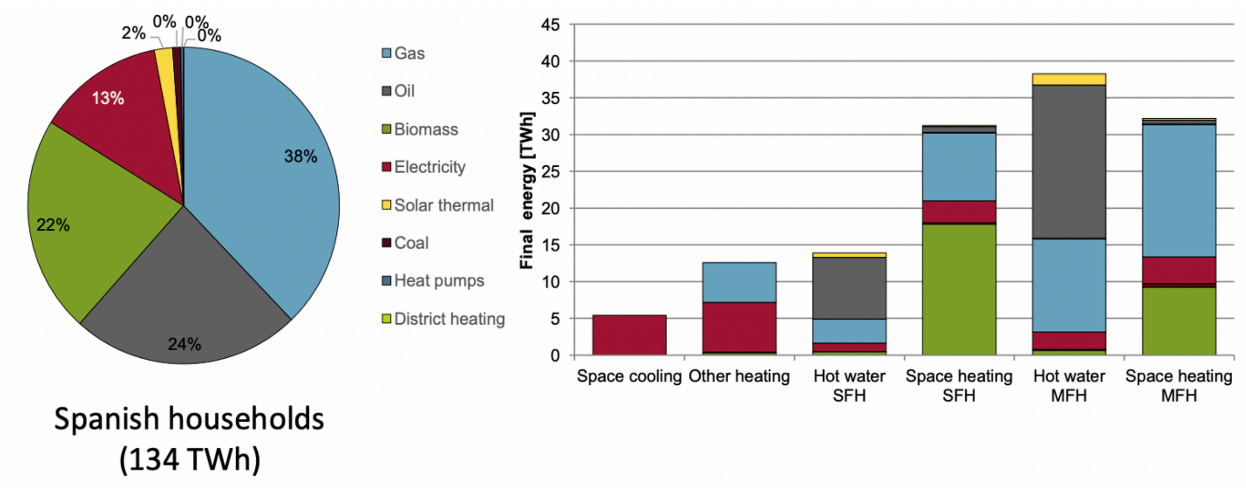

Figure A.8: Energy demand for Spanish Households sector by energy carriers & EUT in 2015 [118]

In this case, as shown in Figure A.8, the total demand for Hot Water and Space Heating is divided into SFH (Single Familiar House) and MFH (Multi Familiar House). For the calculation of the energy carriers/EUD type matrix these two types of residences have been merged. In addition, the EUD called "other heating" has been classified as Space Heating.

HOUSEHOLDS (134 TWh)	**%**		**Total space cooling**	**Total hot water**	**Total S. heating**	**Available for heating**[a] **[TWh]**
		TWh	5	53.08	75.92	
Oil	24	32.16	0	29.7	2.46	**32.16**
Biomass	22	29.48	0	1.3	28.18	**29.48**
Solar thermal	2	2.68	0	2.68	0	**2.68**
Electricity	13	17.42	5	3.1	9.32	**12.42**
Coal	1	1.34	0	0	1.34	**1.34**
Gas	38	50.92	0	16.3	34.62	**50.92**

[a]*own calculation*

Table A.14: Energy available for Heat Low Temperature in the Households sector by energy carrier [118]

In this case, as in the services sector, for the calculation of the available demand for heating has been considered:

- The demand for households cooling is supplied entirely by electricity.
- The total demand of the Households sector in the model will be the respective one for total Space Heating and total Hot Water.

As mentioned above, the Services and Residential sectors are only considered for decentralized systems due to the almost null percentage of district heating in Spain. Table A.15 shows the total demand available for decentralized heat.

	Available for heating [TWh]		
	SERVICES	HOUSEHOLDS	TOTAL[a]
District heating	0.64	0	**0**[b]
Biomass	1.92	29.48	**31.4**
Solar thermal	3.2	2.68	**5.88**
Oil	14.08	32.16	**46.24**
Electricity	2.56	12.42	**14.98**
Gas	18.56	50.92	**69.48**
Coal	0	1.34	**0**[b]

[a]*own calculation*
[b]*considered null*

Table A.15: Energy available for Decentralised Low Temperature Heat [118]

To calculate the different shares of the technologies that will supply the total heat demand, the following assumptions have been made:

- District Heating is considered insignificant for the model due to its low share of the total (less than 1%).
- CHP plants as a source of heat generation are not considered because CHPs normally involve a DHN, since they produce a large amount of heat. All this amount of heat is too much for the case of a decentralized system with few buildings. Therefore, only the use of boilers in DEC systems is assumed.
- The share of coal-fired boilers is zero since there are usually no coal-fired boilers in DEC systems, in addition to the low percentage it represents (0.7%).
- The heat demand supplied by electricity is not provided by heat pumps since their use is negligible as can be seen in Figures A.6 and A.8 but comes directly from the grid.
- For gas, wood, and oil, it is considered that they are used only in boilers to provide the demanded heat.

Table A.16 shows the different shares of each of the technologies in the decentralized low temperature heat & CHP technologies.

	Share Heat [%]
HP	0 %
Thermal HP	0 %
CHP NG	0 %
CHP Oil	0 %
FC NG	0 %
FC H_2	0 %
Boiler NG	41.4 %
Boiler Wood	18.7 %
Boiler Oil	27.5 %
Direct Elec.	8.9 %
Solar Thermal	3.5 %

Table A.16: Yearly shares of decentralised low temperature heat & CHP technologies for the Spanish energy system, in 2015 [118]

The results of the different energy carrier matrices by EUD type of the different sectors can be found in "2015 heating and cooling profiles for all EU28 member states as spreadsheets" in [135].

A.1.4. Mobility shares: Passenger & Freight; Public & Private

Based on the total demand for passenger and freight mobility described in Section A.1.1 of this Appendix, the different shares of each type of transport mode have been calculated. In the case of passenger mobility, the modal split data for land-based modes provided by Eurostat in [136] (See Table 2.3.3) have been used. Table A.17 shows these shares:

	Share [%] in pkm
Passanger Cars	79.9
Buses & Coaches	11.7
Tram & Metro	1.8
Railways	6.6

Table A.17: Modal split of Passenger Transport on Land 2015. Abbreviations: passenger-kilometre [pkm] [136]

Using these shares and adding the passenger mobility demand for non-land-based modes (air & maritime demand), the modal split of passenger mobility for each type of transport can be recalculated. Table A.18 shows in detail the new modal split of passenger mobility considering all the different modes of transport.

		Total Mpkm	**Mode**	**Share [%]**	**Mpkm**	**New Share [%]**
			Passanger Cars	79.9	313643	**74.87**
Road	366092	392544	Buses & Coaches	11.7	45928	**10.96**
			Tram & Metro	1.8	7066	**1.69**
Train	26452		Railways	6.6	25908	**6.18**
Air	25392	25392	Passanger air	-	25392	**6.06**
Maritime	965	965	Passanger boat	-	965	**0.23**

Table A.18: Modal split of Passenger Transport 2015 in Spain. Abbreviations: Million passenger-kilometre [Mpkm] [123,124,136]

To distinguish which percentage of all passenger mobility corresponds to private and which to public mobility, several assumptions have been made. It has been assumed that for both air and maritime mobility private trips are not significant compared to public passenger demand. Therefore, all air and maritime mobility is public.

Considering that Railways, Buses & Coaches and Tram & Metro are all public, only passenger cars are attributed to private mobility. Therefore Table A.19 reports the percentage split between public and private passenger mobility in Spain in 2015.

	Share [%]
Public mobility	25.1
Private mobility	74.9

Table A.19: Shares of public & private mobility in Spain

On the other hand, in the case of freight mobility, the modal split data for land-based modes also provided by Eurostat in [136] (See Table 2.2.3) have been used. Table A.20 shows these shares:

	Share [%] in pkm
Road	89.3
Rail	5.1
Pipelines	5.6

Table A.20: Modal split of Freight Transport on Land 2015. Abbreviations: passenger-kilometre [pkm] [136]

Using these shares and adding the freight mobility demand for non-land-based modes (air & maritime demand), the modal split of freight mobility for each type of transport can be recalculated. Table A.21 shows in detail the new modal split of freight mobility considering all the different modes of transport.

		Total pkm	Mode	Share [%]	Mpkm	New share [%]
Road	209386		Freight road	89.3	196699	**74.53**
Pipelines	-	220268.01	Freight pipelines	5.1	11234	**4.26**
Train	10882.01		Freight Rail	5.6	12335	**4.67**
Air	63.835	63.835	Freight Air	-	64	**0.02**
Maritime	43580	43580	Freight Boat	-	43580	**16.51**

Table A.21: Modal split of Freight Transport in Spain 2015. Abbreviations: passenger-kilometre [pkm] [123,124,136]

Due to the low percentage attributed to air freight mobility within the scope of the Spanish territory (0.02%), its contribution to the modal split has been assumed negligible. Furthermore, the share of freight transport by pipeline is not considered in the modelling in the EnergyScope Spanish model because it is not implemented. Thus, the percentages of each mode of transport in freight mobility are as follows and are shown in Table A.22:

	Share [%]
$\%_{\text{Fr, Road}}$	74.5
$\%_{\text{Fr, Rail}}$	4.7
$\%_{\text{Fr, Boat}}$	16.5

Table A.22: Shares freight mobility in Spain 2015 [123,124,07]

A.1.5. Relative annual shares of Public & Private technologies.

For private passenger mobility, the distribution of the different vehicle models available in the Spanish Energyscope model has been estimated based on the actual number of each type of vehicle in the Spanish vehicle fleet in 2015. It is assumed that each type of car does the same distance over the year. Thus, the car distribution allows to know at the same time the distribution in passenger-km. According to the data provided by DGT [86], we can know the number of each type of passenger vehicle (fuelled by gasoline, diesel, or fuel alternative) and motorbikes. For the case of vehicles using alternative fuel, the repartition has been made according to the data reported by EAFO in [137]**.** In the Spanish case, the only types of vehicles using alternative fuel are Plug in Hybrid Vehicles (PHEV), Battery Electric Vehicles (BEV) and Liquified Petroleum Gas (LPG), although their penetration and contribution to the vehicle fleet is very low (0.05%). Hybrid electric vehicles (HEV) and Hydrogen Cars (H2) are not present in the vehicle fleet in 2015. In addition, there is a significant presence of motorbikes, representing a 12% share of the total. Tables A.23 and A.24 shows the annual shares of each type of private vehicle in Spain in 2015.

	Share [%]
Gasoline Cars	38.05
Gas-oil Cars	49.79
Fuel Alternative Cars	0.05
Motorcycles	12.11

Table A.23: Shares of the different types of private transport in Spain 2015 according to [86]

	Share Mpkm [%]
Gasoline car	38.05
Diesel car	49.79
NG car	0
HEV	0
PHEV	0.01
BEV	0.02
Fuel Cell car	0
LPG	0.02
H2	0
Motorcycles	12.11

Table A.24: Yearly Shares of private vehicles technologies in Spain 2015 [86,137]

For public mobility, the results reported in Tables A.25 and A.26 have been obtained by considering the different shares of passenger mobility calculated above in Section A.4 of the Appendix in Table 6. Knowing also that the total share of public passenger mobility is 25.1 %, the shares of each type of public passenger transport can be recalculated. In 2015 buses and coaches are mostly used (43.63%), followed by trains and metro (24.61%), airplanes (24.12%), tram and trolley bus (6.7%) and passenger ships (0.9%).

	Share Mpkm [%]
Tram and Trolley Bus	6.71
Train	24.61
Boat	0.92
Air planes	24.12
Buses & Coaches	43.63

Table A.25: Yearly shares of public modes of transport in Spain 2015 [123,124,136]

Secondly, to fourthly differentiate all the available technologies for public mobility on buses & coaches, the EAFO observatory has been consulted [138]. In the same way as for private passenger mobility, the distribution of percentages between the different categories of buses & coaches has been done by the number of each of the vehicle types in the whole fleet assuming that each of them performs the same number of kilometres over the year. In this way, the percentage distribution of each type of vehicle in reference to the total public mobility can be quickly calculated.

	Share Mpkm [%]
Diesel Bus and Coach	42.56
Diesel PHEV Bus and Coach	0
NG Bus and Coach	1.03
FC Bus and Coach	0
BEV Bus ans Coach	0.04

Table A.26: Yearly shares of Buses & Coaches in Spain 2015 [138]

Table A.27 shows the summary of the percentage share of each of the technologies within public passenger mobility in Spain in 2015.

	Share Mpkm [%]
Tram and Trolley Bus	6.71
Diesel Bus and Coach	42.56
Diesel PHEV Bus and Coach	0
NG Bus and Coach	1.03
FC Bus and Coach	0
BEV Bus and Coach	0.04
Train	24.61
Boat	0.92
Air planes	24.12

Table A.27: Yearly shares of public mobility technologies for the Spanish system in Spain 2015 [123,124,136,09]

In this case, passenger transport technologies using ships and aircraft have been added in the Spanish Energyscope model, as opposed to the model used to simulate Belgium.

A.1.6. Other parameters

This section details various values that have been modified to perform the model validation in 2015 in an optimal way. In particular, the following are detailed: (i) efficiencies of some energy conversion technologies of electricity, heat, and transport sectors; (ii) consumption of biofuels; (iii) parameters of added resources; (iv) operational emission factors of different resources; parameters of added technologies.
To begin with, the efficiencies that have been modified for technologies in the power generation sector, the heating sector and the transport sector are detailed in Table A.28.

Sector	Technology	Efficiency [%]	Efficiency [Kwh/pkm or tkm]	Source
Electricity Generation	CCGT	58		[139]
	COAL_US	36		[140]
	NUCLEAR	33		[141]
	BIOMASS	50		
Heating	IND_BOILER_GAS	83		[118]
	IND_BOILER_WOOD	85		[118]
	IND_BOILER_OIL	82		[118]
	DEC_BOILER_GAS	82.4		[118]
	DEC_BOILER_WOOD	70		[118]
	DEC_BOILER_OIL	75		[142]
	IND_COGEN_GAS, ELEC.[a]	0.765		[145]
	IND_COGEN_GAS, NG[a]	2.743		[145]
	IND_COGEN_WASTE, ELEC.[a]	0.667		[145]
	IND_COGEN_WASTE, WASTE[a]	2.22		[145]
Transport	CAR_GASOLINE	-	0.481	[143,144,146]
	CAR_DIESEL	-	0.426	[143,144,146]
	TRUCK_DIESEL	-	0.745	[144,147]

[a] These values come from calculations made from the percentages of use of each fuel in CHP plants in Spain in 2015.

Resource						
Kerosene	**Emision factor** [kgCO_2/TJ]	**Conversion factor** [kgCO_2/GWh]				**gwp op** [kt CO_2/GWh]
	71500 [148]	257400.7				**0.257**
Kerosene	**Specific energy** [KWh/Kg]	**Price** [€/l]	**Density** [kg/l]	[KWh/€]	[€/KWh]	**Cop** [M€/GWh]
	11.9 [149]	0.47 [150]	0.804 [149]	20.357	0.049	**0.049**

Table A.28: Modified efficiencies of the different conversion technologies by sector in 2015

These efficiencies have been modified because, based on 2030 efficiency data, to optimally model the model in the year 2015, these efficiencies must be in line with that year, as the efficiencies are usually lower compared to 2030.
To continue, the consumption of biofuels for the year 2015 is specified as follows:

- Bioethanol consumption is set at 192 ktoe and biodiesel consumption at 788 ktoe according to [120].

To continue, as discussed in Section 2.1.2, different technologies and resources have been added to the model. Table A.29 and A.30 shows the different parameters that define these technologies.

Table A.29: Parameters of the resource added in the model.

Efficiencies	Consum [l/100km]	Conversion "[9,61KWh =1l gasoline]"	nº passengers	[KWh/100km x nº]	[Kwh/pkm]
MOTORCYCLE	4.4 [151]	9.61 [144]	1	42.28	**0.422**
PLANES	3.7 [152]	10.31 [144]	-	38.15	**0.381**

Table A.30: Parameters of the technologies added in the model.

The BOAT_PASS DIESEL and BOAT_PASS NG technologies have been added with the same parameters as the same technologies for freight, already defined earlier in the Jeroen and Jean Louis model [75]. Finally, in Table A.31 below, the operational CO_2 emission factors for the different resources, extracted from [99], are specified.

Resource	**Combustion** [kg CO_2-eq / Mwh fuel]
Gasoline /Bio-gasoline	0.25
Diesel / Bio-diesel	0.27
Light Fuel Oil	0.28
NG	0.2
Waste	0.26
Uranium	0
Coal	0.34
Biomass	0
Wood	0
Electricity	0

Table A.31: GHG emissions for different resources. The emissions are given for the impact of the resources **Combustion** only. Biomass and wood are resources assumed sustainable.

A.2 Data in the Spanish Energyscope model in 2030

This section of the appendix provides details:

(i) the end-use data for the different sectors in 2030, used in the *Spanish Energyscope* model.

(ii) The different parameters characterising the conversion technologies added in the *Spanish Energyscope model*, already mentioned in Section 2.1.2 of the work.

(iii) For each of the scenarios developed, it is specified which data have been modified. Some of the modified data are e.g., among others:

- Maximum and minimum capacities of electricity generation technologies.
- $f_{min,\%}$ and $f_{max,\%}$ for energy conversion technologies in the heating sector
- $f_{min,\%}$ and $f_{max,\%}$for energy conversion technologies in the transport sector

All data that do not appear in the following tables, it is assumed that the same values have been used as those used in the work done by Jeroen & Jean Louis for the Spanish case in **[75].**

A.2.1. Energy Demand

2030

The different EUD data for the households, services, and industry sectors in the Spanish energy system in 2030 have been extracted directly from the work done by Jeroen and Jean Louis in their work in [75]. Table A.32 below summarises the different end-use values used for the whole analysis of the different scenarios developed with the *Spanish Energyscope* model in 2030.

	Units	Households	Services	Industry	Transportation
Electricity (other)	[GWh]	715	863	1581	0
Lighting	[GWh]	44561	53764	98469	0
Heat High T	[GWh]	0	0	91759	0
Heat Low T (SH)	[GWh]	93158	70520	23866	0
Heat Low T (HW)	[GWh]	23812	15808	6183	0
Cold Process	[GWh]	0	13000	15000	0
Cold Space	[GWh]	16837	41163	14000	0
Mobility passanger	[Mpkm]	0	0	0	568000[a]
Mobility freight	[Mtkm]	0	0	0	282000[b]

[a] Unlike the Jeroen & Jean Louis data, this value is taken from the European Commission's Reference Scenario in [98]. The value is found by subtracting the total value of international aviation demand from the 2030 Gpkm value, which as discussed in Section A.1 is not considered in the study.
[b] Unlike the Jeroen & Jean Louis data, this value has been extracted from the European Commission's Reference Scenario in [98].

Table A.32: End-uses demand in Spain ($endUses_{year}$) in 2030

A.2.2. Parameters of new technologies

To continue, the different parameters defining the energy conversion technologies added to the model are explained in detail, compared to previous work.
In this case, the technologies added are technologies related to passenger mobility. These technologies are grouped into two categories: public and private. From the literature, mobility data cannot be passed directly into the model. Mobility data are usually given per vehicle, such as vehicle cost, average vehicle occupancy or maintenance cost. These data are summarised in Table A.33 below.

Vehicle type	Veh. Cost [k€2015/veh]	Maintenance [k€/veh/y]	Occupancy [pass/veh]	Av. Distance [1000km/y]	Av.speed [km/h]	Lifetime [years]	gwp_{constr} [Kg CO_2-eq /veh]
Motorcycle	7.5[a]	1[b]	1.05[c]	2.9[d]	40	10	326.2[e]
Planes	85916[f]	3600[g]	114.6[h]	2550[i]	850[j]	30	-

[a] the cost of a motorbike is assumed to be 7500 €, according to [153].
[b] the maintenance cost of a motorbike is assumed to be 1000 € per year, in accordance with [154].
[c] the average occupancy of a motorbike is assumed to be 1.05 passengers, according to [155].
[d] the average distance of a motorbike is assumed to be 2900 km/year, according to [156].
[e] the value is obtained from [157]
[f] the cost of a plane is assumed to be 85916 k€, according to [158].
[g] the maintenance cost of a plane is assumed to be 3600 k€ per year, in accordance with [159].
[h] the average occupancy of a plane is assumed to be 114.6 passengers, according to [160].
[I] average of 3000 h/a * 850 km/h = 2550000 thousand km/year
[j] the average speed of a plane is assumed to be 850 km/h, according to [161].

Table A.33: Specific investment cost calculation based on vehicle investment data, in 2030.

From the data in Table A.34 the specific parameters for the model are calculated. The investment cost (C_{inv}) is calculated with the vehicle cost, average occupancy, and average speed (Eq. A.1). The capacity factor (C_p) is calculated by the ratio between the annual distance travelled and the average speed (Eq.A.2). The maintenance cost (C_{maint}) is calculated with the maintenance cost, average occupancy, and average speed (Eq. A.3). Below are the equations that allow the calculations of the parameters and Table A., which summarises this information for each technology.

$$C_{inv}(i) = \frac{vehicle\ cost\ (i)}{Occupancy\ (i) * average\ speed\ (i)} \qquad \forall i\ \in techofeut \qquad (Eq. A.1)$$

$$C_p(i) = \frac{average\ distance(i)}{average\ speed\ (i) * 8760} \qquad \forall i\ \in techofeut \qquad (Eq. A.2)$$

$$C_{maint}(i) = \frac{maintenante\ cost\ (i)}{Occupancy\ (i) * average\ speed\ (i)} \qquad \forall i\ \in techofeut \qquad (Eq. A.3)$$

Vehicle type	Cinv [€/pkm/h]	Cmaint [€/pkm/h]	gwp constr [Kg CO_2-eq /pkm/h]	Cp [%]
Motorcycle	178.6	23.8	326.2	0.8
Planes	881.9	36.9	-	34.2

Table A.34: Passenger mobility financial information, in 2030 (based on Table A.33)

A.2.3. Scenario constraints

In this section, for each of the scenarios developed, it is specified which data have been modified.

A.2.3.1. ESP30_S1

This section explains and justifies how the ESP30_S1 scenario has been developed and what data has been introduced into the model for its performance.

In the case of the ESP30_S1 scenario, the model tries to represent an energy system as in 2015 but adapted to the higher energy demand in 2030. Therefore, no changes are made to the f_{min} and f_{max} parameters of the different conversion technologies in the case of the power generation sector. What is done to model this scenario is to set the $f_{min,\%}$ and $f_{max,\%}$ parameters of all technologies used in the 2015 model validation. In this way, the Spanish energy system in 2030 uses the same shares as in 2015 (same energy system) and adapts it to the new energy demand in 2030. It is worth mentioning that in this case, the efficiencies of all conversion technologies are those already used by Jeroen and Jean Louis in [75].

The values of $f_{min,\%}$ and $f_{max,\%}$ for the heating and mobility sectors are the same as in 2015 and can be found in Appendix A, Sections A.3, A.4 and A.5. In contrast, the values of $f_{min,\%}$ and $f_{max,\%}$ for the power generation sector can be found in Table A.35 below.

Assumptions			
	Subject	fmin_p	fmax_p
		[%]	
Power	Nuclear	23.51	
	CCGT	15.39	
	Coal_US	22.67	
	Coal_IGGC	0	
	PV	3.54	
	PT_Power_Block	2.11	
	ST_Power_Block	0.08	
	Stirling Dish	0.001	
	Wind onshore	20.66	
	Hydro Dam	8.51	
	Hydro River	3.54	
	Wave	0.0001	

Table A.35: $f_{min,\%}$ and $f_{max,\%}$ of the different electricity generation technologies for the ESP30_S1 scenario in 2030.

A.2.3.1. ESP30_TEND

In this section, it is specified which data have been modified for the case of the ESP30_TEND model in the power generation, heating, and mobility sectors. In the different tables, the sources and justifications for all data and assumptions made are specified. In this case, these data are summarised in Tables A.36, A.37, A.38.

	Assumptions					
	Subject	fmin_p	fmax_p	fmin	fmax	Source/Comments
		[%]		[GW]		
Power	Nuclear			7.362	7.362	[21]
	CCGT			27.286	27.286	[21]
	Coal_US			2.165	2.165	[21]
	Coal_IGGC			0	0	[128]
	PV			4.664[a]	18.921	[21]
	PT_Power_Block			2.2225	2.2225	[131,132,133]
	ST_Power_Block			0.051	0.051	[131,132,133]
	Stirling Dish			0.002	0.002	[131,132,133]
	Wind onshore			23.020[a]	38.033	[21]
	Hydro Dam			16.261[a]	16.261	Same as 2015
	Hydro River			1.167[a]	1.167	Same as 2015
	Tidal Stream			0	0.07	[75]
	Tidal Range			0	0.07	[75]
	Wave			0.0003	0.0003	[130]
	Biogas [GWh]			10400	10400	[106]
	Geothermal			0	0	

[a] Same as 2015

Table A.36: Modifications in the f_{min} and f_{max} in the power generation sector for the ESP30_TEND scenario in 2030.

	Subject	Assumptions fmin_p [%]	fmax_p [%]	fmin [GW]	fmax [GW]	Source/Comments
Heating	Ind. Boiler Gas	0	30[a]			[162]
	Ind. Boiler Waste	0	20[b]			[162]
	Ind. Boiler Wood	10[c]	100			[162]
	Ind. Boiler Coal	0	9[d]			[162]
	Dhn HP Elec.	0	30			[108]
	Dec. Boiler Gas	0	42[e]			[162]
	Dec. Boiler Oil	15[f]	28.57[f]			[162]
	Dec. Boiler Wood	18.69[g]	100			[162]
	Dec. HP Elec.	0	30			[108]

[a] from 2015 to 2030, there will be a shift from natural gas to biomass, therefore a maximum of 30 % has been set as a logical maximum.
[b] from 2015 to 2030, there will be a shift from waste to biomass, therefore a maximum of 20 % has been set as a logical maximum.
[c] from 2015 to 2030, there is a shift from natural gas and coal to biomass, so at a minimum there should be the same share (10%) as there was in 2015.
[d] from 2015 to 2030, there is a shift from natural gas and coal to biomass, so at most there should be the same share (9%) as there was in 2015.
[e] from 2015 to 2030, there is a shift from natural gas and coal to biomass, so at most there should be the same share (42%) as there was in 2015.
[f] from 2015 to 2030, there is a shift from natural gas, oil and coal to biomass, so at most there should be the same share (28.57%) as there was in 2015 and at least 15% has been set as a logical minimum.
[g] from 2015 to 2030, there is a shift from natural gas and coal to biomass, so at a minimum there should be the same share (18.69%) as there was in 2015.

Table A.37: Modifications in the $f_{min,\%}$ and $f_{max,\%}$ in the heating sector for the ESP30_TEND scenario in 2030.

	Subject	Assumptions fmin_p [%]	fmax_p [%]	fmin [GW]	fmax [GW]	Source/Comments
Mobility	Tramway Trolley	0	30			[75]
	Bus Coach NG	1.03[a]	5[a]			
	Bus Coach Fuel Cell	0.25	0.5			[165]
	Train Public	25	50			[75]
	Boat Pass. Diesel	0	1			
	Boat Pass. NG	0	0,5[b]			
	Planes	24.4	25			[163]
	Car gasoline	48.93	48.93			[109]
	Car diesel	30.68	30.68			[109]
	Motorcycle	12.07	12.07			[110]
	Car NG	3.32	3.32			[109]
	CAR_HEV CAR_BEV	5	5			[111]
	Boat Freight NG	0	5[c]			
	Truck Fuel Cell	0	0.5			[164]
	Truck NG	0	4			[164]

[a] as a minimum value, the same share has been set as in 2015. As a maximum value a 5 % is set.
[b] as a maximum value a 0.5 % is set
[c] a maximum value of 5% has been set as a logical figure, since in Spain the use of NG in the transport of goods by sea is not at all widespread.

Table A.38: Modifications in the $f_{min,\%}$ and $f_{max,\%}$ in the mobility sector for the ESP30_TEND scenario in 2030.

A.2.3.1. ESP30_OBJ

In this section, it is specified which data have been modified for the case of the ESP30_OBJ model in the power generation, heating, and mobility sectors. In the different tables, the sources and justifications for all data and assumptions made are specified. In this case, these data are summarised in Tables A.39, A.40, A.41.

	Subject	fmin_p	fmax_p	fmin	fmax	Source/Comments
		Assumptions				
		[%]		[GW]		
Power	Nuclear			3.181	3.181	[21]
	CCGT			27.286	27.286	[21]
	Coal_US			0	0	[21]
	Coal_IGGC			0	0	[128]
	PV			4.664[b]	39.181	[21]
	PT_Power_Block			7.016	7.016[a]	[21]
	ST_Power_Block			0.295	0.295[a]	[21]
	Stirling Dish			0.0071	0.0071[a]	[21]
	Wind onshore			23.02[b]	50.333	[21]
	Hydro Dam			16.261[b]	16.261	Same as 2015
	Hydro River			1.167[b]	1.167	Same as 2015
	Tidal Stream			0	0.070	[75]
	Tidal Range			0	0.070	[75]
	Wave			0.0003	0.0003	[130]
	Biogas [GWh]			10400	10400	[106]
	Geothermal			0	0	

[a] the PNIEC in [21] plans an increase of 5 GW compared to 2015. This increase has been assumed with the same weight as each of the CSP technologies in 2015.
[b] same as 2015

Table A.39: Modifications in the f_{min} and f_{max} in the power generation sector for the ESP30_OBJ scenario in 2030.

	Subject	Assumptions fmin_p	fmax_p	fmin	fmax	Source/Comments
		[%]		[GW]		
Heating	Ind. Boiler Gas	0	20[a]			[162]
	Ind. Boiler Waste	0	20[b]			[162]
	Ind. Boiler Wood	10[c]	100			[162]
	Ind. Boiler Coal	0	9[d]			[162]
	Dhn HP Elec.	0	40			[108]
	Dec. Boiler Gas	0	42[e]			[162]
	Dec. Boiler Oil	15[f]	28.57[f]			[162]
	Dec. Boiler Wood	18.69[g]	100			[162]
	Dec. HP Elec.	0	40			[108]

[a] from 2015 to 2030, there will be a shift from natural gas to biomass, therefore a maximum of 20 % has been set as a logical maximum.
[b] from 2015 to 2030, there will be a shift from waste to biomass, therefore a maximum of 20 % has been set as a logical maximum.
[c] from 2015 to 2030, there is a shift from natural gas and coal to biomass, so at a minimum there should be the same share (10%) as there was in 2015.
[d] from 2015 to 2030, there is a shift from natural gas and coal to biomass, so at most there should be the same share (9%) as there was in 2015.
[e] from 2015 to 2030, there is a shift from natural gas and coal to biomass, so at most there should be the same share (42%) as there was in 2015.
[f] from 2015 to 2030, there is a shift from natural gas, oil and coal to biomass, so at most there should be the same share (28.57%) as there was in 2015 and at least 15% has been set as a logical minimum.
[g] from 2015 to 2030, there is a shift from natural gas and coal to biomass, so at a minimum there should be the same share (18,69%) as there was in 2015.

Table A.40: Modifications in the $f_{min,\%}$ and $f_{max,\%}$ in the heating sector for the ESP30_OBJ scenario in 2030.

	Subject	Assumptions fmin_p	fmax_p	fmin	fmax	Source/Comments
		[%]		[GW]		
Mobility	Tramway Trolley	0	30			[75]
	Bus Coach NG	1.03[a]	5[a]			
	Bus Coach Fuel Cell	0.25	0.5			[165]
	Train Public	25	60			[75]
	Boat Pass. Diesel	0	1			
	Boat Pass. NG	0	0,5[b]			
	Planes	24.4	25			[163]
	Car gasoline	45.979[d]	45.979			[109]
	Car diesel	28.834[d]	28.834			[109]
	Motorcycle	12.07	12.07			[110]
	Car NG	3.12[d]	3.12			[109]
	CAR_HEV CAR_BEV	10	10			[111]
	Boat Freight NG	0	5[c]			
	Truck Fuel Cell	0	0.5			[164]
	Truck NG	0	4			[164]

[a] as a minimum value, the same share has been set as in 2015. As a maximum value a 5 % is set.

[b] as a maximum value a 0.5 % is set

[c] a maximum value of 5% has been set as a logical figure, since in Spain the use of NG in the transport of goods by sea is not at all widespread.

[d] the different shares of fossil fuel-based vehicles have been recalculated due to the increased penetration of electric vehicles (10%).

Table A.41: Modifications in the $f_{min,\%}$ and $f_{max,\%}$ in the mobility sector for the ESP30_OBJ scenario in 2030.

A.2.3.1. ESP30_P1

In this section, it is specified which data have been modified for the case of the ESP30_P1 model in the power generation, heating, and mobility sectors. In the different tables, the sources and justifications for all data and assumptions made are specified. In this case, these data are summarised in Tables A.42, A.43, A.44.

	Subject	fmin_p	fmax_p	fmin	fmax	Source/Comments
		Assumptions				
		[%]		[GW]		
Power	Nuclear			0	3.181	[21]
	CCGT			0	27.286	[21]
	Coal_US			0	0	[21]
	Coal_IGGC			0	0	[128]
	PV			4.664[b]	907.764	[75]
	PT_Power_Block			2.2225[b]	7.0164[a]	[21]
	ST_Power_Block			0.051[b]	0.29449[a]	[21]
	Stirling Dish			0.00225[b]	0.0071[a]	[21]
	Wind onshore			23.02[b]	214.404	[136]
	Hydro Dam			16.261[b]	16.261	Same as 2015
	Hydro River			1.167[b]	1.167	Same as 2015
	Tidal Stream			0	0.07	[75]
	Tidal Range			0	0.07	[75]
	Wave			0.0003	0.0003	[130]
	Geothermal			0	0	

[a] the PNIEC in [21] plans an increase of 5 GW compared to 2015. This increase has been assumed with the same weight as each of the CSP technologies in 2015.
[b] same as 2015

Table A.42: Modifications in the f_{min} and f_{max} in the power generation sector for the ESP30_P1 scenario in 2030.

In the case of the heating and transport sectors, no lower bounds are applied to any of the conversion technologies because the intention of the scenario is to identify which technologies are relevant. Therefore, imposing a certain use of any technology results in the study not providing the desired outcome.

	Subject	Assumptions fmin_p [%]	fmax_p	fmin [GW]	fmax	Source/Comments
Heating	Ind. Boiler Gas	0	80			[78]
	Ind. Boiler Waste	0	50			[78]
	Ind. Boiler Wood	0	100			[162]
	Ind. Boiler Coal	0	9[a]			[162]
	Dhn Deep Geo.	0	50			[78]
	Dhn HP Elec.	0	40			[108]
	Dec. Boiler Gas	0	80			[78]
	Dec. Boiler Oil	0	30			[78]
	Dec. Boiler Wood	0	100			[162]
	Dec. HP Elec.	0	40			[108]
	Dec. Solar	0	20			[78]

[a] from 2015 to 2030, there is a shift from natural gas and coal to biomass, so at most there should be the same share (9%) as there was in 2015.

Table A.43: Modifications in the $f_{min,\%}$ and $f_{max,\%}$ in the heating sector for the ESP30_P1 scenario in 2030.

In the case of the transport sector, upper bounds are only applied to conversion technologies that for physical and logical reasons are not able to supply the entire demand of their layer alone.

	Subject	fmin_p [%]	fmax_p [%]	fmin [GW]	fmax [GW]	Source/Comments
Mobility	Tramway Trolley	0	30			[75]
	Bus Coach NG	0	100			
	Bus Coach Fuel Cell	0	100			
	Train Public	0	50			[75]
	Boat Pass. Diesel Boat Pass. NG	0	25[a]			
	Planes	0	100[b]			
	Car gasoline	0	100			
	Car diesel	0	100			
	Motorcycle	0	100			
	Car NG	0	100			
	CAR_HEV	0	100			
	CAR_BEV	0	100			
	CAR_FUEL_CELL	0	100			
	Boat Freight NG	0	100			
	Truck Fuel Cell	0	100			
	Truck NG	0	100			

[a] a constraint has been applied in the model where the sum of the technologies BOAT_PASS_DIESEL + BOAT_PASS_NG must have a maximum share of 25 %. This share is the same as the aviation share in the previous scenarios. As the passenger transport between mainland and islands can only be done with plans or boats, this percentage is set as a maximum.

[b] it is set at 100% because the model may choose that passengers should be transported with boats rather than planes.

Table A.44: Modifications in the $f_{min,\%}$ and $f_{max,\%}$ in the mobility sector for the ESP30_P1 scenario in 2030.

Appendix B

B. 2030 Sankey Diagrams

This chapter shows the Sankey diagrams of the different scenarios developed with the *Spanish Energyscope* model explained in Section 3.2. Taking advantage of the fact that the model can represent the different energy flows of the Spanish energy system in each scenario, Figures B.1, B.2, B.3, B.4 and B.5 represent the energy flows resulting from the scenarios ESP30_S1A, ESP30_S1, ESP30_TEND, ESP30_OBJ, and ESP30_P1 respectively. These graphical representations of the Spanish energy system allow to easily identify the resources supplied (on the left side of the diagram), the energy conversion technologies used (centre of the diagram) and the different end-use demands (right side of the diagram) for each modelled scenario.

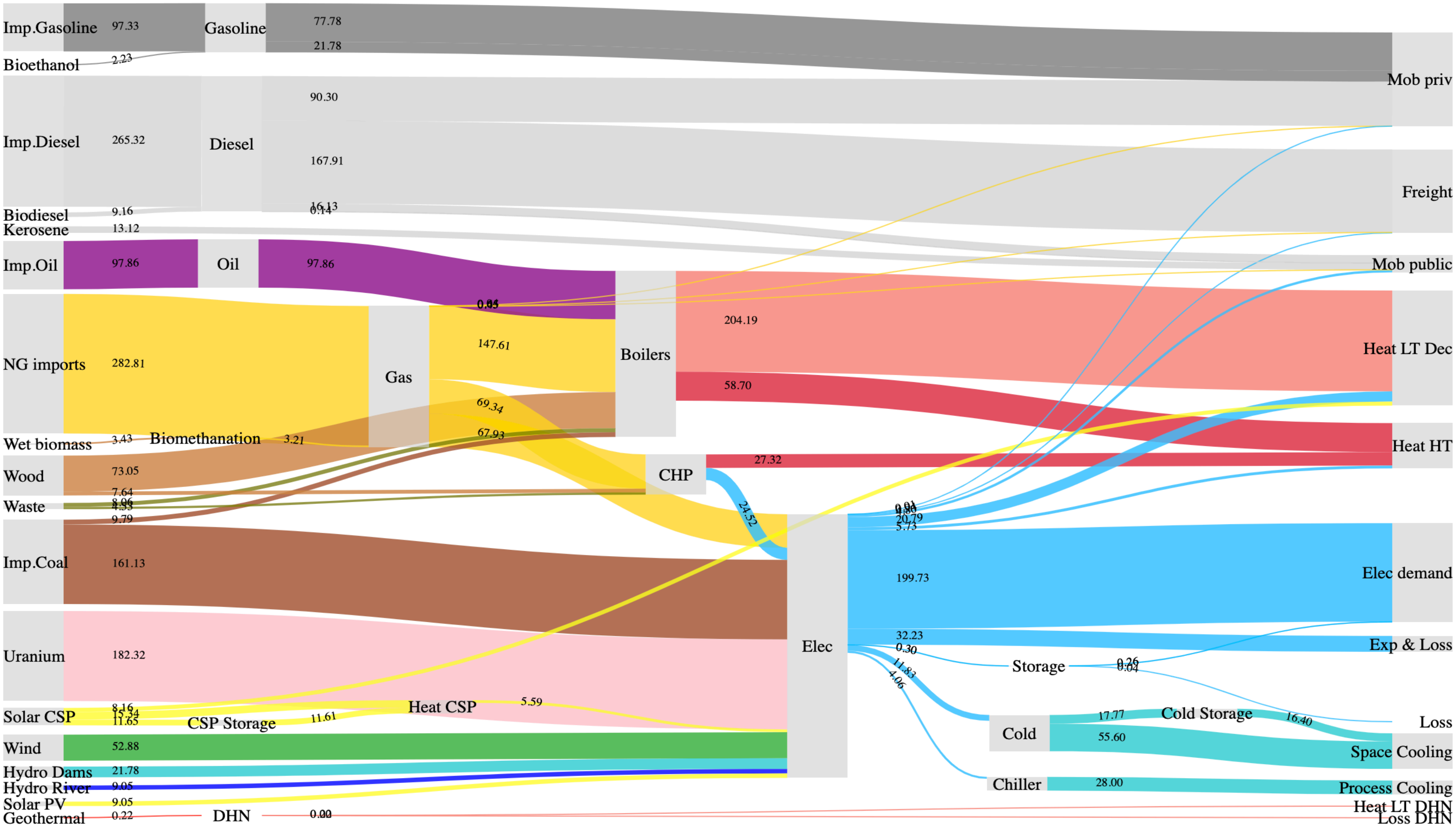

Figure B.1: Energy flows in Spain in the year 2030 according to the ESP30_S1A scenario. All values are in TWh.

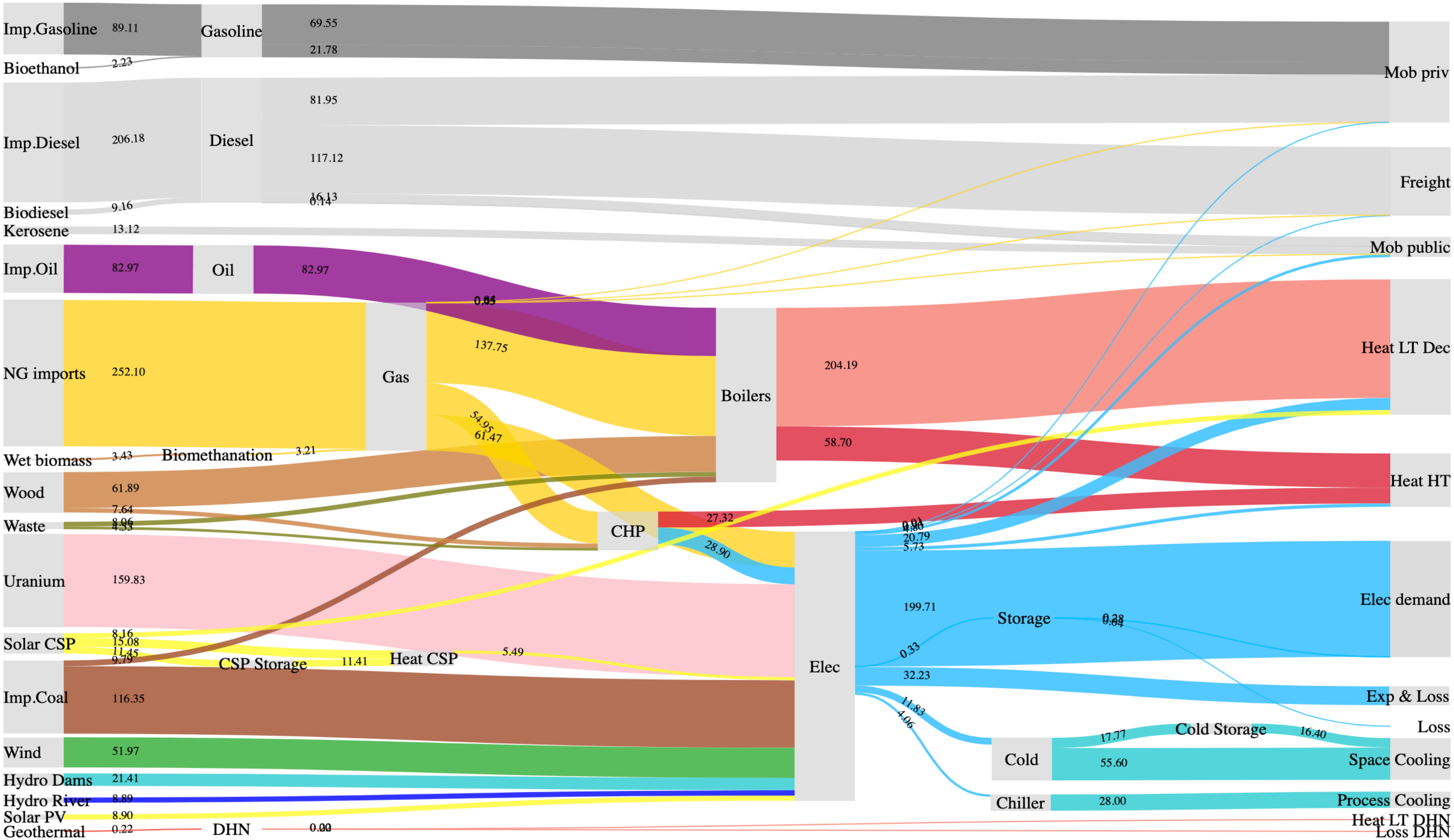

Figure B.2: Energy flows in Spain in the year 2030 according to the ESP30_S1 scenario. All values are in TWh.

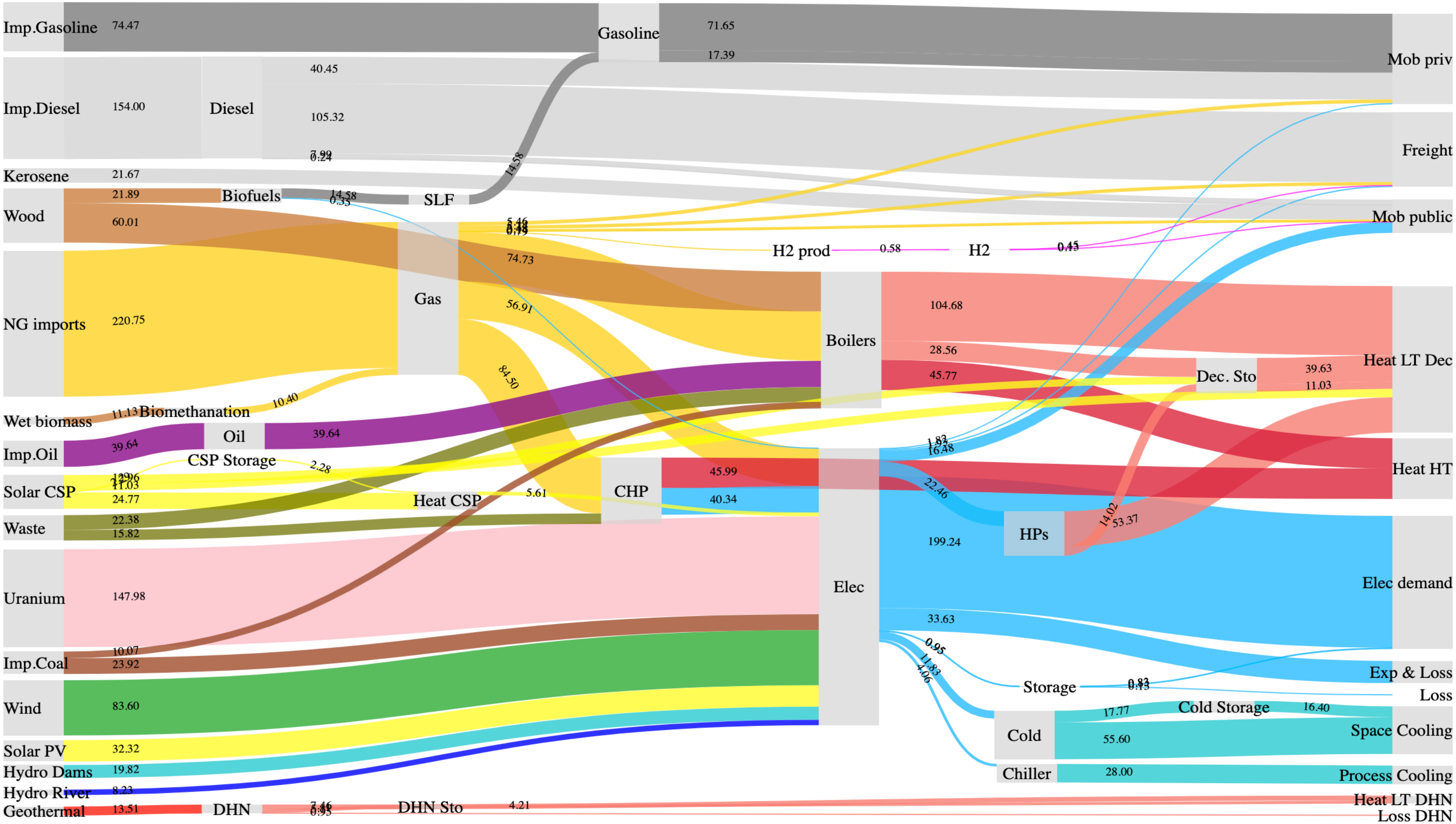

Figure B.3: Energy flows in Spain in the year 2030 according to the ESP30_TEND scenario. All values are in TWh.

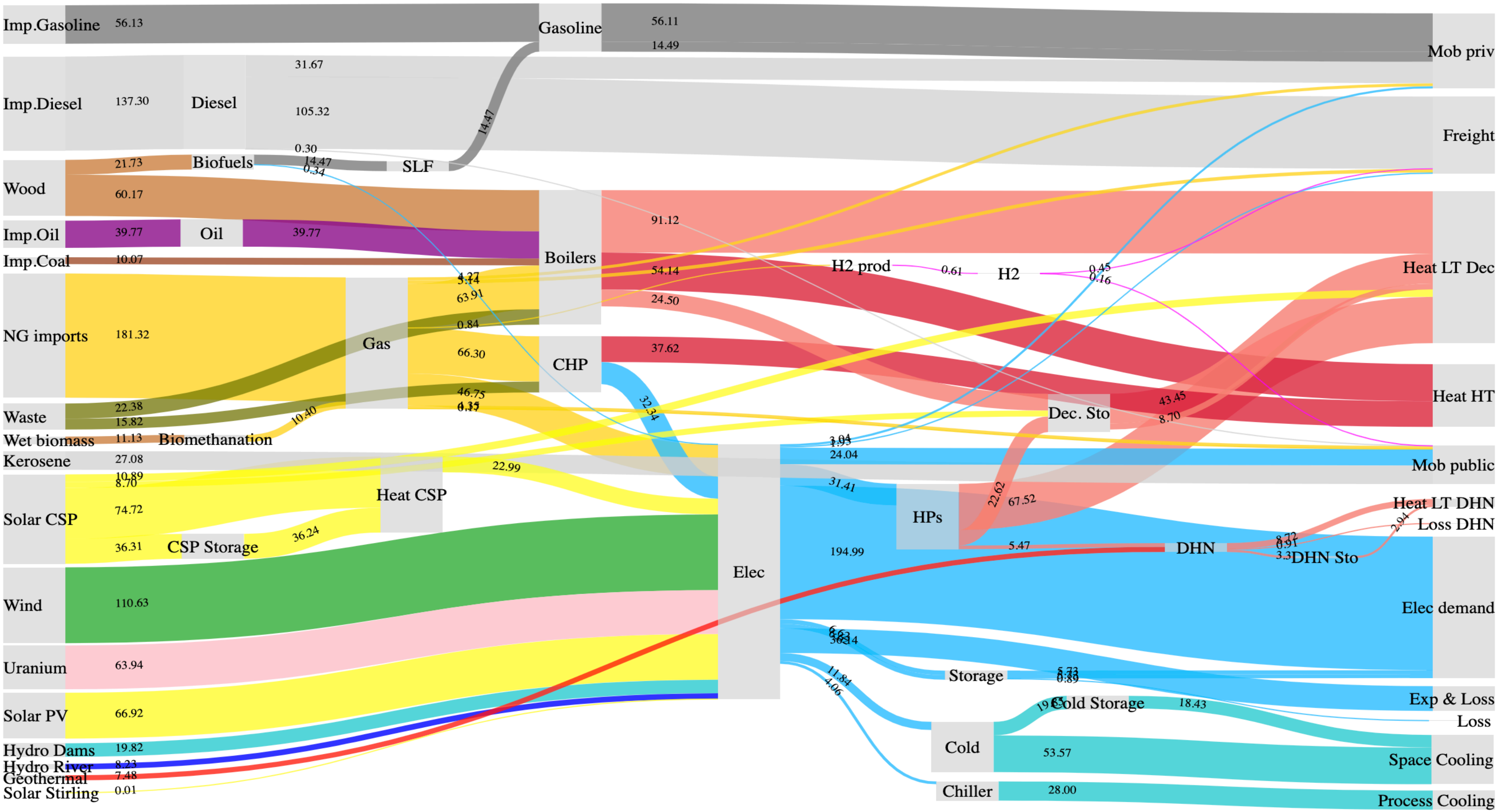

Figure B.4: Energy flows in Spain in the year 2030 according to the ESP30_OBJ scenario. All values are in TWh.

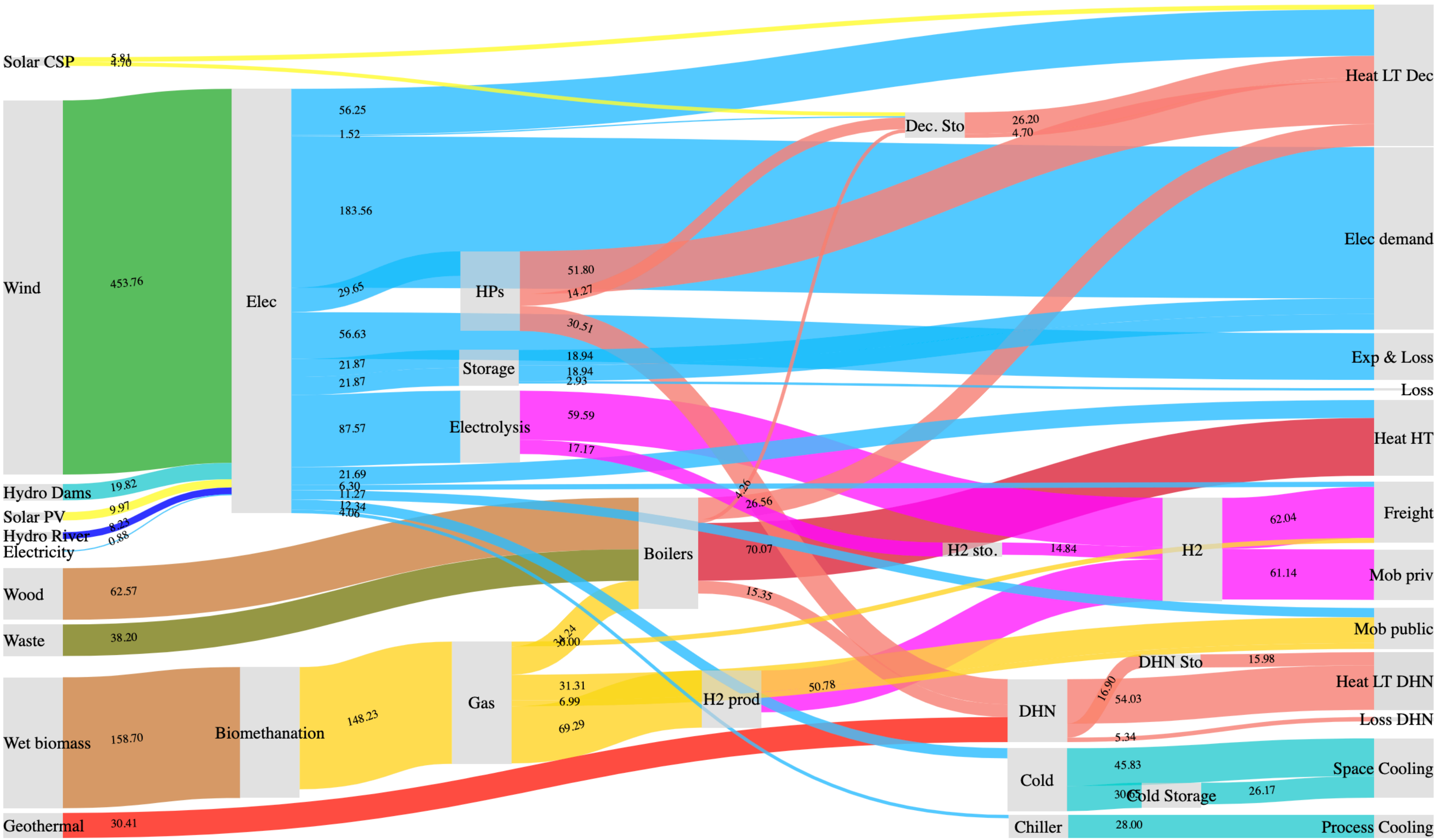

Figure B.5: Energy flows in Spain in the year 2030 according to the ESP30_P1 scenario. All values are in TWh.

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UNIVERSITÉ CATHOLIQUE DE LOUVAIN
École polytechnique de Louvain
Rue Archimède, 1 bte L6.11.01, 1348 Louvain-la-Neuve, Belgique | **www.uclouvain.be/epl**