Impacts of the Hydrogen Integration Process in the 2030 Iberian Peninsula Energy System's Energy Transition Process

A Case-Study Model-based Approach

by

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Preface

A preface...

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Summary

The present study addresses the integration of green hydrogen technologies into the energy transition process of the Iberian Peninsula towards the year 2030, focusing on the associated impacts and uncertainties. The energy transition, driven by the global need to reduce carbon emissions and combat climate change, has led Spain and Portugal to develop national plans such as the Integrated National Energy and Climate Plan (PNIEC) and the National Energy and Climate Plan (PNEC), respectively. These plans aim to decarbonize critical sectors such as industry, transportation, and households, using renewable energies and technologies such as green hydrogen.

The research focuses on analyzing how the integration of hydrogen can act as a buffer for excess electricity produced by renewable sources and how it can partially substitute the use of fossil fuels in industrial and power generation sectors, as well as lead to a higher degree of system coupling within the overall energy system. The main research question is how Spain and Portugal can achieve their decarbonization goals by integrating energy storage and hydrogen technologies into their energy systems.

The methodology employed in this study combines an optimization model based on case studies with an Exploratory Modeling and Analysis (EMA) approach to address the complexity and uncertainty inherent in the Iberian energy system. An optimization model efficiently allocates and distributes system components, minimizing total costs and considering necessary energy production capacities and predefined energy demand levels.

Technical and financial parameters were extracted from energy storage systems, energy sources, and selected transmission lines for data collection for the model. Data were obtained from public organizations such as the International Energy Agency (IEA) and transmission system operators of both countries, as well as market reports and forecasts from private companies.

The study's findings underscore that the Iberian energy system exhibits greater sensitivity to the capacity of electrolyzers than to the capacities of renewable sources. This sensitivity arises from the substantial influence electrolyzers wield over the energy system, as their capacity dictates the quantity of green hydrogen that is producible and storable. Despite uncertainties regarding costs associated with renewable energy production and hydrogen technology, the system will install comparable amounts of renewable energy capacity to meet diverse demands, driven by the primary objective of cost minimization to fulfill established energy needs.

The selection of renewable sources is also influenced by costs. When costs decrease, the model favors wind over solar due to higher capacity factors, resulting in greater energy efficiency. Conversely, as costs increase, the model opts to reduce costs by trimming installed renewable capacity, relying more on slightly higher solar capacity, and increasing hydroelectric and non-renewable sources. Costs associated with electrolyzers do not affect the solar PV/wind onshore ratio onshore. However, a more significant reduction in electrolyzer costs boosts the system's total renewable generation capacity and electricity production. However, the effect is less pronounced than expected due to the small difference in installed capacity.

Results also indicate that, based on cost minimization, the system will tend to rely more on natural gas than nuclear energy. The most significant difference is observed between all scenarios compared to the PNEC scenario. Non-renewable electricity production increases significantly due to the lower installed renewable capacity in that system. Non-renewable sources must compensate to supply the electricity required by the system. Furthermore, increased renewable electricity production is associated with greater capacity and heat production by electric boilers.

In the discussion, robust policy recommendations based on the study results, the validation process with the benchmark, and the expert consultation process were developed, focusing on the necessary policies to overcome economic, institutional, and social barriers that could hinder the achievement of established objectives in the energy transition of Spain and Portugal. The importance of adaptive policies capable of addressing the uncertainty and complexity of the energy system was stressed through the use of the model. Recommendations include considering the main differences between the results obtained and the real situation to avoid a mistaken decision-making process.

Additionally, implementing policies promoting green hydrogen production and use is key. It will generate a major incentive to keep deploying renewables by covering the necessities from a technical and financial perspective as an energy storage medium. Thus, it reduces the necessity to reach higher renewable capacities to cover the demand and avoid very low electricity prices, which would generate a lack of investment. Finally, its development can become the energy vector linking the electricity and gas markets.

Finally, the study's conclusions underline the technical and economic viability of hydrogen integration into the energy system of the Iberian Peninsula, provided it is accompanied by an appropriate policy framework and continuous commitment to innovation and cooperation between the public and private sectors. The importance of continuing research and development in hydrogen and energy storage technologies is highlighted to ensure a successful and sustainable energy transition towards 2030.

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Nomenclature

Abbreviations

Abbreviation	Definition
RES	Renewable Energy Sources
PEM	Proton Exchange Membrane
AEL	Alkaline Electrolyzer
BC	Base Case
CAPEX	Capital Expenses
CHGS	Compressed Hydrogen Gas Storage
DEA	Danish Energy Agency
ESS	Energy Storage Systems
EMA	Exploratory Model Analysis
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LCOH	Levelized Cost of Hydrogen
LNG	Liquified Natural Gas
MIBEL	Iberian Electricity Market
MIBGAS	Iberian Gas Market
MITECO	Spanish Ministry for the Ecological Transition
NUTS	Nomenclature of Territorial Units
NPV	Net Present Value
OPEX	Operational Expenses
REE	Red Eléctrica Española
REN	Red Energeticas Nacionais
SC1	Scenario 1
SC2	Scenario 2
SC3	Scenario 3
SC4	Scenario 4
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolyzer
CCS	Carbon Capture Technology
Li-on	Lithium-Ion
PHS	Pumped Hydro-storage
PNEC	Plano Nacionais de Energia e Clima
PNIEC	Plan Nacional Integrado de Energía y Clima
PV	Photovoltaic
MWh	Mega-watt Hour
TWh	Tera-watt Hour
GW	Giga-watt
CCGT	Combined Cycle Gas Turbines

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Introduction

1.1. Problem Context and Introduction to Hydrogen Technology

Over the last century, technology development has been tied to using fossil fuels as the main energy carrier, creating a strong dependence between the two. However, the excess use of fossil fuels has negatively affected the released pollution when combusted. The most significant consequence is climate change in the form of temperature rises, tide changes, and others [88]. Because of this global climate crisis, the energy transition has raised awareness worldwide, becoming one of the most researched topics. The core of this transition consists of decarbonizing the global power sector first, followed by other sectors such as industry, transport, or households toward the use of sustainable energy [154].

The energy transition effort must be performed worldwide. To this end, a global agreement was established in 2015, known as the Paris Agreement, signed by 196 countries. The original objective of this agreement was to take the necessary actions to limit the temperature rise to the threshold of 2ºC. However, recent studies have demonstrated that the threshold has to be reduced to 1.5ºC since it is the proven threshold at which there is a higher risk of triggering far more harsh climate consequences [159]. Based on the formulation of the Paris Agreement, the EU parties, part of the first agreement, developed a strategy in 2020 to achieve a net-zero carbon emissions economy by the year 2050 [40]. Thus, the member countries of the EU must start applying policies and measures to diminish the probability of reaching a point of no return.

Spain and Portugal, as members of the EU, have developed their national plan for the transition of their power sector, named ”Plan Nacional Integrado de Energía y Clima” (PNIEC) and ”Plano Nacional de Energia e Clima” (PNEC). Developed in 2020, this strategy aims to double RES in the power sector, achieving a 74% share of the energy mix by 2030, and conclude with a carbon net-zero economy by 2050, accomplished with the European Green Deal and the Paris Agreements. Additionally, the plan includes estimations about the specific necessity of wind and solar thermal power generation, as well as the corresponding need for Energy Storage Systems (ESS) [11], [108].

Introducing renewable energy sources (RES) into the current energy system is crucial to unchain the transition of the power sector and the electrification of energy-intensive sectors to switch from their strong fossil-fuel usage. However, the nature of RES is unpredictable and uncontrollable. The power generation varies according to weather conditions, and thus, it is unable to bring up a constant supply of energy [111]. Many models have already been built to predict how the energy transition will happen. However, most conclude that the full integration of RES into the energy system will be the determinant factor of the transition without accounting for the complementary technologies and changes that RES needs to manage the energy demand. In addition, few studies have defined the necessary path to effectively integrate renewables, the specifications of the necessary Energy Storage Systems (ESS), or the definition of possible scenarios to achieve the objectives above for 2030 and 2050. Still, none have done a successful complete analysis of these factors [11].

Due to this fact, researchers are considering these complementary systems in their estimations. One of the most relevant components to successfully integrate renewable energy sources (RES) in the energy system is the creation of ESS, which is necessary to counteract the unpredictability of these types of energies. Between the different options, hydrogen has great potential to act as a buffer for the excess electricity produced through renewables and partially substitute fossil fuels in industrial and power sectors [88].

1.2. State of the art

1.2.1. Literature Analysis

Dealing with global climate change and the continuously increasing scarcity of non-renewable energy sources, which in turn increases their value, the world community has raised awareness and is slowly committing to transition toward a sustainable energy system as well as to optimize the energy demand and supply by reducing losses [154]. Some of these efforts have been translated into agreements and strategies, such as the Kyoto Agreement in 1997, in which the CO_2 pricing system was established [160], the Paris Agreement [159], the European Green Deal [42], or the PNIEC [108] and the PNEC [101], specifically developed for the Spanish and Portuguese energy transition strategies, respectively. The main objective of the systematic review is to find and analyze the latest advancements in the role of hydrogen as the key component of the decarbonization process in the Spanish and Portuguese energy systems. Several research tools were used to do so, and they are described below.

After a systematic review, 13 papers out of the 25 screened were analyzed. The common point found throughout the selected and reviewed literature is that the transition of the energy system and other sectors from conventional power sources to renewables will require integrating other technologies into the system and social and policy support. For example, in the review by Mikulčić, Wang, and Duić, 2020, it is stated that implementing a high share of variable renewable power sources, the periods with an extensive surplus or a lack of energy will happen more often. To solve that problem, the authors focus on the importance of developing ESS, both for the short- and long-term, to diminish the gaps between the demand and supply of energy. However, the interaction between renewable energy supply and the necessary storage systems is underdeveloped. Another pathway that could lead to phasing out conventional power sources is the integration and promotion of self-generation of power by implementing solar PV on people's rooftops to reduce the reliance on the energy transmission infrastructure or a reduction in the capital investments which would be required to meet the levels of demand. This would require implementing energy storage components and applying demand-response systems [141].

The common point found among the literature is the importance of investing and developing energy storage systems to ensure a secure supply of the necessary energy and specifically the importance of further developing the potential of hydrogen technology applied to the power generation sector, as well as a novel energy vector that could be used to substitute fossil fuels in other sectors of the economy (industry, households...) [82], [99]. To achieve a 100% share of renewables in an energy system, hydrogen as a storage system and its utility as a fuel are required to contribute to sustaining the system [12].

Hydrogen's potential role as a power source encompasses different functions and, thus, different sectors. First, green hydrogen has the potential to close a vicious cycle when integrated with renewable energy generation, acting as a safeguard for non-dispatched renewable energy by transforming the electricity to hydrogen to be stored and back when the conventional production of energy is not sufficient. This functionality gives the necessary flexibility to power generation and transmission systems [22]. Secondly, hydrogen is capable of acting as a gaseous or liquid fuel, similar to the currently used natural gas or oil, which expands its potential even further by reducing the dependency on these two. A power-to-gas system consists of the electrochemical conversion of electricity to hydrogen gas or other useful fuels such as methane, which can be used in many applications. It is important to mention that if the gas synthesis generates CO_2 as a by-product, the process needs to incorporate a carbon capture and storage system to close the carbon cycle. This chemical property creates a more powerful synergy between the electricity and thermic sectors, as well as for the combination of natural gas and hydrogen networks for their transportation [170] [52]. This process enables the possibility of using hydrogen in other sectors by being converted to liquid and used as a fuel for the transportation sector, as a heat source for the industrial sector in the form of gas, or as a feedstock for the processing sector, being able to synthesize into other useful feedstock for chemical processes [22] [99], [52]. All of these beneficial properties brought up by the integration of hydrogen could lead to plausible and economically feasible direct electrification (shifting from fossil fuel energy to electric energy usage) of all of the main energy-consuming sectors such as industry or transportation [25].

However, several reasons are causing the slow implementation of hydrogen into these many functions. The main problem of the massive hydrogen production through clean methods is the high cost of the complementary equipment for the conversion processes, which in turn renders an elevated price per kg of hydrogen compared to other, less sustainable chemical pathways. Because of this, minor investments are put into the development of green hydrogen, which, in turn, slows down the rate of innovation, producing a slow implementation into the energy sector and, thus, delaying a faster deployment of RES in the power sector [22]. Another technical problem found with hydrogen is the low efficiency of its conversion process to electricity and back compared to battery efficiency, as well as its efficiency as a fuel much lower than fossil fuels, making its adoption less attractive [88]. Moreover, apart from the problems related to the technical properties and the associated costs, social issues are slowing the development of green hydrogen technology even more. Sánchez et al., 2022 developed a framework to measure the social acceptance of hydrogen technology based on 10 different ratios, such as GDP per capita. The authors concluded that in several cases, the energy transition and creation of storage sites rendered more employment, cleaner air, or higher supply security. Nevertheless, this is not fully correct. People unfamiliar with the benefits might be against adopting hydrogen because of the comfort of using what they currently use. To ensure a high acceptance rate and the fact that hydrogen will play a major role in future energy systems, the technology must be accessible, generate sufficient power, and be simple to use for non-familiar users [88]. It is also important to note the importance of policy support in successfully implementing renewable technologies and energy storage systems, thus helping reach a decarbonized power sector. Eventually, a decarbonized economy [98].

Since the objective of this research is applied to the specific case of the energy transition involving the development of novel hydrogen infrastructure, the massification of RES in the energy mixes, and the electrification of the industry, residential, and transportation sectors in the Iberian Peninsula, most of the screened and finally selected papers develop models and conclude the specific cases of Spain and Portugal. These countries are specifically being researched extensively for being rich in renewable resource potential (high solar irradiation, high availability of biomass, and high potential for wind power generation) [19]. As mentioned in the problem definition section, the PNIEC proposed in 2022 expresses the national climate change targets for the year 2030, attaining to reach 74% of renewable electricity generation, a 42% of renewables over the total energy usage, a 39.5% increase in energy efficiency, and a 23% reduction of greenhouse gas emissions compared to the values registered in the year 1990. The final objective involves a fully decarbonized economy by the year 2050 [108]. On the other hand, the Portuguese PNEC's objectives include a 47% of renewable electricity generation over the total energy consumption, a 20% of renewable energy usage in the transportation sector, a 15% increase in electricity interconnections, a 35% increase in energy efficiency, and a 45% to 55% reduction of greenhouse gas emissions compared to the 2005 levels [101].

All of the screened papers in this literature review that study the specific case of Spain and Portugal use different models to predict future scenarios for their energy systems. For example, in Berna-Escriche et al., 2022, the authors conclude that by the year 2040, the Canary Islands could be fully decarbonized by the implementation of hydrogen technology, the high availability of renewable resources, and the isolation. In Oliveira et al., 2020, the authors highlight the importance of the collaboration between Portuguese and Spanish energy systems to speed up the deployment of renewables by implementing hydrogen EES and an upgrade of the cross-border grid to enhance the bi-directional exchange of electricity leading to a higher security of supply for both nations. Finally, in Bonilla et al., 2022, the authors state that an 87% of RES share in the energy mix is achievable by 2040 in Spain, with similar electricity prices to the current ones, and assuring 100% cover of the demand, by implementing green hydrogen technology. However, while heavy research has been conducted in the implementation of green hydrogen into the chemical industry, much more research is yet needed to study the use of green hydrogen as an energy carrier to substitute the use of fossil fuels in the most energy-consuming sectors [85].

1.2.2. Knowledge Gap and Research Objective

Although much research has been done about the potential of hydrogen in the decarbonization of energy systems and the future of society, there is still uncertainty caused by the premature techno-economic feasibility of the related technologies, both for storage and heat demand satisfaction, which generate higher costs of carbon-neutral hydrogen compared to fossil fuels or grey hydrogen [1]. This creates a lack of investment in the technologies and, thus, slower technological development, sustaining the inherent uncertainty. This uncertainty derives from the complexity inherent in integrating hydrogen technology (green or blue) into a decarbonizing energy system [170]. The analysis of this complexity is usually studied through integrated energy system modeling, as shown in the above section.

Throughout the literature review, it was recognized that most of the created models state and analyze the integration of hydrogen technology in the power sector. Nevertheless, most of the papers focus on one specific hydrogen technology component functionality or discuss the overall challenges without integrating hydrogen into an energy system model [169]. Therefore, the current state of the art creates this knowledge gap that will be covered with the results of this research.

Hence, the research aims to analyze the interplay between the scale-up of a renewable power sector, complemented by the integration of green hydrogen production systems, and the effects of this interaction in the economy and society of Spain and Portugal. This involves the investigation of hydrogen production technologies at a higher level in an energy transition system characterized by the scale-up of low emissions technologies and the effect on the electricity and heat demand of both countries. These demands include the energy necessary to satisfy the needs of both the industrial and residential sectors. Given the complexity of these interactions, it will not be possible to define one but different scenarios of a possible future situation, but different situations with interesting outcomes to consider when defining new policies and strategies. Specifically, the role of hydrogen in decarbonizing both countries will be the main issue to study.

1.3. Research Question and Sub-Questions

Based on the literature analysis and the definition of the research objective and knowledge gap, the main research question is: **To what extent will the integration of green hydrogen technology help Spain and Portugal achieve the established energy transition targets for 2030?** The main research question aims to explore different pathways and, thus, different outcomes from different decisions taken to reach the climate change objectives established in both of the energy transition plans from Spain and Portugal when incorporating the desired levels of blue and green hydrogen technology to complement the energy production from RES.

SQ1: To what extent will the new technologies related to hydrogen production pathways accelerate the Energy Transition Process? The first research sub-question was formulated to give an overview of the most important characteristics of the hydrogen technologies that should be established in the system to scale up the deployment of renewable energy sources process in the Iberian Peninsula, feasibly and realistically. The information retrieved for this part will be one of the pillars to set up the model to be analyzed. Additionally, the finalized set of technologies could be used as a framework to be followed for other countries going through the decarbonization process.

SQ2: How will the variation of the capital expenditure of renewable technologies, including

green hydrogen, affect the overall system's costs, the degree of the system's electrification, the deployment of renewables, and the phase-out of non-renewable sources?

This second sub-question starts digging into the analysis results of the different complex components of the energy sector. Over this phase, model outcomes from other researchers will be reviewed, the base model will be set up, and the different scenarios will be prepared to be run to obtain the desired results based on the increase in demand, the permitted hydrogen production pathways, and the capital costs of each of the technologies to draw initial conclusions. The drawn conclusions will account for the techno-economic and environmental feasibility of the system.

SQ3: How likely is the planned electrolyzer capacity in Portugal and Spain achievable by 2030, and how will it affect the overall energy system by 2030? Since the main future producer of hydrogen is the electrolyzer to satisfy the storage capacity and, thus, the electricity and heating demands of both countries, the third research sub-question focuses on studying the outcomes of varying the installed capacity of electrolyzers. This will generate different scenarios for different capacities of green hydrogen production. The results will show whether the planned electrolyzer capacity for 2030 is feasible in terms of cost, as well as the reaction of the system when this capacity is modified.

SQ4: How can policymakers intervene to facilitate the integration of EES and the utilization of hydrogen as the main energy carrier? The final sub-question aims to relate the literature review process performed when working on the first sub-question and the conclusions drawn from the model by generating a policy framework to follow to achieve the objectives for the year 2030 closely. The result of this sub-question could help in the decision-making process of any other case when initializing or continuing the decarbonization of its energy system and the integration of hydrogen technology.

1.4. Nature of the Research

The nature of the research will determine the research approach that must be taken to answer the main research question and, thus, complete the research objective. Based on the chosen knowledge gap, defined to be the analysis of the interaction between the different systems to be involved in the energy transition process of Spain and Portugal to a decarbonized economy and society, the main research question looks out for the methodology that both countries might follow to achieve its decarbonization objectives. Therefore, given the nature of this research, the selected research approach consists of an optimization model-based approach combined with case study [61].

The case study approach derives directly from the knowledge gap and from the focus of the research, which targets the national plans for the energy transition of Spain and Portugal for the year 2030 and the steps the countries require to integrate EES and hydrogen technology into their power systems, as stated in their objective list. Since few existing papers fully focus on the specific details of the case involving Spain and Portugal, the case study approach brings up great methodologies to fill the knowledge gap. This first methodology aims to explain the complex interrelations between the technical side of the system to study its feasibility. Secondly, the outcomes will be brought up to the current economic, institutional, and social situation to address further barriers that might partially limit achieving the established objectives involved in the Spanish and Portuguese energy transition, leading to a robust policy recommendation.

On the other hand, the model-based approach also derives from the knowledge gap, but more specifically, from the main research question. A modeling approach is usually considered when filling a lack of understanding in a complex socio-technical system and its interaction with the other sectors. In a large-scale interconnected network such as the Spanish power sector and its relation with the others, decision-makers require model simulation to support their choices [162]. Additionally, a model-based approach suits research questions that try to explain how different bodies or actors in a complex system interact, which is exactly the aim of the formulated main research question.

1.5. Research Methodology

In this section, the methods used to answer the proposed research sub-questions will be described and explained from the context of the problem. Additionally, the data analysis tools used in each of the selected research methods will be analyzed. The core of the research will consist of the design process of the model, the desired scenario definition, the most relevant outcomes and conclusions obtained from the sensitivity analysis given the different input conditions, and the established policy framework.

Overall, the main methodology used for this research will be a case study. This includes the design of the case study, being proposed with this document, collecting the necessary data, analyzing the obtained data, in this case through a model, and reporting and discussing the obtained results [168].

The first proposed research sub-question covers the first stage of the case study methodology, involving the exploration of the Spanish and Portuguese energy systems, a review of the current technologies, and the future ones that could be implemented into the system. Therefore, a desk-research methodology can approach this first phase of the research. Throughout this stage, the research methods used will include a systematic process involving a more in-depth document analysis and a more extended literature review to find the necessary information to build the desired base model and support the assumptions and its functioning.

The second research sub-question lies between the desk-research methodology and a model-based approach. The first step of this research phase will consist of gathering all of the necessary data from the technologies discussed throughout the first phase and information and results from other integrated energy system models, sharing similar research objectives and methodologies. Once the data is gathered, the model will be created. The model combines an energy system transition framework with an optimization tool whose objective is to minimize the overall system costs. To verify the model's accuracy, several iterations will be run to ensure that the model results align with the input data and the made assumptions. Throughout the different iterations, the model will be put under stress to examine the limits of its feasibility. Once the model is verified, the different scenarios, parameters, and variables of interest will be decided.

The validation process, which establishes the model's accuracy with respect to the real system in the study, will be performed in a two-step process. First, a benchmark will be established based on the literature review of the case study, including the official national plans for the energy system transformation in Portugal and Spain. The results of the model will be compared to the extracted information. Then, the results will be discussed with experts through an interview to get a final confirmation of the validity of the model results based on the application given to the model.

The third research sub-questions focus on the system model's main issue: green hydrogen's production capacity. Therefore, the methodology of this phase consists of the aforementioned model-based approach. The first step includes the analysis of the base model, in which the necessary parameters (production, demand, and a few nodes), without yet modeling new technologies necessary for the system electrification. Once the base model is functional, the model will start to be expanded in an iterative process based on the information gathered through the desk research methodology and the first results of basic simulation runs of the base model. Once the final model is ready, the different scenarios built with the second research sub-question will be applied to conclude a sensitivity analysis. Therefore, the chosen research methodology will follow the methodology explained in Van Dam, Nikolic, and Lukszo, 2012, and similar to the modeling process performed in Sánchez et al., 2022, or Auguadra, Ribó-Pérez, and Gómez-Navarro, 2023.

The final research sub-question was created to create a general framework as a guideline for future energy modeling of any case study. It does not follow a specific methodology since it combines part of the previously done desk research. It is based on the sensitivity analysis results from the model output.

1.5.1. Data Analysis Tools

Once the research methods have been selected, it is crucial to define the necessary data analysis tools for each. More than one tool will be selected for each method. For the first selected research method, the desk research, the data analysis tools to be used are scientific document research tools such as Scopus, Google Scholar, IEEE, Web of Science, ScienceDirect, and non-scientific document research, in which regular websites are found through Google [16]. A cross-referencing process will be performed to complement these systematic review tools. Finally, Mendeley and “Cite this for me”, will be used as reference tools.

In addition to the aforementioned desk-research data analysis tools, the first two research sub-questions also entail the collection of the necessary parameters with their respective values to establish a realistic and sufficient base model. Some of the data required include the technical characteristics (capacities, lifetime...) of the energy storage systems (electrolyzers, salt caverns...), the energy sources (solar, wind, nuclear, natural gas), and transmission lines selected for the model. Furthermore, the financial characteristics of all the components of the model will also be needed, including the capital and operational expenses. Finally, the demand profiles in the model are introduced, accounting for the consumption patterns proper from each of the different modeled sectors (industrial, residential, services, or transport).

This data will be extracted from public organizations such as the International Energy Agency (IEA) [74], ENTSO-E [39], or the MITECO (Spanish Ministry of the Energy Transition) [108], REE (Red Electrica Española) or REN (Red Energeticas Nacionais), the transmission system operators of both countries, local Spanish and Portuguese newspapers such as ”El Pais”, ”The Portugal News” or ”El Mundo”, energy-related newspapers and websites such as ”Recharge” or ”ET Energy World” or useful websites such as ”Renewables.ninja”. In addition, public reports of different countries left out of the scope will also be used in case the necessary characteristics of one of the energy system’s components cannot be found. Finally, to find reliable value forecasts for the necessary parameters for the year 2030, some reports were created by private companies such as Aurora or Afry [13], [84], together with well-formulated assumptions and some calculations.

The second selected research method, the modeling approach based on the Spanish energy systems as the case study, involves the implementation of the necessary parameters and information extracted from the desk research. This methodology includes the design of the initial model and its expansion and improvement through an iterative feedback loop process. For this purpose, the Calliope Framework is selected based on its capacity to design energy system models from scratch towards a final model with specific objectives based on the matter of study [124]. Additionally, since part of the objective of the research is an optimization process based on total system costs, it needs to include system constraints, the specific optimization objective for each desired outcome, and the characterization of the inter-dependencies from the included variables. The chosen optimization tool for the model is the Gurobi Solver, complementary to the Calliope framework.

Calliope tackles the design of energy system models from the most basic goals that this kind of model tries to achieve to a more specific objective of the model, such as the modeling of a country’s energy system in the future. Therefore, the model outcomes may be different from any other attempt to design an energy system. For example, the design of the nodes in Calliope is based on the power nodes modeling framework proposed by Heussen et al., 2010. The rationale behind its design consists of addressing questions about the transition to renewable energy sources in the power sector, by giving the necessary freedom to adjust the model to the researcher’s preferences [124]. Optimization models are data analysis tools applied in engineering applications, which usually lead to great results. Combined with decision-support systems, or decision-makers criteria, they support and improve the critical decisions that need to be taken at strategic and tactical management degrees [119]. In this case, the selected optimization tool, as mentioned before, is the Gurobi Solver, which is easily installable in the Python environment where Calliope functions. Gurobi Solver is a state-of-the-art solver for mathematical optimization modeling [58].

For the last research method selected, the objective is to perform a sensitivity analysis of each defined scenario for the Spanish energy system and a comparative analysis between these. Therefore, a table and graphs created through Python, Matlab, and/or Excel will be the selected data analysis tools for this phase. Additionally, a design tool such as ”Draw.io” will be used to visualize the policy framework, which concludes with the proposed research.

1.5.2. Research Flow Diagram

A Research Flow Diagram was built to summarize and visualize the different research steps with the corresponding data analysis tools used, the research sub-questions answered at every stage, and the time planning, shown in figure 1.1.

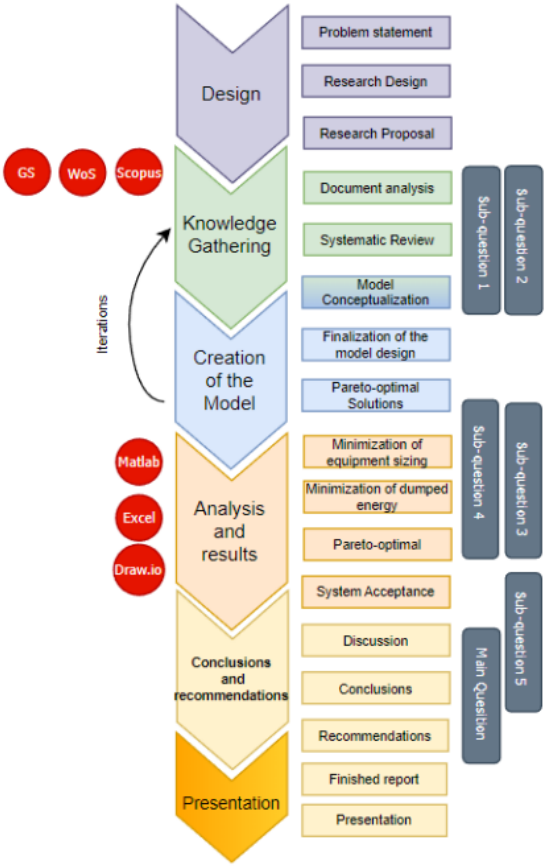

Figure 1.1: Research Flow Diagram

1.6. Link to COSEM program

The link with the MSc of Complex System Engineering and Management has been demonstrated throughout this first chapter of the thesis. The overall integrated energy system of Spain and Portugal is considered complex socio-technical systems due to the complexity inherent in the interaction between the system elements, which comes from the integration of many subsystems into a national or geographical energy system such as the case of Spain and Portugal. To create a design and modify such a complex environment, the presence of some complex elements must be considered, since they influence the functionality and the interaction of the new components to be established. Moreover, the system’s complexity rises further, since implementing new features can also affect these fundamental energy system items. Some of these complex and inherent elements of an energy system include demand (from different sectors) and supply, existing policies and rules of the game, the current state of the system, and involved stakeholders have to be accounted for. The components to be included that create a change in the system are the different energy production, storage, conversion, and transmission technologies. The complexity increases even further when trying to predict the future state of the energy system when implementing hydrogen technology since the exact outcome is completely uncertain due to the path dependence of the choices.

The complexity of this socio-technical system is a clear example of the type of systems we work with throughout our CoSEM studies. Being able to swim around, manage, and create designs in such socio-technical systems is the core of this master's program. The skills and knowledge needed to integrate a new technology in the energy system, have been taught throughout the CoSEM program. Therefore, this master thesis topic fits perfectly in the program due to the above-shown commonalities.

1.7. Master Thesis Layout

The thesis report is composed of seven more chapters different from the current one. Chapter 2 consists of the literature review process needed to gather the necessary knowledge to create a realistic and robust model, backing up the choices made in its design. This includes findings from other researchers about the role of hydrogen in future energy systems, the existing hydrogen production, transportation, and storage technologies, the composition and functionality of the energy demand, and past examples of integrated energy system modeling. Chapter 3 expresses the methodology followed in this research paper. It explains the integrated energy modeling approach, including its exploratory character, as well as the optimization tools used. Moreover, the overview of the designed system, together with the steps taken on its development are also described. Chapter 4 presents the Case Study of Spain and Portugal in 2030, together with both national strategies for the energy transition, assumptions, calculations, and gathered data. Chapter 5 comprises the different decided scenarios to be run in the model, with their corresponding explanation. Chapter 6 presents the obtained results from the different simulations using tables and graphs. In chapter 7, the obtained results are analyzed using a sensitivity analysis, drawing the outcomes. Finally, chapter 8 concludes with the report.

2

Literature Review

2.1. The Role of Hydrogen in Future Energy Systems

Implementing carbon limitations to achieve the imposed CO_2 reduction objectives has been proven to increase electricity prices. However, incorporating storage technology mitigates this cost escalation. According to the study produced by Haller et al., storage components increase the overall system cost by 28% but lead to a carbon emission reduction of 98% [59]. Furthermore, the electricity storage value increases with tighter emission boundaries and promotes the use of energy produced from cheaper and low-carbon energy sources [149]. Overall, storage technologies demonstrate great potential and results in the decarbonization process. Nevertheless, for a power system to be economically viable with a renewable share of more than 80%, it is necessary to have accessibility to large-scale storage, power imports, and other flexible choices such as hydrogen [123].

In most of the developed studies for the decarbonization process, variable renewable sources, such as wind, solar, and wave, are widely considered to be the primary contributors to electricity generation in future power systems that aim to reduce carbon emissions significantly [171]. Nevertheless, when the power system has a significant presence of variable renewable sources, it is inevitable to encounter the challenge of intermittency, which must be well addressed and managed [81]. Therefore, finding a new method that overcomes these limitations is necessary. The most potential solution is hydrogen, which is used as an energy carrier. Renewable electricity can produce low-carbon or carbon-neutral hydrogen by electrolyzers, or natural gas can be converted into low-carbon hydrogen through steam methane reforming (SMR) while capturing and storing the resulting carbon emissions (CCS). Both methods generate pure hydrogen, which has a notable benefit as a medium for transferring heat due to having three times more energy content than liquefied natural gas (LNG) and as a buffer for electricity surplus [145] [117]. Overall, hydrogen will replace the role of fossil fuels, particularly natural gas, for heating purposes. Additionally, it can be integrated with the electricity sector via the application of the electrolysis process [60] [114].

Currently, the global annual production of hydrogen amounts to 50 million metric tons. The primary application of this substance is as a raw material for the production of ammonia, which is essential for the food sector. Additionally, 35% of it is utilized in oil refining to produce different types of gasoline from crude oil [60]. There are various methods for creating hydrogen from fossil fuels, with the primary ones being hydrocarbon reforming (steam methane reforming) and pyrolysis, both of which rely on the utilization of fossil fuels. These systems are highly advanced and widely utilized, satisfying nearly all hydrogen demand. More precisely, hydrogen production is derived from natural gas, heavy oils and naphtha, and coal, accounting for 48%, 30%, and 18%, respectively, summing up 96% of the total hydrogen production. The remaining 4% is obtained by electrolysis procedures [60] [114].

The reason behind the high trend to produce hydrogen through fossil fuels is the lower production costs per kilogram of hydrogen compared to the other methods, reaching 3 to 6 times the cost of production of ”grey hydrogen” [170]. This is due to the technology readiness related to the green hydrogen value chain, which still requires a long development route [120]. In general, hydrogen can serve as a versatile energy carrier in various applications. These include fuel cell vehicles, internal combustion engines for transportation, solid oxide fuel cells, blending with natural gas for thermal uses, and storage in liquid or gaseous form. These characteristics are important to decarbonize many sectors [60] [93]. Specifically, the industrial sector, which accounts for 37% of the global energy usage [164].

In addition, hydrogen can be employed for power-to-gas generation and electricity generation. This is a very important role that hydrogen might play in future energy systems. Power-to-gas is a potential and feasible choice for electricity storage, as it involves hydrogen production from surplus electricity generated from renewables. The produced hydrogen can be stored and used for different functions such as feedstock for the industry and as a fuel for transport [149]. In addition, and especially for long-term and seasonal storage, hydrogen can directly link the electricity and heat sectors. This will enable the sector coupling between the electricity and gas (heat) markets and other sectors in the economy [112].

Based on all the potential that hydrogen has, coupled with the increase in the share of renewable energy sources and the integration of storage technologies, the European Commission has set important and challenging objectives. First, the European Union promotes investment in renewable hydrogen production, targeting 10 Mt of green hydrogen by 2030. To do so, they expect to reach an overall European electrolyzer capacity of 40 GW by this year [93] [26]. Spain and Portugal, as country members, have agreed to contribute to this objective. Spain has a target to reach 4 GW of electrolyzer capacity by 2030 [108]. On the other hand, Portugal has set a target of 1 GW [10].

Hence, to ensure the economic feasibility of producing green hydrogen as a competitive energy source, it is crucial to reduce the expenses associated with water electrolysis components and the required electrical energy while also prolonging the operational lifespan of the facility. Researchers worldwide are now addressing these difficulties [148].

2.2. Hydrogen Supply Chain

The hydrogen supply chain entails all of the technologies needed to incorporate this element as a new energy carrier in any energy system. This chain is composed of hydrogen production, transportation, and storage technologies.

2.2.1. Hydrogen Production Technologies

The first part of a supply chain always involves the production of the desired product. For the hydrogen supply chain, it is not different. Hydrogen can be produced from different energy sources such as solar, hydro, wind, or biomass energy, other renewable sources, and non-renewables, including coal, oil, natural gas, and nuclear energy [100].

However, hydrogen production is still far from being based on the usage of renewable energy. Currently, it almost completely relies on the gasification and steam reforming processes. This type of process requires fossil hydrocarbons (natural gas, oil, carbon, and others), to generate the necessary hydrogen, which in turn, generates 530 Mt/annum of CO_2 [17]. There are alternative pathways for hydrogen production, such as methane pyrolysis or water electrolysis, that are capable of reducing the aforementioned environmental impact only if the necessary feedstocks are obtained through the use of renewable sources or energy. Nevertheless, these processes require a continuous operation to be financially competitive with steam methane reforming (SMR) [63]. Another disadvantage of the greener processes is the dependence on renewable energy production, which is highly characterized by its variability and uncertainty. An additional sustainable process consisting of applying carbon capture and storage (CCS) technology to the massively chosen process of SMR, as a different pathway for environmental hydrogen production [111]. These different production pathways are usually associated with different colors, being grey, blue, turquoise, and green, respectively, ordered from less to more environmentally friendly [62]. Only blue and green hydrogen production technologies will be reviewed for this research.

Blue Hydrogen

As mentioned before, steam methane reforming is the most recurrent process for hydrogen production, being grey as its attributed color, and thus, the most polluting process. [17]. The SMR process entails the cracking of different hydrocarbons (fossil fuels) into smaller molecules of carbon monoxide CO and hydrogen H_2 in the presence of water steam H_{20}, generated by the high process temperatures (700-900ºC). On an industrial scale, the steam reforming feedstock is natural gas, mainly composed of natural gas, which explains the reason for the process' name [23]. Finally, the process has a high hydrogen yield, around 74%, with an estimated cost of 1.8$/kg, and overall energy efficiency between 65 to 70% [163] [56].

Although SMR is a carbon-intensive hydrogen production process, it can be combined with carbon capture and storage (CCS) technology to shift to a lower CO_2 hydrogen production. At the end of the SMR process, the produced CO_2 as a byproduct is partially captured or sequestrated stored forever in geologic sites. At the same time, the rest of the carbon dioxide is emitted to the atmosphere [116] [62]. The carbon capture efficiencies range between 53 to 95% of the total produced CO_2, with the possibility of reaching higher values at the expense of higher energy demand [30]. Nevertheless, it is important to mention that the SMR process efficiency is reduced by 5 to 14% when coupled with CCS [62]. Additionally, the captured CO_2 needs to be transported via pipeline, ship, or other methods to reach the suitable geologic places where it will be stored, meaning that CCS also involves the development of a transport infrastructure [115]. Additionally, geological storage is optimal for a medium-term storage option. In the long run, these geological structures tend to remit the CO_2 into the atmosphere, making the whole process useless. Currently, there is barely any experience with long-term CO_2 storage, which is crucial to making this process sustainable [142].

Although there is a clear environmental benefit from coupling the current production of grey hydrogen with CCS, the extra processing, transporting, and storage technology needed raises the cost of hydrogen to much higher levels due to the new needed infrastructure, causing a difference in the levelized cost of grey hydrogen (LCOH) of 1.02 to 1.48 €/kg [24]. Due to this factor and the lack of blue hydrogen production plants that meet the imposed environmental requirements for the future, it is very uncertain whether this technology will succeed. Even if the SMR + CCS plants reach the necessary decarbonization targets, creating these facilities will remain a challenge [142] [54].

Green Hydrogen

Green is the color attributed to the hydrogen produced most sustainably and environmentally. This type of hydrogen is achieved by the water electrolysis process. This process consists of the division of the water molecule (H_2O) into hydrogen (H_2) and oxygen O_2 molecules by the application of a direct electrical current [62]. The difference in potential between the electrodes, generated by the applied current, unchains the electrolysis reaction, quite similar to the REDOX reaction seen in any battery [161]. The process must be carbon-free, and the electricity used to generate the reaction is produced from a renewable energy source (solar, wind, hydro, and others) [91].

There are currently three main water electrolysis devices. They can be divided into low-temperature and high-temperature electrolyzers. The first cluster is formed by alkaline electrolyzers (AEL) and proton exchange membrane electrolyzers (PEM or PEME). On the other hand, the high-temperature electrolyzers are only composed of solid-oxide electrolyzer cells (SOEC) [95]. The main differences between these three types of electrolyzers are their stage of technological development, the electrolyte and charge carried, the operating conditions (temperature, voltage...), and the capacity to operate dynamically based on a discontinuous power supply from renewable sources (ramping time) [63].

The alkaline electrolyzer (AEL) is the most established and developed technology for green hydrogen production, reducing installation and operation costs. However, they suffer from low cell efficiency (53%) caused partially by the use of low current density and high ramping times (30-60 minutes [2]), which makes it more difficult to couple with the intermittency of RES, and for safety reasons, since there is a risk of explosion if the cell does not operate over 20% of its capacity [95] [91] [153].

The best alternative to using AEL is the proton exchange membrane electrolyzer (PEM) due to its several advantages. Its biggest advantage for energy systems is its capacity to adjust to the dynamic production of renewables due to its much lower ramping times (5-minute cold-start [2]). Other advantages include high current density, which renders higher efficiencies (up to 80% [2]), compact design, safer under higher pressures, and a higher gas (H_2) purity outcome [153]. The PEM electrolyzer's biggest challenge is its components' cost and technological readiness. Because of this, no large-scale PEM electrolyzer plants exist. Thus, its biggest challenge is a cost reduction achieved through further technological development [91]. The third type of electrolyzer is the solid oxide electrolyzer (SOEC). Although it shows promising characteristics to overcome the rest, it is still very undeveloped because of its very low durability and higher needed investment due to the necessary components [91] [63].

Looking towards the future, the production of green hydrogen combined with the use of renewable electricity is the most promising pathway to decarbonization if there are significant cost reductions for the electrolyzers and an increase in renewable electricity [169].

2.2.2. Hydrogen Storage

The capacity to store hydrogen is a crucial part of the hydrogen supply chain. It is a key element that enables the proper integration of sustainable hydrogen into energy systems and assures its success and prosperity [1]. However, hydrogen is difficult to store due to its low energy density by volume compared to fossil fuels. This means that more volume of storage components is required to store the same amount of energy, making the process much less cost-efficient [31]. There are many options for hydrogen storage, which vary in the phase at which hydrogen is kept or through physical or chemical storage techniques [31]. This research focuses on compressed hydrogen gas storage (CHGS), the most developed hydrogen storage technique [1].

Hydrogen Tanks

The first option for compressed hydrogen gas storage (CHGS) is using hydrogen tanks [7]. The hydrogen is stored under high pressures and/or low temperatures in them. This is due to its low density (0.089 kg/m3), which requires an extremely high storage pressure or compensated by extremely reducing the temperature [128]. Also caused by its lightness, the content losses of CHGS in tanks are high [1] [7]. This could be avoided by using carbon fiber instead of the currently used aluminum or steel but would raise the cost substantially [1]. Although the efficiencies of hydrogen tanks are extremely high (around 99%), due to the associated problems, it is most suitable for small-scale applications [7]. Thus, it is not included in the research.

Salt Caverns

The most appropriate option for long-term and large-scale hydrogen storage, needed for the storage on a national energy system scale, is the use of geological storage [7]. The available options for this type of storage include salt caverns, depleted natural gas or oil reservoirs, and aquifers [90]. However, among these options, salt caverns are best for two reasons. First, they cannot contaminate the stored hydrogen, compared to depleted oil and gas reservoirs [32] [21]. Second, salt cavern's efficiencies can reach up to 98%, overcoming the values recorded from aquifers, which have many more losses [32]. Salt caverns are great for short- and medium-term since they allow for multiple and simultaneous injections and extractions of hydrogen, bringing up the capacity to quickly react to strong demand variations [21]. They are also a suitable option for long-term storage due to the chemical characteristics brought up by the presence of salt [102]. Although salt caverns seem to be the best option, their number and availability worldwide are not enough for the uprising demand. However, the availability of these structures in Spain and Portugal shows promising options [151].

2.2.3. Hydrogen Distribution

As mentioned in the last subsection, the low energy density of hydrogen makes its storage very expensive. The same principle is applied to its transport over long distances. To overcome this issue, hydrogen can be compressed, liquefied, or incorporated into a bigger molecule that can be transported as a liquid [7]. Once one of the processes is chosen, the hydrogen is introduced in tanks and transported by trucks [167]. A second option would involve the development of a new hydrogen pipeline network, allowing a higher volume of transportation and a standardized pathway [93]. Nevertheless, the first option creates security problems and a significant loss of hydrogen content, while the pipeline system is highly expensive. Given the conditions of hydrogen and cost minimization, the most suitable option is the blending of hydrogen into the existing natural gas infrastructure. There are almost 3 million km of natural gas pipelines, with a 400 billion cubic meters capacity. If some or all of this infrastructure could be used to distribute hydrogen, it would significantly boost the development of a hydrogen economy. Nonetheless, not all of the network might be usable, or new connections might be needed, so the blending should be accompanied by a possible grid expansion [7] [167].

2.3. System Integration

In the past, many energy sources were not closely interconnected and were produced and operated separately. Nevertheless, these numerous energy streams are progressively interconnected through coupling technologies, such as fusion, gas combined cycle turbines (CCGT), combined heat and power units (CHP), and power to the grid. Others involve using additional renewable energy to produce green hydrogen, which can be introduced into the gas distribution system or converted into synthetic natural gas (SNG) and injected into the gas network. Additionally, heat pumps are employed. The interactions primarily include the conversion of energy between different energy vectors to provide services and maintain optimal control of each energy vector [166].

Implementing the electrification process in the industrial sector is an essential element of system integration, which is recognized as a significant challenge in greenhouse gas emissions. Power-to-heat is a highly promising solution because of its notable advantages, including abundant availability, rapid response time, and a low turndown ratio. There are numerous systems available to generate heat by converting electric power. However, the technological readiness of these components is insufficient for commercialization. Eight distinct P2H technologies have been confirmed to exist at a laboratory scale. These technologies include induction heating, electric arc furnaces, infrared heating, plasma heating, microwave heating, heat pumps, resistance heating, and electrode boilers. The primary factor utilized to evaluate these technologies is how heat is supplied, either directly or indirectly. Direct heating refers to generating heat within the components themselves, whereas indirect heating involves transmitting heat by conduction, convection, or radiation [155]. It is important to emphasize the potential for applying these technologies in residential and service sectors to enhance electrification and attain a sustainable economy.

An indicative example of the significance of integrating different energy sources in achieving a more effective energy system is presented in ”The Role of Electrification and Hydrogen in Breaking the Biomass Bottleneck of the Renewable Energy System – A Study on the Danish Energy System” by Mortensen et al., 2020 [110]. The authors want to establish a range of solutions for fully renewable future energy systems that remain within acceptable limits of biomass consumption. Upon acknowledging the challenges associated with excessive reliance on biomass energy production, they propose two primary approaches to alleviate the biomass bottleneck: the incorporation of hydrogen and the electrification of the system. This involves the expansion of energy services through renewable electricity, along with the reliability and advantages of hydrogen. This integration aims to identify the problems and benefits of this system. According to the authors’ findings, in one out of the 16 scenarios tested, when the system consists of a significant level of electrification and hydrogen integration, the annual biomass requirement per individual in Denmark is zero gigajoules (GJ).

2.4. Energy System Modelling

Integrated energy system models encompass the entirety of the energy system, including integrating the transport, thermal, and electricity sectors. Energy system modeling provides valuable insights for evaluating appropriate policies to facilitate the transition toward a low-carbon economy [60]. The current state of the art of hydrogen integration energy modeling comprises many papers that analyze different aspects of the decarbonization process by integrating hydrogen into the formulated energy systems.

An essential area of research, as demonstrated in the preceding sections of this literature review, is the significance of low-carbon or carbon-neutral hydrogen in reducing carbon emissions in the economy. Seck et al. (2022) [150] try to mitigate this effect by employing a cost-optimization approach that combines three distinct models on a European scale. In addition, two distinct scenarios with policy implications are constructed: Technology Diversification and Renewable Push. Both scenarios demonstrate the significance of implementing both researched methods of hydrogen production, validating the European Union's vision of its hydrogen plan to attain carbon neutrality. Blue hydrogen serves as the initial technology, laying the foundation for the growth and development of green hydrogen starting in 2030. In 2050, imports of hydrogen will supplement local production, accounting for around 10 to 15% of the total need. The authors emphasize the significance of establishing cross-border pipeline interconnection to reduce import expenses.

Visioning the state of future energy systems with the integration of hydrogen as an alternative for energy storage, it is important to study its competitiveness with other storage possibilities. In the paper by Komorowska et al., 2022, a comparison between hydrogen storage and lithium-ion (Li-ion) batteries is conducted, specifically focusing on their competitiveness in the context of price arbitrage in the day-ahead electricity market. The authors use a quantitative model-based approach to do so. In it, they define two different scenarios. The first assumes storage components' charging and discharging during the same hours throughout the year. The second one assumes the same process during historically daily minimum and maximum prices. Results showed that both storage options have a negative net present value (NPV) when the current necessary investment expenditure is assumed. Only a substantial reduction in the investment expenditure would lead to a positive NPV for the Li-ion batteries only. Thus making them more attractive from a financial perspective. Nevertheless, the outcome is based on a small-scale storage system, which could change if the scale of the project is varied [87].

Hydrogen can connect many industries with the electrical market, serving as a significant characteristic or function in future energy systems. This is attributed to its capacity to provide short-term flexibility in the system and fulfill the function of seasonal storage. The authors in Loschan et al., 2023 [97] examine the economic impacts of integrating various national sectors with the European electricity market. To do this, a novel modeling approach is employed, enabling the integration of several marketplaces without requiring many iterative optimization processes. This enables the incorporation of several stakeholder patterns in consumer and producer surpluses. The results indicate that using hydrogen as a seasonal storage component enhances the system's social welfare by a factor of seven by 2030. In addition, Rabbie et al., 2021 [130] state that hydrogen can mitigate the seasonal fluctuations in power generation and consumption. Utilizing hydrogen as a seasonal storage solution can be a viable business model if the local community seeks self-sufficiency. Nevertheless, to maximize profits, it is imperative to have adequate grid capacity for bigger systems.

Fernández et al., creates different mathematical models to analyze the techno-economic feasibility of increasing the share of green hydrogen in the Iberian electricity market by following the predefined strategy. The authors base the different models on operational optimization and market opportunities of relevant stakeholders, including hydrogen producers, consumers, and electricity generators. The outcomes demonstrate that the viability of the green hydrogen strategy depends on the evolution of the capital investment required to increase the share of RES, the speed of development of hydrogen technologies, and the difference in carbon prices in the future. The model results also suggest that the integration of green hydrogen could bring more flexibility into the system, as well as a reduction in the dependence on fossil fuels and an increase in the certainty of energy supply [51].

3

Methodology

Chapter 3 exposes the methodology followed for the proposed research. Specifically, section 3.1 explains the research approach to tackle the problem and produce the necessary knowledge to fill the defined gap. Section 3.2 presents an overview of the system to be analyzed. The system represents the Iberian energy system but does not include all its components. Section 3.3 describes the integrated energy system modeling tool used for the research. Finally, section 3.4 develops a thorough description of the steps taken to develop the model.

3.1. Research Approach

Throughout Chapter 1, a knowledge gap in the state of the art of hydrogen technology integration in energy systems was identified. This knowledge gap led to defining the main research question and sub-questions. To discuss the formulated research questions, a case study approach is presented, analyzed through the use of a model-based approach were taken.

The case study approach allows a researcher to deeply study a specific event or process involving one or more actors. The cases are temporally and behaviorally delimited, with researchers employing diverse data collection methods to gather comprehensive information over an extended duration [27]. Since the research aims to thoroughly study the hydrogen integration process in both the Spanish and Portuguese energy systems and its effect on decarbonization towards the year 2030, this approach fits the research scope.

Secondly, the model-based approach involves an exploratory and an optimization modeling technique. Exploratory modeling and analysis (EMA) is a promising tool for dealing with deep uncertainty. It uses computer experiments as a means to examine systems that are characterized by complexity and inherent uncertainty [8]. The use of exploratory modeling and analysis (EMA) is employed in this study in response to the intricate nature of the system, which gives rise to significant uncertainty concerning its status in the year 2030. Several parameters incorporated in the model, such as fluctuations and growth in energy consumption, advancements in technology, projected costs of infrastructure in the future, and the potential production capacities of various technologies, exhibit a degree of uncertainty and will be set fix to see the effect on the values kept as variables. Moreover, the interplay between these is characterized by a high level of complexity.

On the other hand, optimization models focus on an efficient allocation and distribution of system components, given an objective function (optimization criterion) and a set of constraints, parameters, and decision variables [119]. The model's character enhances the exploratory method by effectively reducing resource consumption to attain specified objectives inside the system. The optimization tool aims to minimize the system's total cost, considering a pre-defined energy demand level, investment costs, and the required energy production capacity. This is done by the decarbonization objectives set for the energy sectors of Spain and Portugal by the year 2030.

It is noteworthy to emphasize that while optimization models of complex systems often yield limited objective resolutions, integrating an EMA approach expands the set of possible outcomes, enabling a more comprehensive analysis of the inherent uncertainty in the system and providing a foundation for advancing adaptive policies. Overall, the approach taken has been demonstrated to properly tackle the uncertainty inherent in socio-technical systems and their evolution. However, this approach can lead to an overwhelming amount of information, posing challenges for researchers in terms of computing capacity to obtain results and subsequent analysis [92].

3.2. Overview of the Iberian Integrated Energy System

The model-based approach is implemented in the context of the energy sectors of Spain and Portugal. Figure 3.1 illustrates the modified configuration of the energy systems, tailored specifically for the objectives of this research. The diagram depicts the various elements that constitute the energy sectors of Spain and Portugal in the year 2030 and the connections and interactions between them. The system can be categorized into four primary energy carriers: electricity, heat, natural gas, and hydrogen. The four carriers demonstrate distinct patterns of development within the system. Nevertheless, they are coupled with one another. Each energy carrier comprises a specific level of demand, along with diverse production, transmission, storage, and conversion methods. These components are visually represented by different colors, as indicated in the legend.

Electricity generation can be categorized into two main types: renewable and non-renewable, as illustrated by the discontinuous bordered box encircling it in Figure 1. The non-renewable generation consists of two primary sources: combined cycle gas turbines (CCGT) and nuclear reactors. In contrast, renewable electricity is produced using multiple forms of energy, such as solar photovoltaic (PV) or thermal, offshore or onshore wind, and hydro-power. Non-renewable electricity is directly integrated into the current power grid for subsequent utilization, whereas renewable electricity can be divided into two distinct categories. The necessary electricity is supplied to the power system, while the uncurtailed energy is utilized to generate green hydrogen. After the electricity has been integrated into the power grid, it can be utilized to meet the requirements for electricity consumption in the commercial, residential, and industrial sectors. Secondly, it can fulfill heat demand by transforming electrical energy into heat using electric boilers or heat pumps. Finally, it can also be stored in lithium-ion (Li-ion) batteries or through pumped hydro-storage methods when there is an electricity surplus.

On the other hand, the heat energy vector can be generated through various alternative energy carriers. The production routes encompass multiple kinds of boilers: electric, gas, and hydrogen. These boilers generate heat through electricity, gas, and hydrogen, respectively. Heat pumps are also employed to extract heat from a source and amplify it with electricity, directing it to the desired location. These devices provide a significantly higher efficiency level, three to five times more, compared to conventional gas boilers [6]. One notable distinction of this energy carrier is its inability to be stored or moved inside the boundaries of this particular system. After the heat generation, it meets the heat requirements of both industrial and residential sectors. In the proposed model, heat pumps would be utilized to meet the residential demand requirement, whereas the remaining technologies will be allocated for industrial applications.

In contrast, the production of hydrogen is completely dependent on the use of other energy carriers. There are two primary approaches to hydrogen production: SMR + CCS (often called blue hydrogen) and electrolysis (known as green hydrogen), which can be achieved using AEL or PEM electrolyzers. The SMR + CCS might be perceived as a conversion element within the system; nonetheless, it is regarded as a production technology largely because of the reduced importance of gas as an energy carrier in this particular system. Hydrogen can be immediately integrated into the new hydrogen distribution infrastructure like electricity. In addition, hydrogen can be stored in salt caverns to store any surplus. Upon reaching the grid, hydrogen may carry out three different tasks. First, dealing with the industrial demand for hydrogen, which serves as a key feedstock for many processes, or to meet the external demand for hydrogen. In the present model, the previous factor holds less relevance as the primary focus is on satisfying internal demand. Additionally, hydrogen can be employed to tackle the extra need for electricity. The conversion of hydrogen into electricity is achieved by the use of combined cycle hydrogen turbines (CCHT). Finally, hydrogen can also serve as a supplementary resource to natural gas to meet the heat requirements of industrial or residential sectors. This is achieved through the utilization of hydrogen boilers.

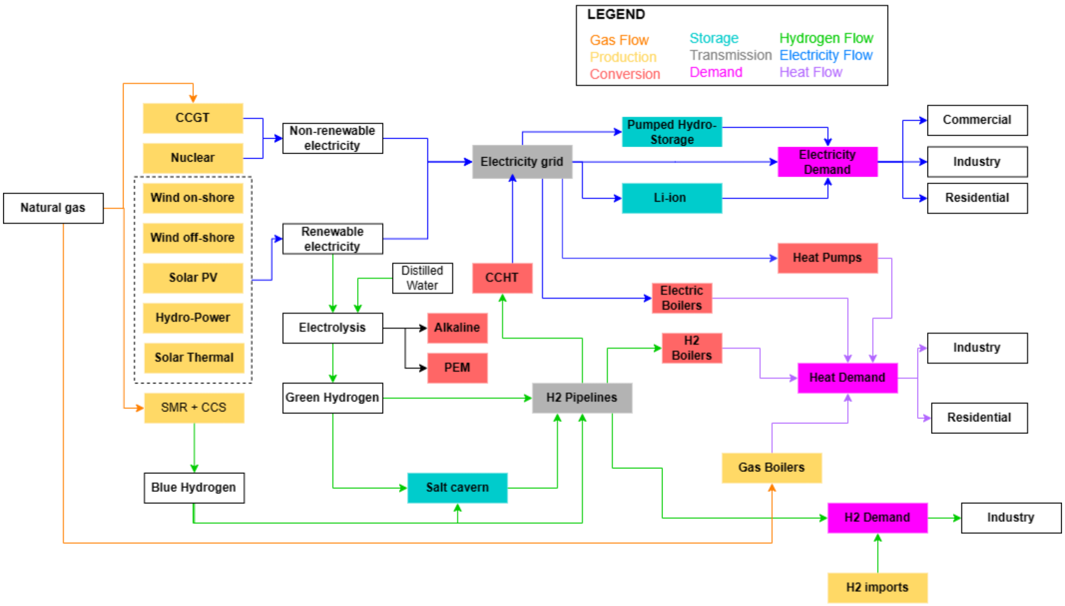

Figure 3.1: System Overview

In this system, gas is both the least and most important energy carrier. Its primary objective is to generate different energy carriers. This capability is crucial to meeting the demand for all of these energy carriers when alternative production methods are not feasible. This gas network's transit and storage aspects are not considered, while its demand is encompassed within the overall demands of the other energy carriers.

3.3. Calliope

The chosen research tool for implementing the modeling-based approaches in the context of Spain and Portugal in 2030 is the Calliope multi-scale energy system modeling framework, created by Pfenninger and Pickering in 2018. The primary aim of developing this framework is to tackle concerns related to the shift of the energy system towards renewable sources [124]. This includes the effects of various modeled technologies, existing and planned energy policies, and examining location-specific decarbonization goals. Due to this logic, Calliope facilitates the integration of both sustainable and non-sustainable energy generation sources, diverse energy carriers, and the corresponding technologies for energy storage, consumption, conversion, and transmission. The Calliope framework is specifically built to analyze energy systems at various scales, encompassing from little urban areas to entire continents, with a focus on high spatial and temporal resolution [124].

In a very summarized way, the framework functions by taking the input data, using CSV files and the programmed constraints, analyzing the optimization problem to be solved, processing the input data, and presenting the results accounting for the formulated constraints. The input data contains information about energy carriers, supply, demand, capacity factors, conversion ratios, costs, and CO_2 emissions. Thus, this tool allows easy construction of the current Spanish and Portuguese energy systems and makes sound predictions of their state in the year 2030, perfectly matching the needs of the proposed research.

The key features of the Calliope framework include the capacity to tackle energy transition problems in a high spatial environment and long periods, as well as running easily in high-performance computing systems. Its design makes it easy to identify the general code from the problem-specific data. Its command-line interface is useful for both experienced and starter users of Python environments [124]. In addition, the publicly available aspect of the research offers the opportunity to compare and verify the obtained results, creating a robust method to generate new outcomes.

Nevertheless, the framework also presents some disadvantages. First, its computational capacity is limited to the specifications of the used computers, meaning that certain assumptions must be made to simplify the results and reduce the computational time. Secondly, Calliope requires already existing and updated data, which can become difficult and time-consuming. Finally, Calliope, like almost any other energy modeling tool, cannot incorporate more parameters relevant to the energy sector, such as social acceptance, existing policies, and the rules in use of the system, which need to be accounted for, especially when trying to identify the impacts of the integration of hydrogen technology in the future Spanish and Portuguese energy systems.

Overall, Calliope functions as a robust tool for modeling energy systems, possessing numerous strengths that allow for complete evaluation and subsequent assistance for decision-making. Nevertheless, it is very important to acknowledge the limitations of this approach and supplement its findings with other analytical methods and factors to comprehend energy systems and their transitions thoroughly.

3.4. Model Development

The Calliope model comprises a collection of YAML and CSV files that define elements such as technologies, locations, links between locations, resource opportunities, and other boundaries. The framework employs a series of files to create an optimization problem. Next, it solves the matter and displays the results as xarray Datasets. These can be conveniently saved as NetCDF or CSV files for further analysis. The software utilizes Pyomo as a base to connect with open-source and/or commercialized solvers, which can solve linear and mixed-integer optimization problems. Although the model is not built to include non-linear optimization problems, the tool allows for the inclusion of external solvers to make their resolution feasible. Finally, the built-in capabilities provided by Calliope facilitate interactive examination of results through the utilization of Plotly [124].

According to the guidelines for creating energy system models using Calliope, the modeling procedure comprises three stages. Initially, the construction of the model can be undertaken through two approaches: either by developing it from scratch or by using an existing pre-built model. Secondly, the execution of the model and, ultimately, the analysis and illustration of the results obtained from the model execution.

In the first step, the YAML files containing all of the information about the different nodes in Spain and Portugal, as well as the already existing technologies and the technologies to be implemented in the 2030 energy systems, had to be created. To do so, the older models built by other researchers available in the Calliope were used as a basis, as well as the instructions given in the Calliope website [124]. Specifically, the files containing the current and future technologies will be based on the already-built projects in the Calliope repository. These are ”Euro-Calliope”, ”Italy-Model” and ”UK-Calliope” [122] [158] [96]. The model YAML file, which contained the necessary information to run the model by combining all the different files was based on the instructions given in the website.

In addition, a set of different CSV files containing useful information, such as the hourly demand or the capacity factors of renewable energy technologies, will be created and introduced into the different YAML files. The information contained in these files will be extracted from different sources, explained in Chapter 4. The YAML files also contain the pertinent constraints for the distinct types of technologies and for each of the included regions of the system based on current real data. In this model, six different types of technologies were modeled, including ”supply”, ”supply_plus”, ”conversion”, ”demand”, and ”transmission” technologies. These different types of technologies are internally defined in the model as the ”parent” of a specific technology.

Once the model is finally built, the simulation run starts. Throughout this step, the framework solves the linear programming optimization problem formulated in the first stage using an optimization tool, ”Gurbobi” [58]. The optimal values for the given optimization goal, constraints, and decision variables are found and stored.

Ultimately, the process of concluding necessitates the division of the results analysis and investigation into two distinct processes. Initially, a general comprehensive analysis was conducted to examine the overall outcomes of the system, with a focus on grasping the energy flow and total costs, as well as the realistic nature of the system. In a subsequent phase, a deeper examination of the system’s insights was performed by aggregating and contrasting the results obtained for each specified node. The overall quality of the study improved by including more detailed information regarding the target characteristics and decision variables. The outputs of this stage will be presented using tables and graphs to simplify the interpretation of results.

Technology Description

As previously stated, the model includes six different categories of technologies that require definition. The previously mentioned technologies encompass transmission, demand, conversion, storage, supply_plus, and supply. The initial four clusters can be easily understood without more elaboration. However, a comprehensive explanation is needed for the supply technologies. Supply technologies refer to a category of technologies responsible for generating energy as a designated energy carrier. In contrast, supply_plus technologies refer to energy supply sources that can internally store a resource before its conversion into the designated carrier. The working of this type of technology is depicted in figure 3.2. Within the model framework, the supply technologies are depicted as renewable and non-renewable energy generating methods, while the supply_plus technologies include solar thermal and hydro-power energy.

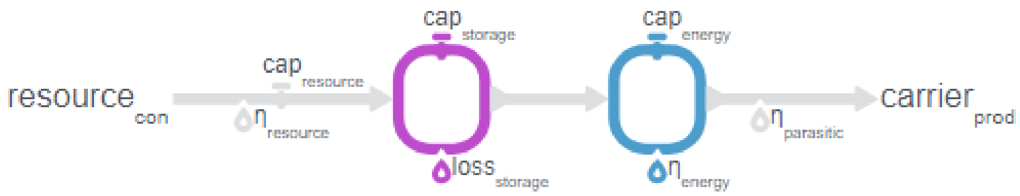

Figure 3.2: Illustration of the supply_plus technology [124]

Figure 3.3 illustrates the same diagram shown in figure 3.1 adapted to the terminology used in calliope.

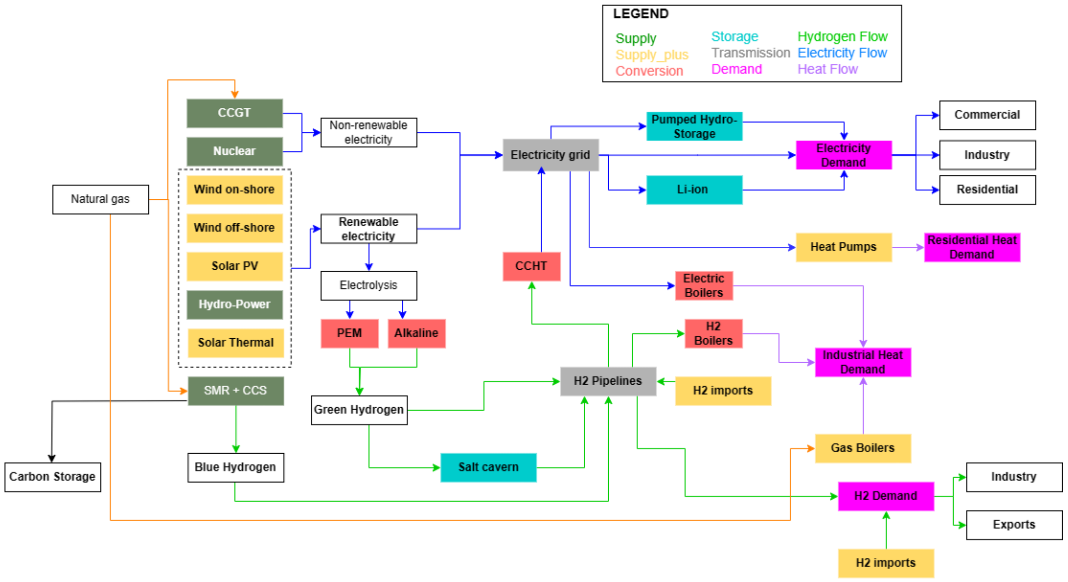

Figure 3.3: Illustration of the implementation of the Spanish and Portuguese energy systems into Calliope

It is possible to utilize three distinct clusters of constraints to distinguish between the various implemented technologies within the model. The initial set of constraints is called default constraints or "essentials." These constraints apply to all technology clusters. Secondly, there are tech constraints that are particular to each technology cluster. Lastly, cost constraints are similar across all technology clusters, except for those technologies that produce carbon emissions. Considering the financial implications associated with these emissions for these technologies is crucial. The essential constraints are shown in table 3.1

Essential	Description
Name	The given name to a specific tech
Parent	The cluster to which a tech belongs to
Color	The given color to a specific tech
Carrier_out	The supplied energy carrier (Supply and Supply_plus)
Carrier_in	The input carrier needed in conversion techs
Carrier	Demanded, transmitted, or stored energy carrier

Table 3.1: Description of the essential constraints defined in the model

The second category refers to technical constraints, which can be used in the different modeled components based on their parent cluster. Hence, every table will serve as a representation of the technical constraints that are allowed for each type of technology. The limitations imposed on the supply, supply_plus, and conversion technologies in the developed model are succinctly presented in Table 3.2. Secondly, the technological limits employed for the storage systems are summarized in table 3.3. Finally, the precise technical constraints for transmission technologies are compiled in table 3.4. Only the essential constraints were employed in the demand cluster, with no additional constraints being utilized.

The final category of constraints refers to the cost-related or monetary constraints. Unlike the other constraints, monetary constraints are similar for every type of technology except for their given value. Inside this cluster of constraints, the costs associated with CO2 emissions are included and considered for non-renewable production and conversion technologies. Table 3.5 compiles all of these constraints.

Allowed Constraint	Unit	Description
Resource	dmnl	The resource availability. For supply technologies, the value is assumed to be infinite. For supply_plus the value is extracted from the capacity factors imported through the CSV files. For the demand, the resource is also input in the same way.
Resource Unit	MWh or MWh/MW	The unit of an available resource. The two options in this model include energy units (MWh), for supply, and energy per capacity units (MWh/MW) for supply_plus.
Lifetime	Years	The lifetime of a specific technology. Crucial to be defined when the capital cost is also defined.
Energy_eff	dmnl	The conversion efficiency of a supply, supply_plus, and conversion technology. Between 0 and 1.
Energy_ramping	fraction/hour	Expresses the ramping rate of the technology. Instead of being expressed in hours, it is expressed on how much technology can activate in the span of 1 hour.
Energy_cap_max	MW	Maximum installed capacity of a specific supply or supply_plus resource.
Energy_cap_equals	MW	The specific installed energy capacity for a supply or supply_plus technology
Force_resource	Boolean	True or false. Forces the technology to use all of the available amount of resource, rather than creating a maximum allowed quantity
Energy_prod	Boolean	True or false. Allows the technology to supply energy to the specific energy carrier. Used for both conversion and supply technologies.
Energy_con	Boolean	True or false. Allows a conversion technology to consume energy from a specific carrier

Table 3.2: Summary of the used technical constraints for conversion and supply technologies

Allowed Constraint	Unit	Description
Energy_eff	dmnl	The efficiency that a storage technology posseses when energy is extracted from it.
Storage_loss	fraction/hour	The rate of storage loss per hour of activity.
Storage_cap_max	MWh	The maximum storage capacity allowed for a specific technology.
Energy_cap_max	MW	Maximum allowed capacity of a storage technology to be installed.
Energy_cap_per_storage_cap_max	1/h	The ratio of maximum charge or discharge (kW) for a given storage capacity. Used when one of the two constraints above is not defined.
Lifetime	Years	The lifetime of a specific technology. Crucial to be defined when the technology is to be built and not already existent.

Table 3.3: Summary of the allowed technical constraints for storage technologies

Allowed Constraint	Unit	Description
Energy_eff_per_distance	Fraction/distance	The efficiency of transmission per kilometer of grid. A value of 1 is no loss, and 0 is fully lost.
Lifetime	Years	The specified lifetime of a specifc transmission technology, Crucial when implementing an initial investment cost.

Table 3.4: Summary of the allowed constraints for transmission technologies.

Monetary Constraint	Unit	Description
Interest_rate	dmnl	The interest rate. Used to calculate costs over time
Energy_cap	€/MW	The cost of energy capacity. Also known as capital investment or CAPEX
Om_con	€/MWh	Expressed the cost associated with the consumption of a specific energy carrier
Om_annual	€/MW/year	The yearly operational and maintenance costs of a technology. Can also be expressed as annual OPEX.
Om_annual_investment_fraction	dmnl	Expresses the annual operational and maintenance costs as a fraction of the initial investment.
Storage_cap	€/MW	The cost of storage capacity. Also referred as the CAPEX for storage technologies.
Energy_cap_per_distance	€/MW/km	The cost of energy capacity per unit of distance. Used as the CAPEX for transmission technologies.
Om_prod	€/MWh (CO2)	Costs associated to the production of an energy carrier. In this model, this variable is used to define the \ce{CO2} emission costs.
Export	€/MWh	The export costs of a specific energy vector. It is negative since its a benefit and not a cost.

Table 3.5: Summary of the monetary and carbon dioxide cost constraints for all of the clusters of technologies

4

Case Study: Spanish and Portuguese Energy Systems

In Chapter 4, an analysis of the case studies regarding Spain and Portugal is provided. The integrated energy system of the Iberian Peninsula is described in Sections 4.1. In addition to providing descriptions of the energy system, these sections also include an in-depth elaboration of the national energy transition plans for 2030, with particular emphasis on the strategy for hydrogen development. Sections 4.3 and 4.5 provide a comprehensive overview of the data collection process and the necessary data for constructing a representative model of the integrated national energy systems. This data is divided into the five technology clusters the Calliope framework provides. Finally, section 4.5.4 provides an analysis of the underlying assumptions that were employed to address the data gaps that were encountered during the research process.

Before delving into the chapter, it is significant to highlight that the inclusion of these two countries in the case study is based on the resemblance of their energy system behavior to that of an ”island” energy system. The concept of an ”energy island” has not formally been defined. However, it can be deduced that it refers to a geographically distinct parcel of land that exhibits limited or negligible linkages with adjacent regions. The geographical characteristics of the Iberian peninsula contribute to a more complex connection to the rest of Europe, in contrast to nations that possess extensive shared borders [140].

Spain and Portugal are vastly and well connected. Their electricity and gas markets are connected more than 95% of the time [140]. Because of this reason, both their electricity and gas markets are coupled into MIBEL (Mercado Ibérico Eléctrico) and MIBGAS (Mercado Ibérico del Gas). The Iberian Peninsula, mainly Spain, has 6000 MW of interconnection capacity with the rest of Europe, which limits the energy transmission around the European Union, based on Spain and Portugal's great capacity to generate energy through RES. The interconnection capacity is currently at 6% of its total transmission capacity, far away from the 15% target required in the new regulation on the governance of the Energy Union [44].

The designation of the Iberian Peninsula as an ”energy island” can be attributed to an analysis of relevant data about electrical consumption, electricity exports, and electricity imports. In 2022, 6.8 TWh were exported, and 12.6 TWh were imported to and from Morocco and France. These figures hold limited significance for the overall internal electricity demand for that particular year, which amounted to approximately 250 TWh. Due to the significant disparity between the internally produced electricity and the amounts exported and imported, it can be assumed that the net trade balance of the Iberian Peninsula is negligent, so metaphorically transforming it into an insular entity [140]. This fact is expressed in figure 4.1

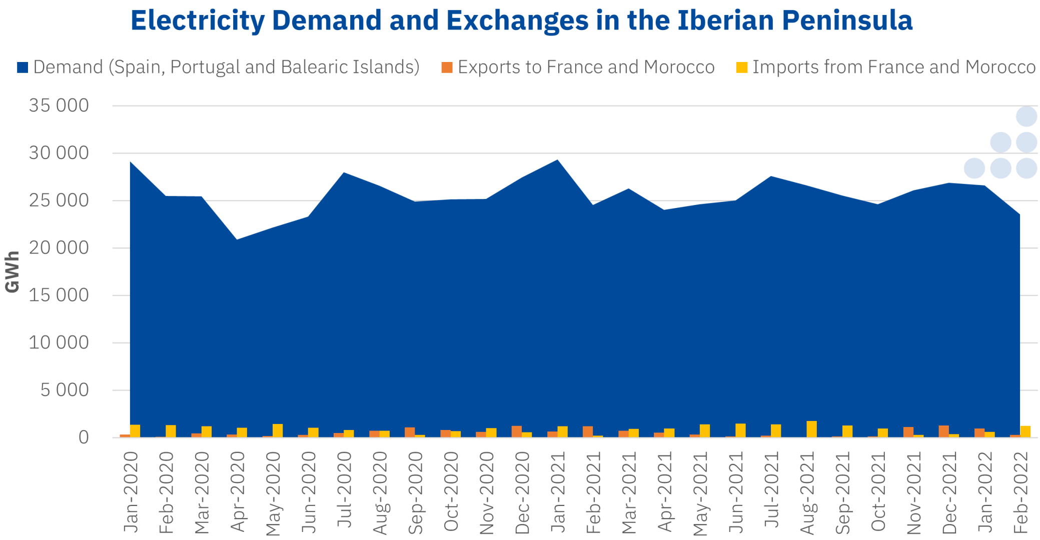

Figure 4.1: Electricity Demand and Exchanges in the Iberian Peninsula. Prepared by AleaSoft Energy Forecasting using data from REN and REE

4.1. Iberian Integrated Energy System

The framework followed by the Spanish and Portuguese governments about climate change politics and energy production is highly determined and aligned by the agreements made on a European and global scale. In 2023, the European Council adopted the set of proposals in the ”Fit for 55” package, targeting a 55% reduction of greenhouse emissions compared to the 1990 levels by 2030. In this set of proposals, the European Council includes new regulations over the carbon-emission permits in the EU, as well as new measures for the sectors not affected by the original permits, such as maritime transport and new objectives as a minimum share of renewable energy in the final energy consumption, and an improvement in energy efficiency and interconnections [41].

To achieve these objectives and generate advancements in the five dimensions mentioned above (decarbonization, energy efficiency, energy security, internal commerce, and R&D accounting for competitiveness) the European Commission proposed a set of policies updated in 2023, targeting the years 2030 and 2050. These policies include increasing the uptake of greener fuels in aviation and maritime sectors, achieving a more sustainable transport sector, reaching climate goals in the land use and forestry sector, shifting from fossil fuels, boosting renewables, and supporting the most affected citizens and businesses from the transition [41].

In addition to these new regulations, the EU also generated and further emphasized the importance of securing the energy supply, causing a massive reduction in gas imports from Russia due to the war with Ukraine. The main idea of this proposal, accepted in May 2022, is to generate bigger energy savings by increasing the energy efficiency of the different European energy systems while producing clean energy. The results of this proposal would lead to an ”Energy Union” around the EU to face together the lack of natural gas imports and establish a more robust security of energy supplies [45].

This developed framework can reduce regulatory uncertainty and bring up favorable conditions to generate incentives to invest, involving the final energy consumers in the supply chain by allowing them to auto-produce their energy and fixing some goals to reach for the year 2030 at a national and European scale. The main established objectives for the EU member countries towards the year 2030 include:

- 55% reduction in greenhouse gas emissions compared to 1990 by 2030
- 45% of renewable energy over the final gross energy consumption
- 38 to 40.5 % of improvement in energy efficiency
- 15% of electrical interconnections between the member countries

4.1.1. PNIEC: Spanish Plan for the Energy Transition

Spain, being a member of the European Union, has agreed to the propositions put forth by the European Commission and is, therefore, bound to stick to the European Commission's objectives for 2030. As a result, the Spanish government, under the purview of the Ministry for the Ecologic Transition, has produced an extensive national energy and climate-integrated plan known as the ”PNIEC,” approved in the year 2021 [108]. The targets for the Spanish Energy Transition in 2030 were defined at the PNIEC, based on studies undertaken by the ministry, considering the country's current capabilities and the established European objectives. Nevertheless, due to the COVID-19 pandemic and the war between Russia and Ukraine, the objectives had to be updated per the ”Fit for 55” and the ”RepowerEU” regulations. The original objectives were:

- 23% reduction in greenhouse gas emissions compared to 1990, by 2030, according to ”Fit for 55”
- 42% of renewable energy over the final gross energy consumption
- 39.5% of improvement in energy efficiency, compared to the 2007 scenario, used as a reference
- 72% share of renewables in the final energy generation mix

In 2023, the Spanish government released a draft for the update of the ”PNIEC,” which still needs to be fully approved. The main objectives changed to:

- 32% reduction in greenhouse gas emissions compared to 1990 by 2030, according to ”Fit for 55.”
- 48% of renewable energy over the final gross energy consumption.
- 44% of improvement in energy efficiency, compared to the 2007 scenario.
- 81% share of renewables in the final energy generation mix.

These targets will enable Spain to pursue the long-term goals for the year 2050, as outlined in the Paris Agreement, which serves as the foundation for the current National Integrated Energy and Climate Plan (PNIEC). The targets encompass a substantial reduction of 90% in greenhouse gas emissions relative to the levels recorded in 1990 and the pursuit of a complete transition to a renewable energy sector [108].

The PNIEC also establishes some requirements for partially decarbonizing other sectors. The energy sector is expected to reduce emissions by 36 $MtCO_2$-eq. The second most polluting sector, the transport sector, is expected to reduce the emissions by 27 $MtCO_2$-eq. Finally, the residential/commercial and industrial sectors are expected to reduce the emissions 10 and 7 $MtCO_2$-eq [108].

According to the original PNIEC, the projected total installed capacity in the energy sector in 2030 is estimated to be 161 GW. Among the aggregate capacity, 50 GW will be derived from wind energy, 39 GW from solar photovoltaic (PV) systems, 27 GW from combined cycle gas turbines (CCGT), 16 GW from hydro-power, 9.5 GW from pumped-hydro, 3 GW from solar thermal energy, and 3 GW from nuclear power, alongside different smaller technologies [108]. On the other hand, the newer draft expects 62 GW of wind energy, from which 4 GW will be offshore, 76 GW of solar energy, 4.8 GW of solar thermal, 1.4 GW of biomass capacity, and 22 GW of storage capacity [105].

The values have been determined using a model incorporating cost limitations and other set hypotheses. The future allocation and aggregation of capacity in the year 2030 will be reliant on the cost trajectory over the decade, as well as the accessibility and adaptability upon installation, which may result in variations within the projected scenario. [108] [105].

By adhering to these principles, the proportion of renewable energy sources in the overall energy generation mix is projected to reach 81%, which significantly contributes to the goal of attaining a 100% share by the year 2050. Additionally, it is expected that developments in storage technologies will result in a decrease in their overall costs. Based on the aforementioned projections, Spain anticipates achieving a storage capacity of 22 GW, thereby enhancing its potential to control energy generation effectively. According to the Spanish Ministry for the Ecologic Transition, the enhanced storage capacity, coupled with the amplification of system flexibility and demand side control, will facilitate the integration of variable energy generation (renewable), hence bolstering the security of supply [105].

A very important factor of the European plan for the energy transition towards the year 2030 is implementing and integrating offshore wind technology into the country members' energy systems. This is due to the expected capacity factors that this technology presents, which makes it capable of generating electricity stably and predictably compared to other renewable energy sources. Because of this, offshore wind farms could help deal with the higher energy demands during the colder seasons, where the capacity factor of solar energy technologies is also lower. Therefore, leading to a higher energy security and sovereignty [107].

According to the predictions made by the International Renewable Energy Agency (IRENA), to achieve the objectives of the Paris Agreements, the total installed capacity of offshore wind energy would need to reach 228 GW by 2030, on a global scale [78]. On the other hand, the IEA states that by the year 2040, 50% of the total installed wind capacity will be offshore 2040 in Europe [67]. As a third opinion, the European Commission's strategy for maritime renewable energies expects to reach 60 GW of offshore wind energy by the year 2030, leading to 300 GW by the year 2050 [121].

As the 5th country with the most installed wind energy capacity, Spain is in a great position to develop a significant network of offshore wind farms. Additionally, Spain is the fourth country with the highest budget in R& D, as well as a highly developed naval industry, many great ports, availability of materials, and engineering capabilities that could help a high development of offshore wind technologies. Spain expects to reach 50 GW of installed wind energy capacity, combining both onshore and offshore, from the already 25.7 GW installed. This will require an investment of around 30 billion euros in the current decade [107].

Overall, all of these predictions based on the current capacity make Spain the 8th country with the highest attractive for investments in renewable energies, according to the ”Renewable Energy Country Attractiveness Index” elaborated by Ernest & Young [50].

Spanish Hydrogen Strategy

Spain has the potential to establish itself as a technological benchmark in producing and utilizing renewable hydrogen, which would pave the way for a decarbonized economy in the country. The way to accomplish this is by boosting the green hydrogen value chain by establishing technological clusters and pilot projects at a regional level. This may be achieved through industry innovation, support in the energy transition process, and ensuring an ample supply of renewable energy at a reasonable price [108].

The Spanish strategy to integrate renewable hydrogen into its energy system is aligned with the established actions in a European context following the ”Hydrogen Initiative” and the ”European Green Deal”. The hydrogen strategies stated in these documents set hydrogen as the backbone to establish a decarbonized economy for 2050 and reach the goals set in the Paris Agreement. Additionally, it indicates that the integration of hydrogen in Europe might develop gradually due to the difference in sectors and regions. To guarantee the proper development of hydrogen technologies, the European strategy establishes three different phases [106].

The first phase encompasses the period from 2020 to 2024, in which at least 6 GW of electrolyzers must be installed all over Europe, producing 1 million tons of green hydrogen to decarbonize the current production of hydrogen needed in sectors such as the chemical or similar. The electrolyzers will be installed next to the demand centers. Additionally, more electrolyzers will be needed to feed the necessary hydrogen for the first hydrogen-powered vehicles [106].

The second phase entails the years 2025 to 2030. By the end of this phase, Europe expects to have installed 90 to 100 GW of electrolyzers, including 10 million tons of imports, according to the new plans approved in the ”RepowerEu” document [45]. Throughout this period, renewable hydrogen gradually reaches a competitive price compared to other hydrogen production methods. Green hydrogen will start to create its expected impact on the energy sector by improving the system flexibility and helping balance the demand and supply mismatches by transforming electricity to hydrogen and vice versa. Additionally, renewable hydrogen will be stored in a daily and seasonal way, acting as a buffer to improve the security of supply in the short and mid-term [106].

The contribution of Spain to the European objectives established for the year 2030 involves the installation of 11 GW of electrolyzers, compared to the 4 GW established in the original document. This means that Spain alone will bring up around 10% of the total expected electrolyzer capacity in Europe by the year 2030 [106]. Nevertheless, these results seem somewhat unrealistic, given that currently, no capacity is installed, and 600 MW are expected by the end of this year [105].

4.1.2. PNEC: Portuguese Plan for the Energy Transition

As a member of the European Union, Portugal has also accepted the European Commission's proposals regarding the decarbonization goals set for 2030 to align with the objectives outlined in the Paris Agreement. Consequently, the Portuguese government has implemented the national energy and climate strategy, referred to as the ”PNEC” in Portuguese. The Portuguese government has set the following targets, which encompass the five elements of the energy transition, based on the country's current capacities and specified goals [10]. These objectives are:

- 45 to 55% reduction of greenhouse gas emissions compared to 1990
- 85% of renewable energy share in the energy generation mix
- 32.5% of improvement in energy efficiency by reducing the primary energy consumption by 35%
- Reduction to 65% of energy dependence

The European Union has set a target to reduce greenhouse gas emissions by 55% by 2030, compared to the levels recorded in 1990 in sectors not included in the European Union Emissions Trading Scheme. The Portuguese contribution to this target is a baseline of 17% regarding the emissions recorded in 2005. However, to achieve the goal of the Paris Agreement to achieve carbon neutrality by 2050, it is essential to achieve a reduction of 55% in greenhouse gas emissions by 2030 as a first measure, according to the ”Fit for 55”. This implies a collection of revolutionary changes in consumption trends, energy generation and use, urban structure, and mobility [10].

Regarding renewable energy development, Portugal possesses solid reasons to continue developing a strategy centered around renewable energy sources to achieve a carbon-neutral economy. Portugal's aspiration and resolve to lead the way in energy transition is shown in its ambitious yet attainable objectives for 2030. Portugal's commitment to the European Union's target of obtaining a minimum of 32% renewable energy by 2030, in terms of the proportion of renewable sources in total energy consumption, is among the most ambitious in Europe. Based on the existing plan established by the Portuguese government and the country's capacity, the proportion of renewable energy in the gross final energy consumption is anticipated to rise to 47% by 2030. To achieve this, there is a strong focus on electrifying the economy, expanding the capacity of renewable energy generation, increasing the use of electric vehicles, integrating renewable gases, adopting highly efficient technologies, and conducting research and innovation to reduce costs. [10].

In this context, Portugal has established particular objectives for future power generation. Firstly, the hydropower capacity in Portugal can be enhanced by finalizing the construction of the three ongoing projects. These represent an additional 1.2 GW of renewable capacity. In addition, Portugal has considerable potential to establish an extensive wind energy infrastructure. The national goal is to achieve a total onshore capacity of 21 GW, counting on an offshore capacity of 10 GW [138] [10].

Portugal and Spain possess significant potential for solar energy due to their abundant sun irradiation and the consistent decline in the associated costs of these technologies. The solar photovoltaic (PV) capacity is projected to grow from the 2021 levels of 1.9 to 20.7 GW by 2030 [80]. On the other hand, solar thermal power, currently not present in the country, is projected to attain a capacity of 2 GW by 2030. This objective is anticipated to be accomplished by conducting auctions to distribute network injection capacity and enable developers to undertake expansions in collaboration with network operators, particularly for projects of significant size. Like this, a total renewable installed capacity of 40 to 45 GW is expected for 2030 [10].

Portuguese Hydrogen Strategy

The government of Portugal expects to reach carbon neutrality by the year 2050, following the European and Global agreements mentioned above. Renewable gases, especially hydrogen, have the potential to play a big role in the Portuguese decarbonization targets, and they are one of the hydrogen production centers in Europe. This is due to the high capacity to generate low-cost renewable energy, high maritime accessibility, and a highly developed natural gas network. The objective behind the Portuguese hydrogen strategy is to achieve a successful integration of hydrogen as a pillar towards sustainable progress, bringing up the security of supply, energy independence, and higher accessibility to energy [10] [55].

The 2020 National Hydrogen Strategy (EN-H2) promotes an industrial policy focused on hydrogen. This policy aims to provide guidance, coordination, and incentives for public and private investments in projects related to various aspects of the green hydrogen value chain. The government anticipates that the most impactful hydrogen integration processes comprise replacing natural gas as a heat source in the industrial sector and substituting fossil fuels in the transportation sector [10]. Nevertheless, these two sectors require great amounts of energy, which is still impossible to achieve using renewable hydrogen. In addition, the integration process offers significant advantages in utilizing hydrogen as an energy source in the electricity sector and as a heat source in the residential and service sectors. This strategy was defined after identifying five key aspects of the green hydrogen value chain [55] [10]. These key points are:

- Power to Gas (P2G): direct injection of hydrogen into the natural gas network
- Power to Mobility (P2M): locally produced hydrogen to fuel vehicles
- Power to Industry (P2I): replace natural gas with green hydrogen for industrial heating processes
- Power to SynFuel (P2S): replacing fossil fuels with synthetic renewable fuels
- Power to Power (P2P): excess electricity from renewables transformed into hydrogen, stored, and transformed back when needed

The national strategy establishes capacity targets for 2030 and identifies the main impact targets of the hydrogen integration. By 2030, Portugal expects to carry out a large-scale production project for green hydrogen, reaching an electrolyzer capacity of 1 GW. In addition, the total national installed capacity of electrolyzers should be set between 4 and 5 GW by 2030. Furthermore, it is also expected to reach a 15% share of the total amount of gas in the current network and 5% of green hydrogen in the final energy consumption, both in road transport and industry. Finally, the government expects to reach at least 50 refueling stations nationally [55]. The expected impacts include the aforementioned objectives stated in the ”PNEC,” as well as 9 to 13 million tons of CO_2 of carbon sequestration by 2050 [10].

Additionally, the strategy brings up policies to support and encourage the integration of green hydrogen into the energy system. Three main policies are identified as the most effective for the phase until 2030. The first policy suggests introducing hydrogen into the gas network might benefit from a partial or total exemption from network access tariffs as an initial step. Secondly, subsidies or premiums should be created to cover the difference in the cost of production between green hydrogen and other production routes. Finally, the use of fiscal mechanisms to incentivize the replacement of natural gas with green hydrogen by adjusting the price difference between them with financial regulatory tools such as Pigovian taxes [55].

4.1.3. Incorporation of the Integrated Energy System into the model

Node Selection Process

To accurately represent Spain and Portugal’s integrated energy system, it is important to define its administrative division first so that the distinct nodes within the model can be established. In addition, it is crucial to define the present energy system and its allocation between the selected regions. This entails providing an in-depth description of the energy generation mix at national and regional scales and an overview of the electricity grid, the gas pipeline network, and the projected hydrogen pipeline network.

Spain comprises 17 autonomous communities and two autonomous cities in North Africa, serving as its primary political and administrative divisions. Every autonomous community possesses a designated capital city. In addition, Spain consists of 50 provinces, each of which possesses its capital, constituting the second layer of administrative division within the country [86]. On the other hand, Portugal is composed of 18 main regions, serving as the first-level administrative division of the country. The districts serve as the designated regions of authority for the local branches and field offices of various governmental ministries and agencies [165].

The nomenclature of territorial units for statistics (NUTS) has been used to interpret the administrative division of the countries into the model. The NUTS terminology is a hierarchical framework utilized for categorizing and delineating different economic regions within the European Union and the United Kingdom. The classification system comprises three hierarchical levels: NUTS-1, which represents the primary socio-economic regions on a European size; NUTS-2, including the fundamental areas utilized for the implementation of regional policies on a national scale; and NUTS-3, which pertains to the smaller regions employed for specific diagnosis on a regional scale [46]. The NUTS-2 division is employed for the Spanish and Portuguese nodes in the model. Excluding the islands and autonomous cities from the analysis, the total number of Spanish nodes shown in table A.1 is 15, following the division by autonomous communities. According to the NUTS-2 division, Portugal comprises 7 regions, of which 2 account for the two conglomerations of islands (Azores and Madeira) [9]. Therefore, 5 nodes were selected within the confines of Portugal, accounting for the NUTS-2 regions in mainland Portugal. The nodes are shown in table A.2

In addition, six separate off-shore nodes were set up as illustrated in A.3. OFF1 and OFF6 are situated along the coastline of Portugal, while OFF2, OFF3, and OFF5 are situated along the coastline of Spain. The unique aspect of OFF4 is its geographical location, as it is positioned in the coastal region near the border. Therefore, it is connected to both countries at the same time. The offshore nodes in Spain have been designated based on the maritime spatial planning strategies (POEM) officially endorsed by the government. The aforementioned geographical regions encompass the North Atlantic, South Atlantic, Gibraltar's strait, Alborán, and Levantino-balear zones [126]. In contrast, the government of Portugal has identified three distinct sites for the establishment of offshore wind farms. These places comprise Viana do Castelo, which has previously undergone the installation of 25 MW, as well as Leixoes and Figueira da Foz [20]. The geographic regions under consideration are depicted in figures A.1 and A.2 for Spain and Portugal, correspondingly.

Description of the Energy Generation Mixes

The determination of the energy generation mixes is highly important for the development of the model, as it serves as the basis necessary to validate the outcomes obtained from the simulations conducted for the year 2030. The characterization of both countries was based on the publicly available information from the Transmission System Operators (TSOs) of Spain and Portugal, namely REE and REN, respectively.

In 2022, Spain experienced a growth of 4.9% in its overall installed capacity, resulting in a total of 119,091 MW. Throughout the year, the total installed capacity of renewable energy sources experienced a significant increase of 5.9 GW, resulting in a cumulative renewable capacity of 70.5 GW. This number accounts for exactly 59.2% of the total installed capacity. In contrast, the implementation of the coal phase-out program has led to a decrease of 0.8% in the non-renewable installed capacity, with 8.5% of the coal capacity being destroyed [133]. The energy mix of Spain is depicted and summarized in figure 4.2 and table A.4, respectively.

On the other hand, Portugal experienced a decline of approximately 6% in its total installed capacity in 2022 compared to the preceding year [28]. This phenomenon can be attributed to a more substantial decline in non-renewable capacity than the corresponding rise in overall renewable capacity. However, the nation is currently implementing renewable energy infrastructure to compensate for the decrease in capacity. In 2022, 890 MW of solar energy capacity was constructed, surpassing the installation rate of other renewable energy sources. Nevertheless, the nation did not achieve its self-imposed objectives

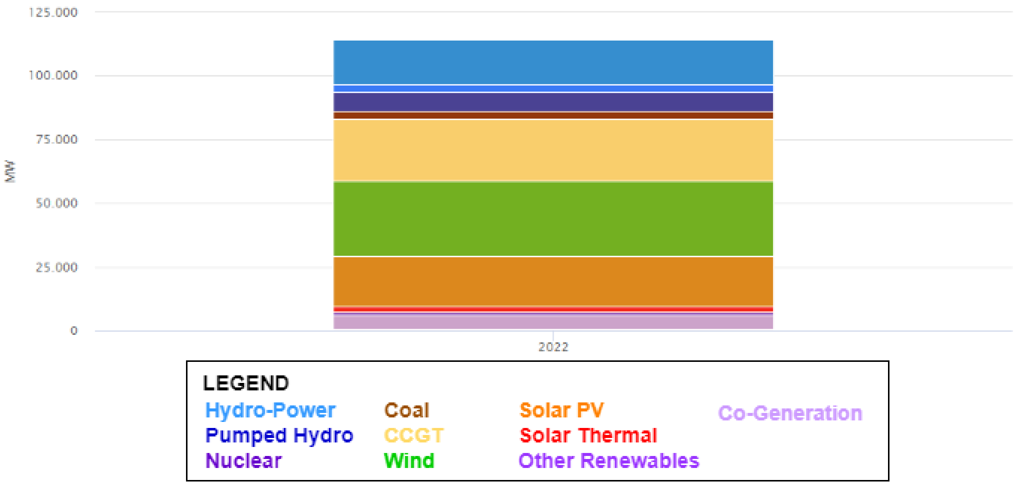

Figure 4.2: Total Installed Capacity in Spain on 2022 [133]

for installation capacity by the year 2022 [147]. Hydropower remains the prevailing energy source with an installed capacity of 8.2 GW [157]. Nevertheless, it is worth noting that the nation continues to depend heavily on imported fossil fuels to sustain most of its economic endeavors [68]. Figure 4.3 and table A.5 provide a visual representation and a summary, respectively, of the energy composition in Portugal for the year 2022.

Electricity Grid

In light of the combination of the electricity market in Spain and Portugal, the power grid will likewise be combined for this research. The diagram in Figure 4.4 depicts the current interconnections within the peninsula. The map displays distinct lines of varying colors, each representing various voltages or types of electrical lines (AC/DC) present inside the peninsula. This model-based research focuses exclusively on the 220 kilovolt (kV) and the 380 to 400 kilovolt (kV) transmission lines. This is attributed to the fact that those are the lines that establish connections between the nodes that have been previously established. In addition, the diagram presented in Figure A.3 depicts the many geographical points where cross-border grid connections are established between Spain and its neighboring nations. The relevant relationships for the model are the connections between Portugal and Spain.

To simplify the network, direct connections were established between the nodes without considering the voltage of the lines. Given the absence of active connections with the offshore parks in Spain, none of these linkages were initially built. Similarly, Portugal has a comparable situation, except for the link between PT11 and OFF1. This distinction arises from the fact that despite its small capacity, the offshore park is currently producing electricity for the nation.

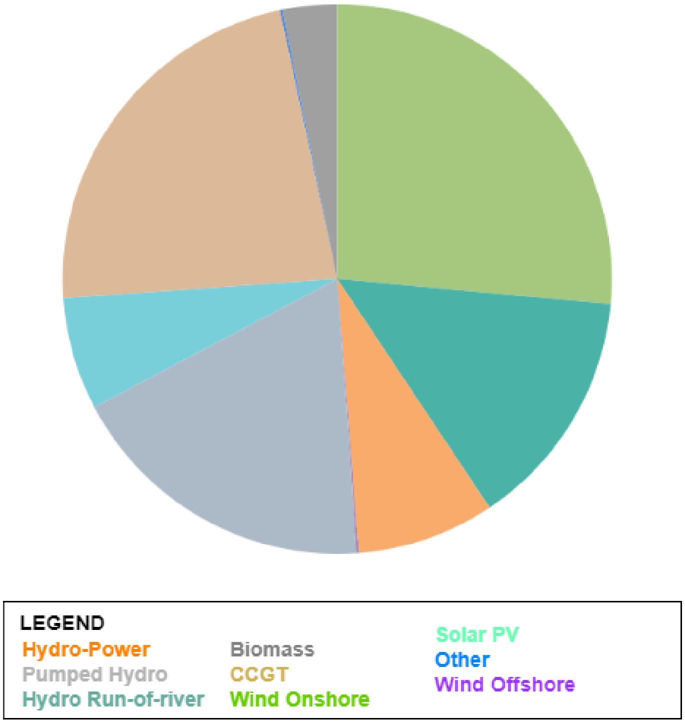

Figure 4.3: Total Installed Capacity in Portugal on 2022 [39]

Gas and Hydrogen Network

Concerning the gas infrastructure of the Iberian Peninsula, figure A.4 provides a visual representation of the Spanish gas network, as reported by ENAGAS, the designated operator of the gas system [34]. Similarly, figure A.5 depicts the gas network of Portugal. Spain and Portugal are connected by three distinct cross-border connection points. The initial connecting point is situated in Badajoz and was constructed in 1996. The subsequent facility is situated in Pontevedra, where operations commenced in 1998. The final facility was integrated in 2012 and is located in Castilla y Leon. This particular facility serves as a virtual balance point, where gas is compressed and prepared for transportation in tanks [34].

According to Enagas, the planned hydrogen grid in Spain has significant resemblances to the existing gas network, as visually depicted in figure 4.5. Indeed, the envisioned hydrogen infrastructure for Spain in the year 2040 bears a striking resemblance to around 80% of the existing natural gas pipeline networks. In addition, the design of this hydrogen grid is strategically aligned with the H2Med initiative, which aims to establish a transnational European hydrogen network to distribute environmentally friendly hydrogen generated in Spain and Portugal to other member nations. Enagas presents a proposal encompassing two primary transportation corridors for hydrogen transportation within and beyond national borders. The initial route commences in the region of Cantabria and traces the trajectory of the Ebro River, namely along the right-hand side of the provided map. The second route originates from the northern region and proceeds towards the southern region by tracing the ”La Plata” pathway, which establishes a connection between Sevilla and Gijon (as indicated by the left cluster on the map) [35].

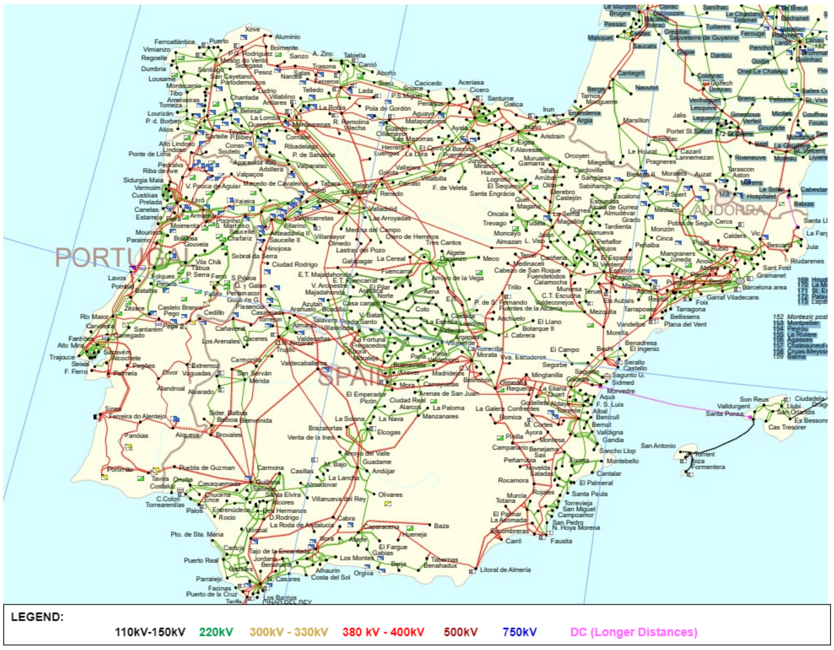

Figure 4.4: Current electricity grid in the Iberian Peninsula, [39]

In contrast, Portugal has yet to develop an elaborate plan for a future hydrogen grid, except for the corridor linking the nation to the H2Med initiative. However, the government has officially declared that a portion of their existing gas network, ranging from 10 to 15%, will need to be modified to facilitate hydrogen transportation by the year 2030. [83].

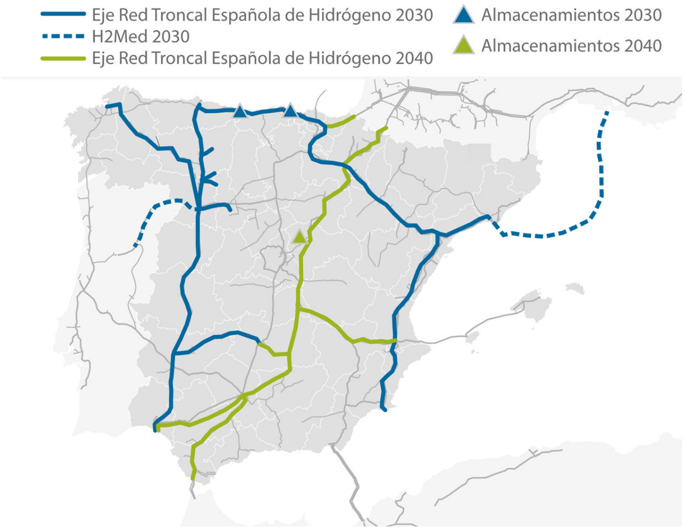

Figure 4.5: The 2030 and 2040 planned hydrogen networks by ENAGAS

4.2. Required Data

Based on the system overview shown in figure 3.3 and the necessary variables shown in tables 3.1 3.2 3.3, 3.4, and 3.5 the required data per technology type is shown in table 4.1. This table summarizes the needed information to characterize each of the technologies in code language.

Technology	**Data Needed**
Electricity Demand	Hourly demand per node
Industrial Heat Demand	Hourly demand per node
Residential Heat Demand	Hourly demand per node
Hydrogen Demand	Hourly demand per node
Nuclear, CCGT	Location, Capacity, Lifetime, Efficiency, Ramping time, CAPEX, OPEX, cost of fuel, CO2 costs
Onshore and offshore wind, Solar PV, Solar Thermal, Hydro-power, Run-of-River	Location, Capacity, Lifetime, Capacity Factor, CAPEX,OPEX
PEM, AEL	Location, Capacity, Lifetime, Efficiency, Ramping time, CAPEX, OPEX
SMR + CCS	Location, Capacity Lifetime, Efficiency, CAPEX, OPEX, cost of fuel, CO2 costs
Li-ion, Salt Caverns, Pumped-Hydro	Location, Storage/Energy Capacity, Lifetime, Efficiency, Charge/Discharge rate, CAPEX, OPEX, Storage Loss
CCHT, Gas Boilers, H2 Boilers, Heat Pumps	Location, Capacity, Lifetime, Ramping time, CAPEX, OPEX, CO2 costs
Electricity Lines, H2 Pipelines	Links, Lifetime, Efficiency per distance, CAPEX ‘per distance, OPEX per distance

Table 4.1: Required data to model the 2030 integrated energy system of the Iberian Peninsula

4.3. Data Gathering Process

In this section, the data collected for the model is shown, along with the methodology employed to gather it. According to the data requirements in table 4.1, the pertinent information compises demand, production, conversion, storage, and transmission data. Before starting this section, it is important to emphasize that the available data for Portugal was considerably lesser in comparison to Spain, requiring a greater number of assumptions.

4.4. Demand Data

The first part of the data-gathering process involves generating the demand information, introduced in the model through the CSV files. The data for the demand that was encountered could not be found precisely. Therefore, this first step involves data processing and assumptions, affecting the final results. However, the difference will only be noticeable when compared to the real situation since the system functioning in the model is not affected by the demand input.

4.4.1. Hydrogen Demand

Currently, hydrogen is still not integrated into any energy system as an energy carrier since the technologies for the production of blue and green hydrogen are not operational and fully commercialized yet in the relevant countries [68] [71]. Therefore, the input hydrogen demand included in the model represented only the industrial consumption of hydrogen as a feedstock for different processes. This does not mean that the model results for hydrogen consumption will be equal to the input hydrogen demand since hydrogen is programmed to help satisfy both the electricity and heat demands for the year 2030 through the use of conversion technologies.

Before explaining the data processing, it is important to mention that since this hydrogen consumption is related to industrial activity, it was assumed to be constant throughout the year. Thus, to create the dataset for the demand for hydrogen as a feedstock, the annual hydrogen consumption of Spain and Portugal in their industrial sectors needed to be found. The data for Portugal could not be found, which led to the assumption that no activity in the country requires hydrogen as a feedstock. Oppositely, the data for Spain was found and gathered from the Spanish Hydrogen Strategy written by the Ministry for the Ecologic Transition (MITECO) in 2021 [106].

First, the value retrieved had to be multiplied by a conversion factor to find hydrogen consumption in MWh instead of metric tons. Thus, it was multiplied by 33 MWh per ton of hydrogen [36]. Then, the value was divided by 8760 hours to find the hourly value of industrial hydrogen consumption. Once the hourly value was found, it was necessary to adapt it to the year 2030, since the data found for hydrogen consumption was for the year 2021. To do so, the demand's compound annual growth rate (CAGR) was selected as the expected evolution of industrial hydrogen demand. This value was retrieved from the ”The Iberian Power and Renewable Market Forecast” written by Aurora (2022) [13]. In this forecast, they assumed a CAGR of 0.3% until 2030. Therefore, the compound interest formula was used to find the hydrogen consumption for the year 2030. This formula is expressed in equation 4.1. The value of ”n” represents the number of years for the accumulation, which in this case was 9.

$$H_2\ Demand_f = H_2\ Demand_i * (1 + CAGR)^n \tag{4.1}$$

Once the value was updated to the expected growth for 2030, it had to be divided by the different relevant nodes created in the model. Since only Spain was considered for this input data, the hourly hydrogen consumption had to be divided between the 15 Spanish nodes. The methodology followed to do so consisted of using the distribution of the Spanish GDP between the different autonomous communities. This method was selected since, in energy consumption models, the GDP significantly helps to determine the final energy consumption, as demonstrated in Nayan et al., 2013. The GDP distribution was obtained from the website ”Datosmacro.com”, which provides different relevant data about Spain [48]. The annual GDP of 2021 per autonomous community was retrieved from this website, excluding the two archipelagos and the cities in North Africa. The total GDP for mainland Spain was calculated by summing the values of all the relevant regions, and the percentages were created. Finally, the processed hourly industrial hydrogen consumption in 2030 was multiplied by each percentage as shown in equation 4.2. The ”x” represents each of the relevant Spanish autonomous communities. Table 4.2 summarizes this process.

$$H_2\ Regional\ Demand = Total\ H_2\ Demand * \%\ GDP_x,\ \forall x = 1 \rightarrow 15 \tag{4.2}$$

4.4.2. Electricity Demand

To obtain data on the electricity demand in Spain and Portugal for 2030, the hourly demand per nation was collected from the ENTSO-E Transparency Platform [39]. The data set was only available for the year 2022. Hence, it was necessary to apply a projected percentage increase to the gathered data to characterize the data for 2030.

For the Spanish demand, The Iberian Power and Renewable Market Forecast study from Aurora (2022) was utilized for this purpose [13]. This article derived the projected value of the final electricity consumption for 2030 in Spain. Then, a comparison was made between the aforementioned data and the corresponding value for 2019, obtained from the ENTSO-E. The calculated percentage increase from the year 2019 to the year 2030 was approximately 13%. The expression utilized to determine this percentage is represented by Equation 4.3.

$$\triangle\% = (Demand\ 2030 - Demand\ 2019)\ /\ Demand\ 2019 \tag{4.3}$$

After determining the annual national hourly demand, it was necessary to allocate this demand among the 15 established nodes within the borders of Spain and disaggregate it according to the demand of different sectors. The process of dividing by node was executed. However, the division per sector was not conducted, as this study focuses on the two primary sectors of energy consumption, service and industrial, which uptake almost all of the electricity demand. This phenomenon is seen in figure A.6 [131]. The electricity demand for the year 2022 in Spain and its autonomous communities was obtained from the electricity balance data hub of ”Red Eléctrica Española” (REE) [132]. Upon retrieval of the numbers, the percentages of each node about the overall national demand were computed using the expression presented in equation 4.4. The procedure is summarized in Table A.7, which presents the demand values and their corresponding percentages for each node.

$$\% \ of \ Demand = (Demand \ Node \ x) \ / \ Total \ Demand, \ \forall x = 1 \rightarrow 15 \tag{4.4}$$

In Portugal, demand per node was determined using an alternative approach due to the unavailability of such information in the ”Redes Energeticas Nacionais” (REN) data hub. However, the consideration of demand segmentation per sector was still not considered for the same reason as Spain. Therefore, an alternative method was employed to determine the electricity usage per location. To accomplish this, Portugal’s population values by region (node) were obtained from the Eurostat database [47]. Furthermore, the per capita energy consumption in Portugal for 2022 was obtained using the Energy Profile of Portugal produced by IRENA [77]. Next, the population figures were multiplied by the electricity consumption per capita, yielding the electricity consumption per region. The ultimate stage entailed the utilization of equation 4.4 to calculate the proportion of the overall demand per node.

To ensure reliability, a comparison was made between the total demand for 2022 obtained from the REN data hub [137] and the total demand computed. The calculated value deviated by 1.1% from the value reported in the REN data hub, resulting in a minor error in the results obtained. However, the magnitude of this discrepancy is not considered very important. The outcomes of the data processing are presented in table A.8.

4.4.3. Heat Demand

The heat demand in the model was divided into industrial heat demand and residential heat demand as shown in figure 3.3. This was done for two reasons. First, because of the difference in the utilization patterns. Usually, the industrial demand is more stable throughout the year, caused by the function of heat energy in that sector. On the other hand, the residential heat demand has seasonal and daily variations caused by the difference in temperature between seasons and throughout the day [129]. Based on these patterns, the industrial heat demand was assumed constant every month for both countries, while the residential heat demand was not.

Industrial Heat Demand

The main reason the industrial heat demand was assumed to be constant monthly was caused by the lack of data available to characterize it properly. Additionally, the lack of Portuguese data was substantially higher than Spain, making the data process even less accurate. Nevertheless, the assumptions made were based on reliable studies and statements, reducing the inaccuracy of the results.

For the case of Spain, the monthly industrial heat demand, which was based on the natural gas demand, was obtained from the monthly reports published by ”Enagas,” the Spanish gas transmission operator (GSO), on their historical demand datahub [33]. The obtained monthly heat demand values were divided by 30 or 31 days, depending on the month, and by 24 hours in a day, achieving the hourly values for the industrial heat demand based on the previously explained assumption. Once the hourly data was collected, it had to be updated to the year 2030 based on the expected growth rate of industrial activity. To do so, the same procedure utilized for the hydrogen demand data was chosen to estimate industrial heat demand, as seen in equation 4.5, using the compound interest formula and the CAGR retrieved from The Iberian Power and Renewable Market Forecast study from Aurora (2022) [13]. In this case, the value given to ”n” was equal to 8 since the data gathered was from 2022.

$$Industry \ Heat \ Demand_f = Industry \ Heat \ Demand_i \ * \ (1 + CAGR)^n \tag{4.5}$$

Once the monthly future industrial heat demand values were estimated for the year 2030, they had to be divided between the different autonomous communities of Spain, which were also selected as the nodes of the model. The methodology used to estimate the regional distribution consisted of using the GDP distribution over the 15 autonomous communities in mainland Spain. This methodology was selected since, in energy consumption models, the GDP is one of the main parameters for the determination of final energy consumption [113]. Therefore, the GDP distribution data was gathered from the website ”Datosmacro.com,” where information about national statistics is published [48]. The percentages on the website were not used since Spain’s archipelagos and autonomous cities are included. Therefore, the values for the GDP per remaining region were retrieved and summed to calculate the total GDP in mainland Spain. After this, the percentages were generated and multiplied by the obtained demand values, as shown in equation 4.1 but for the monthly industrial heat demand. Table A.9 summarizes the process showing the demand values for January.

The process followed to obtain the data for Portugal was similar. The monthly consumption of natural gas in Portugal for industrial purposes was obtained from the REN datahub for natural gas [136]. The data was also adapted to an hourly value and updated to the expectations for the year 2030, following equation 4.5. Once the values were obtained, they had to be distributed over the 5 defined Portuguese nodes. To do so, the GDP distribution per region had to be found. However, this information was not available. Therefore, to solve this problem, the GDP per capita was obtained from the website ”Datosmacro.com,” and the distribution of population per region in Portugal was obtained from the National Institute of Statistics in Spain [49] [75]. The distribution of GDP per region in Portugal was achieved by multiplying both values, as shown in equation 4.6. Then, the percentages of GDP per region over the total were calculated, and by applying equation 4.1, the distribution of industrial heat demand per Portuguese node was obtained. Table A.10 summarizes the process showing the demand values for May.

$$GDP\ per\ Region = Regional\ Population * GDP\ per\ capita \tag{4.6}$$

Residential Heat Demand

As previously stated, the home heat demand was not considered constant but rather permitted to fluctuate during the day and throughout the seasons. This can be accomplished due to data availability that facilitated the formulation of logical assumptions. The data was obtained from the heating and cooling demand trends in ”renewables.ninja” [125]. Renewables.ninja enables the precise identification of each node’s location to retrieve relevant data related to it. The data obtained from this website was presented in dimensionless units and needed to be converted to real consumption values specific to Spain and Portugal. To accomplish this, the numbers for each site were aggregated for the entire year of 2019 to derive a cumulative total. After obtaining the sum of all the nodes, each value was divided by the total to generate a ratio for every hour throughout the year. This way, the ratios could be employed to calculate an annual hourly distribution of residential heat demand throughout the year.

Following the data-gathering process for the hourly ratios per node, it was necessary to determine the consumption per capita of natural gas in both Spain and Portugal. Spain’s per capita natural gas use was obtained from the Eurostat datahub, held by the European Commission [43]. The amount was subsequently multiplied by the population in each Spanish autonomous community included in the system to determine the yearly natural gas usage in the residential sector per site. The population data was obtained from the website ”Datosmacro.com” [48]. The per capita data for Portugal was unavailable. Instead, the total residential natural gas consumption in Portugal for the year 2019, obtained from ”Enerdata,” was divided by the total population of Portugal, sourced from the Spanish Institute of Statistics [38] [75]. The yearly per capita residential natural gas consumption for every node was multiplied by the previously determined hourly ratios for each relevant node, using equation 4.7. The variable ”x” indicates the hour within the year, whereas the variable ”y” denotes one of the 20 inland nodes. Ultimately, equation 4.5 was utilized to adjust the demand with the year 2030 using the CAGR obtained from the Iberian Power and Renewables Market Forecast authored by Aurora [13]. The approach described above is summarized in Table A.11.

$$Hourly\ Residential\ Heat\ Demand_{(x,y)} = Ratio\ Hour_x * Annual\ Residential\ Heat\ Demand_y \tag{4.7}$$

4.5. Technology Data

Once the relevant information was collected for the four different demands in the model, the data required to characterize the various technologies included was compiled to finalize the model. It is important to note that throughout the construction phase of the model, a distinction was made between the existing technologies already installed and the future technologies that will be installed by 2030. The assumption made in this study is that the existing technologies do not incur any capital costs (CAPEX); however, the technologies to be implemented do require such expenditures. The current technologies were incorporated into the model with their respective specifications from 2019 to 2022 in the ”tech” file, whereas the technologies projected for installation in 2030 were included based on future estimates and placed in the ”new techs” file.

The locations and capacities of the technologies under current utilization in Spain and Portugal were found and used to characterize the model’s initial state. This was done by using the data hub of the Red Electrica de España (REE) for Spain and an open infrastructure map together with ”The Wind Power” database for the case of Portugal [133] [144] [127]. This was done because the Red Electrica Nacionais (REN) data hub did not provide the exact location of the installed capacities. For validation, the capacities extracted from the map and the website were then summed together and compared to the total installed capacities expressed in the REN data hub.

On the contrary, the future technologies expected to be implemented by 2030 have not been defined in terms of their specific locations and capacities. The rationale for utilizing the model is in its ability to establish the most advantageous placement and capacity allocation for each technology, considering cost considerations, demand levels, and the renewable energy potential at each specific node. In addition, the model also expands the existing renewable technologies like solar photovoltaic (PV) and onshore wind, easier at nodes containing an installed input capacity. The absence of installation limits for offshore wind farms can be attributed to the wide availability of space and the significant capital expenses associated with their establishment, which reduces the feasibility based on cost minimization.

4.5.1. Production Technologies

As previously said, production technologies were categorized into renewable and non-renewable energy sources. To incorporate this attribute into the model, it is necessary to establish the definition of the technology ”parent,” either ”supply or supply_plus,” for non-renewable and renewable, respectively. Additionally, it is important to consider that fuel costs are relevant for non-renewable energy sources, but they are absent in the case of renewable energy sources. This parameter introduces variable expenses to a particular technology based on the existing production volume. It is important to note that only electricity and hydrogen production technologies fall under the category of ”production technologies.” All of the heat production technologies fall into the conversion technologies category.

Renewable Production Technologies

In this model, renewable electricity production was performed using solar PV and thermal, onshore and offshore wind farms, and hydro-power (hydro-reservoir or run-off-river). Since these technologies exist in the current Iberian energy system, they were modeled as already installed technologies. They were also established as technologies to be installed since both countries’ objectives are to significantly increase their capacities by 2030, as stated in sub-section 4.1.

It is also important to remark that synthesizing time and capacity data for solar and wind energy is not easy since data must include enough spatial and temporal resolution, the correlation between these two factors, and the precise representation of a solar plant or wind farm behavior. Poorly processed time and spatial data, such as selecting a typical meteorological behavior of a year or average capacity factors throughout the whole year, will lead to very significant errors in the results of the simulations [156] [125]. To cope with the possibility of causing a big error in the results based on the input data about the capacity factors for solar and wind power plants, the database named ”renewable.ninja” was used. This database was created by Pfenninger and Staffell, 2016 as a result of their research paper.

Solar PV

The required input data to characterize solar PV plants included the location and associated capacity,

the estimated capacity factor of that location, and technology specifications. To gather the data about the capacity factors, a spreadsheet containing the hourly data values throughout the year from ”renewables.ninja” [125]. The values are not estimated for the year 2030. Nevertheless, it was assumed that the capacity factors would be the same. The technology specifications, including lifetime, CAPEX, and OPEX, were retrieved from the ”Technology Datasheet for Generation of Electricity and District Heating from the Danish Energy Agency (DEA) [3]. This database contained information for three types of solar PV structures: rooftop PV, industrial PV, and utility-scale PV. The utility-scale was assumed to be the only type of solar PV structure in the system since it is the most appropriate for the system of analysis and the most common application of solar PV on a global scale [70].
The data for capacity and location were extracted from the electricity generation dataset from REE in the case of Spain [133], and from the generation database from REN for the capacity [137] and the location from the Open Infrastructure Map [144]. For the future solar PV case, some of the technology specifications have changed based on predictions made by the Danish Energy Agency (DEA) for 2030. Regarding location, it is assumed that only the regions with solar PV plants can install more, focusing on the scale-up process. This englobes all of the land nodes in the system.

Solar Thermal

Collecting data about the present installed capacity, location, and technical features was necessary to define solar thermal energy. The data hub of ”Red Eléctrica Española” (REE) was employed to collect information concerning locations and associated installed capacities [133]. Portugal’s exclusion from this search was due to its lack of solar thermal plants. Secondly, to characterize this technology, it was necessary to consider lifetime, CAPEX, OPEX, and capacity factors. The initial three were obtained from the IRENA report on ”Concentrating Solar Power” [76]. Online sources did not provide specific statistics on the capacity factor for solar thermal energy. Therefore, the daily solar thermal energy generation in each specific node with installed solar thermal plants in Spain during 2019 was divided by the total installed capacity. This calculation yielded a series of values representing the capacity factors for each location throughout the year. Both were obtained from the REE datahub [133]. It is important to remark that it was presumed that the capacity factors calculated for 2019 would be similar to those projected for 2030. The calculation is displayed in equation 4.8.

$$Capacity\ Factor = Hourly\ Solar\ Thermal\ Generation\ /\ Installed\ Soalr\ Thermal\ Capacity \tag{4.8}$$

Onshore Wind Farms

To properly represent onshore wind technology, it was necessary to consider many factors such as capacity, technical specifications, capacity, and location associated with onshore wind farms. Initially, the hourly dataset of capacity factors for the various nodes in Portugal and Spain was acquired from ”renewables.ninja” [125]. For this data, it was assumed that the values acquired would be comparable in 2030. The technology specifications, comprising parameters such as lifetime, capital expenditure (CAPEX), and operational expenditure (OPEX), were obtained from the technology datasheet titled ”Electricity Generation and District Heating” sourced from the DEA [3]. The installed capacity per site of existing wind farms was obtained from the Installed Capacity statistics provided by the REE for Spain [133]. In contrast, the data about Portugal was obtained from two sources: ”The Wind Power: Wind Energy Market Intelligence” [127], and the Open Infrastructure Map, which provided information regarding the geographical locations inside Portugal [144].

The methodology employed to characterize future onshore wind farms is similar to that employed for solar technologies. The installation of additional onshore wind farms was restricted to places with existing facilities by the intended scaling-up approach outlined in the decarbonization goals of both countries. Therefore, it is feasible for all 20 nodes between the two nations to install new onshore wind energy systems.

Offshore Wind Farms

The capacity factor, technical specifications, capacity, and location data were needed to characterize offshore wind farms properly. The dataset concerning the capacity factor was obtained by retrieving an hourly collection of information for the year 2019 from renewables.ninja [125]. Due to the absence of meteorological forecasts, the available data was increased by a factor of 20%. This was influenced by the observation that offshore wind farms will display a capacity factor close to 50%, in contrast to the 24% capacity factor exhibited by onshore wind farms [139] [73]. The technology specifications, encompassing lifetime, capital expenditure (CAPEX), and operational expenditure (OPEX), were obtained from the DEA technology datasheet titled ”Electricity Generation and District Heating” [3]. The data regarding the location of the offshore wind farms was acquired from the governmental sources of Spain and Portugal [107] [20]. The capacity data was sourced from ”The Wind Power: Wind Energy Market Intelligence” [127]. Including a single value was sufficient, given the presence of a single offshore wind farm located along the coastline of the Iberian Peninsula, specifically in Viana do Castelo.

Hydro-Power

The data required to characterize the hydro-power source included the technology specifications, capacity, location, and capacity factor. The model divided the hydro-power technologies into ”hydro-reservoir” and ”run-of-river”. The differences between the two were relevant only for their technical characteristics. These data included the efficiency, lifetime, and OPEX retrieved from the DEA technology datasheet [3]. The capital expenses were unnecessary since the model was not allowed to create more hydropower plants. The information about the capacity and location was obtained from the REE and REN datahubs, as well as from the Open Infrastructure Map, needed for the Portuguese locations [133], [137], [144].

In contrast to the other technologies, the capacity factors for hydro-power plants could not be obtained from renewables.ninja, or any other source. Therefore, the variable ”carrier_prod_max” was employed to limit electricity production from hydro-power sources. The limitation was established to an average capacity factor for hydroelectric energy in Spain in the year 2017 of 13.83% [57].

Non-renewable Production Technologies

This study generated non-renewable electricity by employing CCGT and nuclear plants. The technical features of these technologies comprised their efficiency, lifetime, ramping rate, capital CAPEX, OPEX, CO_2 costs, and fuel expenses, encompassing natural gas and enriched uranium. The initial set of five parameters was obtained from the technology datasheet provided by the DEA [3]. Regarding the expenses related to fuel, the costs of both natural gas and uranium were sourced from the Energy Technology Systems Analysis Program (ETSAP) [65]. The cost of CO_2 emissions generated by CCGT plants for the year 2030 was derived from the ”Iberian Power and Renewables Market Forecast” authored by Aurora [13]. The conversion of the data from €/tonne to €/MWh by applying a conversion factor of 0.386 $kgCO_2/kWh$ [53]. The capacity and geographical distribution of these power plants were determined through the utilization of the REE data hub for the Spanish CCGT and nuclear plants and the Global Energy Monitor for the Portuguese CCGT plants [133], [109].

Hydrogen Production Technologies

The model examines the direct production pathway for hydrogen, utilizing SMR with CCS technology, which is capable of generating blue hydrogen. Spain and Portugal do not own any blue hydrogen production facilities, as their focus is mostly on the generation of green hydrogen [29], [106]. According to Roca, 2022 a mere 5% of the hydrogen projects scheduled for implementation in Spain by 2030 are dedicated to developing blue hydrogen technology. Despite its relatively lesser proportion than other European Union countries, including this technology in the future energy system is imperative. This is justified by the current cost advantage of blue hydrogen, which is two to three times more affordable than green hydrogen, as reported by IRENA [79]. Hence, this particular asset has been selected for inclusion within the technologies slated for incorporation by 2030.

To provide an accurate characterization of this technology, it was necessary to consider factors like efficiency, lifetime, CAPEX, OPEX, variable cost of production, and carbon dioxide costs. The technical parameters were obtained from the IEA paper titled ”Global average levelized cost of hydrogen production by energy source and technology, 2019 and 2050” [66]. In contrast, the financial indicators encompassing were obtained from the works of Reis and Glachant, 2021, and Collodi et al., 2017. The cost of CO_2 was determined using equation 4.9. The calculation in question relies on the projected cost of carbon dioxide (CO_2) for the year 2030, derived from the ”Iberian Power and Renewables Market Forecast” report authored by Aurora. Additionally, the emission rate of CO_2 per MWh of blue hydrogen production is sourced from the work of Ayodele et al., 2020. The selection of the model was not restricted in terms of location and capacity and was determined based on the established initial parameters and the fundamental characteristics of the system.

$$\text{CO}_2\ Cost\ 2030\ (€/MWh) = \text{CO}_2\ Production\ (ton\text{CO}_2/MWh) * 2030\ \text{CO}_2\ Price(€/ton\text{CO}_2) \quad (4.9)$$

4.5.2. Conversion Technologies

Regarding the conversion technologies for this model, two different types were identified based on the inlet energy carrier before the conversion process. This can be seen in figure 3.3. The two identified types of conversion technologies can be divided into electricity and hydrogen conversion technologies. The outlet energy carrier, in this case, was not relevant in defining the type of conversion technology. It is important to mention that gas boilers were not considered conversion technologies but production technologies since they directly use gas as a fuel for heat generation. The CO_2 costs for this technology, which other conversion technologies do not have, were also calculated by using equation 4.9

Electricity Conversion Technologies

This analysis characterized the system by four distinct power conversion technologies. Two technologies allow the conversion of electricity into hydrogen via the process of electrolysis, while an additional two technologies allow the conversion of electricity into heat. The electrolysis components utilized in this system consist of alkaline electrolyzers and proton-exchange membrane electrolyzers, as described in section 2.2. The heat generation methods employed in this system comprise electric boilers and heat pumps.

Given the absence of these technologies in the current integrated energy system, they were incorporated into the planned installations for 2030. Hence, the process of characterization exhibited similarities across all components. The necessary technological data covers conversion efficiency, lifetime, ramping time, CAPEX, and OPEX. Capacity and location were important factors to consider too. The technical data for both types of electrolyzers was sourced from the DEA technology datasheet for Renewable Fuels [2]. Conversely, the technical data about the conversion of electricity to heat was obtained from the technology datasheet titled ”Electricity Generation and District Heating” published by the DEA [3].

Finally, the model does not impose any constraints on the capacity and location of these technologies. Given that the model does not currently possess any of the four technologies, it was decided to delegate the determination of location and capacity to the software. This decision was based on the criteria of cost efficiency and demand management. Hence, all nodes were potential candidates for installing the technologies with a non-defined capacity boundary. Later on, constraints will be imposed on electrolyzers’ capacities to facilitate the examination of certain interactions inside the model based on the formulated research questions.

Hydrogen Conversion Technologies

Hydrogen conversion technologies relate to the various technologies integrated within the system that enable the production of energy carriers through hydrogen. This model includes two distinct hydrogen conversion systems. One is the combined cycle hydrogen turbine (CCHT), which possesses the capacity to produce electricity through hydrogen. Secondly, the hydrogen boilers can create heat through hydrogen. The essential technological information includes parameters such as efficiency, ramping rate, lifetime, CAPEX, OPEX, capacity, and location. In parallel with the technologies employed for electricity conversion, the two hydrogen conversion technologies were conceptualized as future installations within the model. This is due to the absence of these technologies within the Iberian Peninsula at present [133] [137].

The technical data about combined cycle hydrogen turbines (CCHT) was sourced from several references. The ramping rate was sourced from the IRENA publication ”Hydrogen: A Renewable Energy Perspective” (IRENA, 2019). The remaining technical data and financial information were sourced from Oberg et al. (2022). However, the characterization of hydrogen boilers presented greater complexity due to the need to maintain industrial data security. The article titled ”Boilers operating on hydrogen:

A comprehensive overview" authored by Gerardo Lara [94] included data on the lifetime and efficiency of the boilers. No sources were identified for the financial data. Hence, it was assumed that the aforementioned system possessed specifications comparable to those of the gas boilers projected for 2030. Thus, the data provided in the DEA technical datasheet titled "Electricity Generation and District Heating" was used [3].

The process exhibited similarities to electricity conversion technologies in both its decided location and its overall capacity. Given the absence of these technologies, the determination of installation locations and quantities was given to the model, which relied on optimization objectives.

4.5.3. Storage Technologies

Two different clusters were defined for storage technologies. The first cluster entails the technologies capable of storing electricity, while the second cluster involves the technologies defined for hydrogen storage. The selected technologies for electricity storage include lithium-ion (Li-ion) batteries and pumped hydro-storage (PHS). These technologies can also be found in figure 3.3.

Electricity Storage Technologies

Lithium-ion batteries (Li-ion) and pumped hydro-storage (PHS) were included to address the inherent fluctuation in production associated with renewable energy sources. The inclusion of PHS in the group of currently existing technologies can be attributed to the heavy reliance of both countries on these structures [133] [137]. However, the model was not allowed to further install this type of technology due to its significant construction time [4]. On the other hand, Li-ion batteries were categorized as non-existent technologies since neither Spain nor Portugal currently have any relevant battery facilities in use [133] [137].

Gathering information about their energy or storage capacity, location, and technological specifications was necessary to characterize both technologies accurately. The information regarding the capacity and location of PHS plants in Spain was obtained from the REE datahub [133]. The Portuguese PHS plants utilized the ENTSO-E Transparency Platform and the Open Infrastructure [39] [144].

The technological data necessary for these technologies included factors such as efficiency, energy capacity to storage capacity ratio, lifespan, charge and discharge rate, storage loss, capital expenditure (CAPEX), and operational expenditure (OPEX). The data for both methods was sourced only from the Technology Data for Energy Storage of the Drug Enforcement Administration (DEA) [4].

Hydrogen Storage Technologies

The modeling of the hydrogen storage components of the system was limited to the salt cavern. The technology in question was conceptualized as a hypothetical innovation for 2030, indicating its current nonexistence. It is important to remark that the installation of this technology is limited to underground salt structures with special features exclusively found in such environments, as mentioned in section 2.2. The location and potential capacities of this technology were derived from the articles written by Simón, Férriz, and Correas, published in 2015, and Simón, Férriz, and Correas, published in 2015. The Technology Data for Energy Storage of the DEA was utilized to obtain the necessary technical and financial information for characterizing the technologies in the model [4].

4.5.4. Transmission Technologies

The transmission technologies were divided into two types for their characterization in the model. The energy carrier they were transmitting in the system differentiated the two formed clusters. The first type of transmission network involves electricity transmission technologies, formed by the electricity grids, and the second type, the hydrogen transmission technologies, formed by hydrogen pipelines.

Electricity Grid

The model considered high-voltage AC transmission lines (220 to 300 kV) as the primary infrastructure for electricity transportation throughout the grid. The technology in question was incorporated into both existent and non-existent technologies. For the existing infrastructure, the current electricity networks of Spain and Portugal were replicated in the model, utilizing data published by the Transmission System

Operators (TSOs) of both countries [133] [137]. Furthermore, the technology could scale up in the 2030 scenarios due to the absence of linkages between offshore and land nodes and the need to expand the grids in response to projected demand growth [13]. The essential technological requirements for characterizing the energy grid include lifetime, efficiency per km, CAPEX per km, and OPEX per km. The information required to characterize the technology was obtained from the publication ”Technology Data for Transport of Energy” authored by the DEA [5].

Hydrogen Pipelines

The model incorporated both onshore and offshore hydrogen pipelines. The absence of a hydrogen transmission network in Spain and Portugal has led to the nonexistence of hydrogen pipelines in the initial model [133] [137]. Hence, the precise locations and capacities of the model were not predetermined and were permitted to be established within the model criteria. However, it is important to note that in a subsequent phase of this study, one of the scenarios will simulate the existing gas network. This is because there are plans to refurbish the gas infrastructure by 80% to establish the forthcoming onshore hydrogen grid [35]. In the context of offshore hydrogen pipelines, the absence of a reference structure resulted in a lack of constraints within the model.

The data for characterizing the hydrogen pipelines included parameters such as the lifetime, efficiency per kilometer, CAPEX per kilometer, and OPEX per kilometer. The data was obtained from the publication ”Technology Data for Transport of Energy” developed by the DEA [5]. The capacity of the hydrogen pipelines to be built was not constrained due to the uncertainty surrounding future hydrogen production. Additionally, the potential for constructing bidirectional pipelines for a specific link between nodes further contributed to this lack of limitation [35].

5

Scenario Definition

Chapter 5 encompasses a concise explication of the key uncertainties regarding the incorporation of hydrogen into the Iberian 2030 energy sector, alongside the parameters that will be examined to mitigate these uncertainties. Subsequently, an in-depth assessment of the selected scenarios will be presented accompanied by a discussion of the logic behind each selection.

5.1. Scenario Selection Criteria

To address the study issues and account for the limited understanding of interactions among system components, six distinct parameters were selected as variables, resulting in the creation of several system scenarios. The proposed scenarios include the base-case scenario, a scenario matrix comprising three distinct variables for analysis, the demand variation scenario, the environmental policy scenario, and the electrolyzer capacity case.

The base-case scenario represents the most commonly estimated situation of the Iberian energy system for the year 2030, based on the chosen literature and data. This scenario run was essential to have a base to compare all of the rest of the scenarios run and be able to gain insights based on the differences between them. This scenario gives a clear picture of how the Iberian Energy System could look in 2030.

The scenario matrix, chosen as the first part of the sensitivity analysis of the system answers the second research sub-question: ”To what extent will the new technologies related to hydrogen production pathways accelerate the deployment of Renewable Energy Sources?”. In this matrix, the different possible supply pathways of hydrogen will produce hydrogen in all the allowed pathways and see the specific effect on the deployment of RES, as well as the effect on the rest of the technologies, CO2 emissions, and the overall system cost, by varying the capital expenses of the new RES and green hydrogen technologies to be implemented. This will lead to a total of four different scenario combinations

In addition, the scenario matrix, together with the established environmental policies in the form of group constraints, and the base case scenario will help answer the second research question: ”How will the variation of future energy demand, electrification, and the substitution of hydrogen for natural gas affect the investment in renewable energy sources and hydrogen technology?”. The base-case scenario covers the first part of the question, consisting of the effect of demand on the system’s costs and the electrification process (technologies that substitute the use of fossil fuels with electricity). The second part of the question covers the reduction of natural gas usage, studied by the environmental policy, the no blue hydrogen scenario, and the scenario matrix, which also affect the overall state of the system, as well as promoting or not the electrification process.

Finally, the last scenario answers the third research question: ”How will the planned electrolyzer capacity in Portugal and Spain affect the overall energy system by the year 2030?”. This sub-question is answered through the PNIEC scenario, in which only one simulation is performed, establishing a boundary that obliges the system to install a specific electrolyzer capacity. This is performed to see the effect of the planned electrolyzer capacity for 2030 in Spain and Portugal on the deployment of renewables, electrification, and overall system costs, to see if the national plans established by both countries are realistic.

Figure 5.1 provides a summary of the scenarios generated in this study and illustrates the connections between each scenario and the specific sub-question it is intended to address.

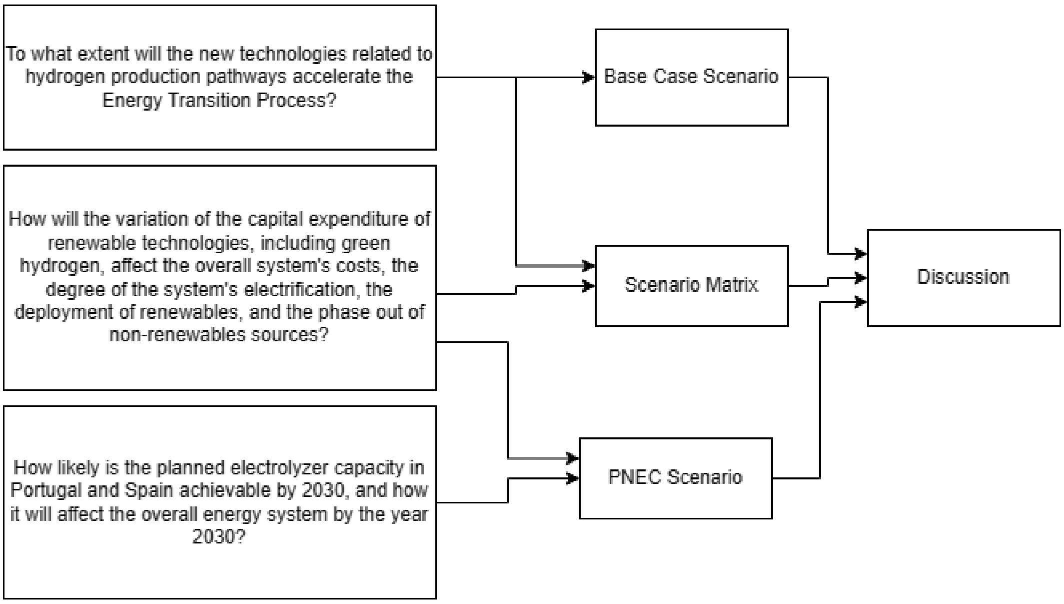

Figure 5.1: Formulated scenarios connected to the different research sub-questions

5.2. Base-Case Scenario

The base case scenario is the one representing the future Iberian integrated energy system fully based on the data retrieved from different sources, shown in sections 4.3 and 4.5. The selected decision variables comprising the allowed routes for the production of hydrogen, the associated hydrogen technology costs, variations in heat, hydrogen, and electricity demand, and the capital investment required to scale up the renewable energy generation technologies form the core of the selected scenarios to answer the defined research questions.

The base case scenario projects a total electricity demand of 246.7 TWh for Spain in 2030, based on forecasts provided by Aurora for the Iberian Power and renewable market [13]. The estimated power demand for Portugal in 2030 is 50.3 TWh, as stated in the Energy Policy Review of Portugal, produced by the IEA [68]. The previously defined heat demand was allocated between residential and non-residential sectors. The residential heat demand for 2030 in Spain was obtained from the Enagas data hub, whereas the heat demand for Portugal was sourced from the REN data hub [33] [136]. The derived numbers for each country's yearly heat demand were 320 TWh and 97 TWh, respectively. The data was divided into residential and heat demand categories, as well as per node and in an hourly distribution, to accurately represent the system in the model, as described in section 4.3. The hydrogen demand as a feedstock for the industry, particularly for Spain, was obtained from the Spanish "PNIEC" and amounts to 500,000 tons of hydrogen per year. The figure was converted to TWh and then adjusted for the year 2030, yielding a value of 0.653 TWh annually [108].

The remaining crucial decision parameters that define the system are the required capital investment for electrolyzers, together with the natural gas price and the cost of CO_2 emissions. The CAPEX for the two distinct types of electrolyzers simulated in the system were obtained from the "DEA" data hub [3]. The obtained values were 460 €/kW for the alkaline electrolyzers and 650 €/kW for PEM electrolyzers. Conversely, the projection generated by Aurora [13] indicated that the prices of natural gas and the costs associated with greenhouse gas emissions were 32.6 €/MWh and 110.8 €/ton of CO_2, respectively. The monetary value of CO_2 emissions was later derived in €/MWh by considering the technical characteristics of each polluting technology (CCGT and gas boilers) and applying a conversion factor. This value was then used as input in the model.

Parameter	**Value**
Natural Gas Price (€/MWh)	32.6
Carbon Emission Costs (€/ton)	110.8
AEL CAPEX (€/kW)	450
PEM CAPEX (€/kW)	650
Spanish Heat Demand (TWh)	320
Spanish Electricity Demand (TWh)	246.7
Portuguese Heat Demand (TWh)	97
Portuguese Electricity Demand (TWh)	50.3

Table 5.1: Summary of the values taken for the decision variables in the base case scenario

5.3. Scenario Matrix

One of the main outcomes required to answer the defined research questions in chapter 1, is the necessity to analyze the effect of hydrogen technologies on the overall system, as well as the interaction between these hydrogen technologies and the scale-up of existent renewable energy generation sources and incorporation of the newer ones. To do so, two different parameters were selected. The capital expenditure of hydrogen conversion technologies (electrolyzers), and the capital expenditure of the renewable energy generation technologies to be installed in 2030. As mentioned in the section 5.1, these technologies will have an optimistic and pessimistic situation to be analyzed. Based on this, it was decided to create a scenario matrix in which both parameters will vary between the optimistic and pessimistic situations. Like this, the model will render 4 different scenarios to be analyzed, based on all the possible combinations. Table 5.2 visually represents this process.

5.3.1. Electrolyzer CAPEX Variation

The choice of associated capital expenditure fluctuation for the electrolyzers relies on forthcoming cost projections proposed by Reksten et al., 2022 [135]. This study provides an estimate of the capital expenditure for AEL and PEM electrolyzers in large-scale projects (over 100 MW), which falls within the range of 384 and 1071 €/kW by 2030. This range also falls in the one proposed in the ”Danish Energy Agency Technology Data” [3]. This estimate considers the anticipated reduction of the capital expenditure gap between these two types of electrolyzers. However, the authors assert that there could be further cost reductions in the future and that PEM may eventually surpass the current less expensive form in terms of cost-efficiency. This pertains to a significant decrease of 45% in the necessary capital expenditure for electrolyzers, based on the prevailing pricing of PEM electrolyzers [89]. Two distinct situations were derived from the provided information: optimistic and pessimistic. The optimistic scenario assumes a 50% decrease in capital expenditure (CAPEX), whereas the pessimistic scenario assumes a 40% decrease according to the ranges given by the Danish Energy Agency.

5.3.2. RES Cost Variation

The ultimate variable of the matrix represents the amount of capital investment required for the establishment of renewable energy sources by the year 2030. Two distinct scenarios were constructed to examine the impact of varying capital expenditure on renewable energy sources (RES) on the total system and its interaction with the integration of hydrogen technology. These examples can be categorized as pessimistic, and optimistic. The ”Technology Data for Generation of Electricity and District Heating” report published by the DEA was utilized to determine the precise CAPEX value for each scenario [3]. This document presents the projected capital expenditure for solar PV and wind energy in the year 2030, together with the specified lower and higher limits set for the forecast. The CAPEX value for the three established scenarios was determined by selecting these three values. The moderate scenario predicts an 8% fall in CAPEX, the pessimistic scenario predicts a 3% increase and the optimistic scenario predicts a 25% decrease.

Scenario Matrix	Electrolyzer CAPEX	RES CAPEX
Optimistic	50% Reduction	25% Reduction
Pessimistic	40% Reduction	3% Increase

Table 5.2: Visual Representation of the Scenario Matrix

5.4. PNIEC Capacity Scenario

The last scenario concerns the completion of the answer to the third research sub-question, which entails the effect of the planned installed capacity of electrolyzers and renewable energy sources on the overall energy system of the Iberian Peninsula. To do so, the total planned capacity of RES in Spain and Portugal was retrieved from both of the national energy transition strategies [105] [10]. The values are presented in table 5.3. This scenario's objective is to validate the model by comparing it to the chosen benchmark, consisting of the objectives stated in both PNIEC and PNEC. Thus, the effect of the expected RES capacity selected as the parameter will result in a specific installed capacity of electrolyzers, based on the cost minimization function. The capacities will then be compared to the values stated in both energy transition plans (11 and 5 GW of electrolyzer installed capacity for Spain and Portugal respectively) for part of the validation process.

Installed RES Capacity by 2030 (GW)	Solar PV	Solar Thermal	Wind Onshore	Wind Offshore
Spain	76	4.8	58	4
Portugal	20.7	2	11	10

Table 5.3: Summary of the Predicted Renewable Capacities by 2030 for Spain and Portugal, according to the PNIEC and the PNEC

6

Presentation and Analysis of Results

Throughout this chapter, the results obtained from the scenarios specified throughout chapter 5 will be presented. In section 6.1, the results from the base case scenario are presented. These results will be used as a base to analyze the effect of the specified variables in chapter 5 on the overall system. In section 6.2, the results from the different scenarios coming from the scenario matrix are presented in section 5.3. Here, the CAPEX of renewable energy sources and electrolyzers, and the available hydrogen production technologies are varied in different combinations to generate different situations. Finally, the last two scenarios test the expected RES and electrolyzer installed capacity stated in the PNIEC and PNEC, from Spain and Portugal, respectively, to see the effect it generates in the overall system.

6.1. Base-Case Scenario Results

6.1.1. System-wide Results

The results for the base case (BC) scenario gathered data regarding the three carriers implemented in the model.

In 2030, the Iberian energy system needed a total installed electricity production capacity of 340.96 GW. Of the entire amount, 264.91 GW was attributed to the installed capacity of renewable energy sources, resulting in an electrical production of 541.73 TWh within a year. Conversely, the capacity of non-renewable energy sources amounted to 36.27 GW. This value represents the original non-renewable installed capacity, as the model was restricted from adding more capacity. The fuel-based energy sources generated a combined total of 53.87 TWh of electricity. The cumulative capacity of electricity conversion and storage technologies, encompassing pumped hydro-storage facilities, Li-ion batteries, and hydrogen turbines (CCHT), reached 39.79 GW. The combined utilization of these technologies resulted in the re-introduction of 21.10 TWh of electricity into the system. Therefore, the total electricity generated by production technologies resulted in 595.6 TWh. Combining these results with the electricity produced through conversion technologies or re-introduced into the system from storage facilities, resulted in a total electricity production of 616.71 TWh to meet a demand of 335.04 TWh. The discrepancy between the electricity demand and the electricity production arises from the system coupling process which will be explained later. Figures 6.1 and 6.2 provide a concise overview of these findings.

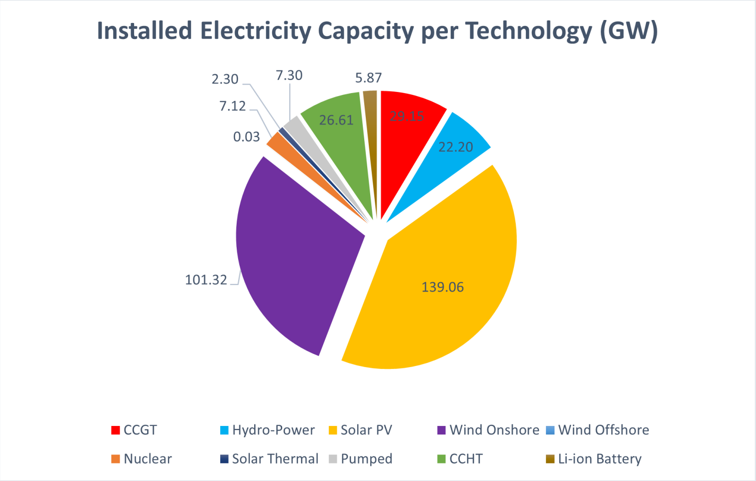

Figure 6.1: Installed electricity capacity per source in the 2030 Iberian Energy System

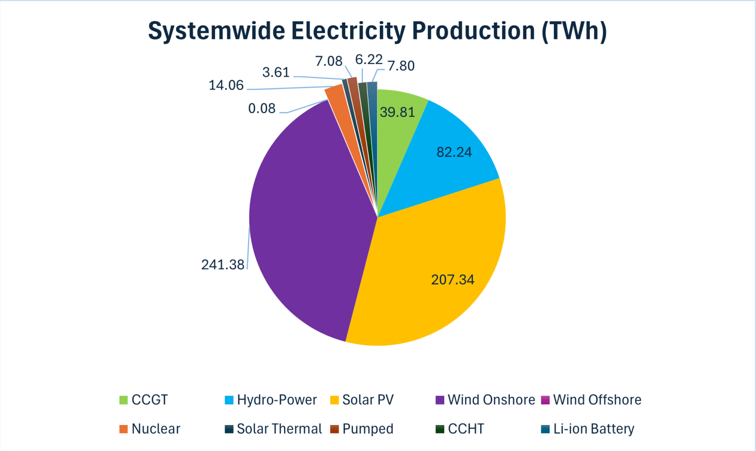

Figure 6.2: Total electricity production per source in the 2030 Iberian Energy System

In 2030, the total installed hydrogen production capacity in the base case (BC) amounted to 25.21 GW. The total comprises the aggregated installed capacity of both PEM and AEL electrolyzers, which contribute to the overall installed capacity of green hydrogen. Furthermore, it encompasses the capacity of SMR + CCS facilities, which provide the overall capacity for blue hydrogen production. The installed capacity of green hydrogen reached 6.66 GW. The total installed capacity consisted of 3.44 GW of alkaline electrolyzers and 3.22 GW of PEM electrolyzers. In contrast, the capacity of blue hydrogen reached 18.55 GW. The green hydrogen generation amounted to 19.28 TWh. PEM electrolyzers contributed to 54% of the green hydrogen production, while the remaining portion was produced by AEL. It is noteworthy that the installed capacity of AEL slightly exceeded the capacity of PEM. However, the increased hydrogen production from PEM can likely be due to its superior efficiency and the shorter ramping times, included in the model as inputs. In contrast, the system produced a cumulative amount of 16.67 TWh of blue hydrogen. Finally, the total amount of hydrogen imported into the peninsula from external sources reached 19.19 TWh, making it the largest contributor of hydrogen in the system. Summing up, the total amount of hydrogen produced was 55.14 TWh, for a total direct hydrogen demand of 19.12 TWh. The rest of the hydrogen was consumed in the other sub-systems or stored to replenish the initial hydrogen stored (4.5 TWh) as shown in figure 6.4. Again, the discrepancies are caused by the implementation of hydrogen storage technologies, and the higher system coupling process. The findings are illustrated in Figures 6.3 and 6.4.

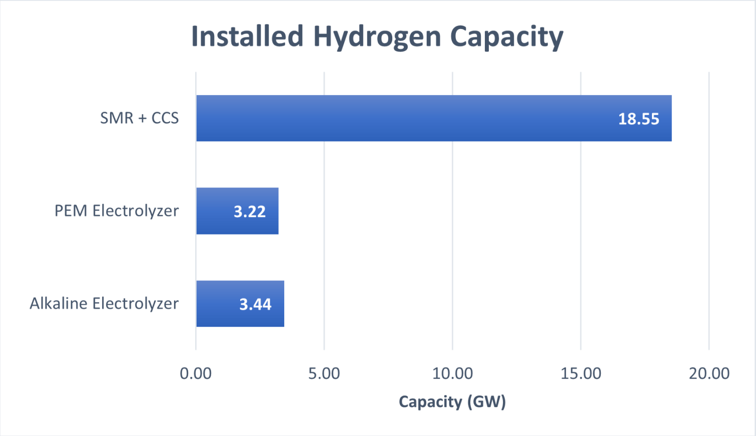

Figure 6.3: Installed hydrogen capacity per production technology in the 2030 Iberian Energy System

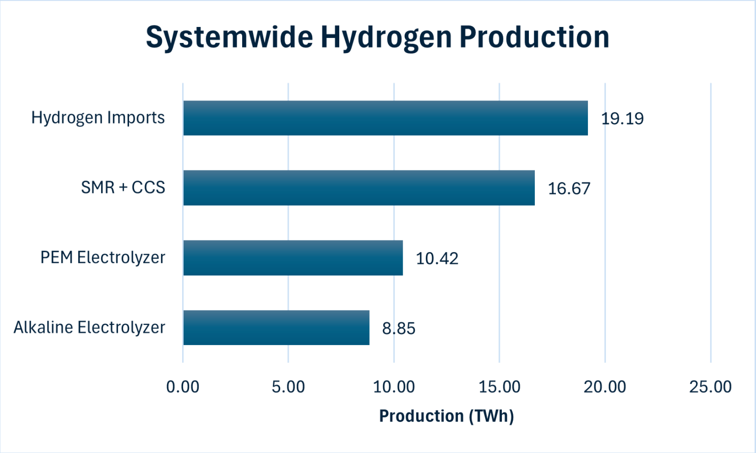

Figure 6.4: Total hydrogen produced and imported in the 2030 Iberian Energy System

The heat generation technologies in the BC have a total installed heat production capacity of 92.46 GW in the year 2030. The overall installed capacity includes electric boilers and hydrogen boilers, which contribute to the renewable heat production capacity. Gas boilers, on the other hand, represent the non-renewable installed heat capacity. The combined installed capacity of hydrogen boilers (18.63 GW) and electric boilers (47.28 GW) accounted for 71.3% of the total installed heat capacity. The remaining was completed with the conventional gas boilers, which had an installed capacity of 26.55 GW. Figure 6.5 displays the findings of the installed heat capacity. In 2030, the system's heat demand reached 287.62 TWh of heat consumption and the same amount was generated, since in this system, heat can only be used to meet its requirements. The total is derived from the aggregate output of the three distinct heat-generating technologies mentioned above. The hydrogen boilers generated 19.76 TWh of heat, whereas the electric boilers produced 195.24 TWh, followed by 73.63 TWh of non-renewable heat generated from gas boilers. The results are displayed in figure 6.6.

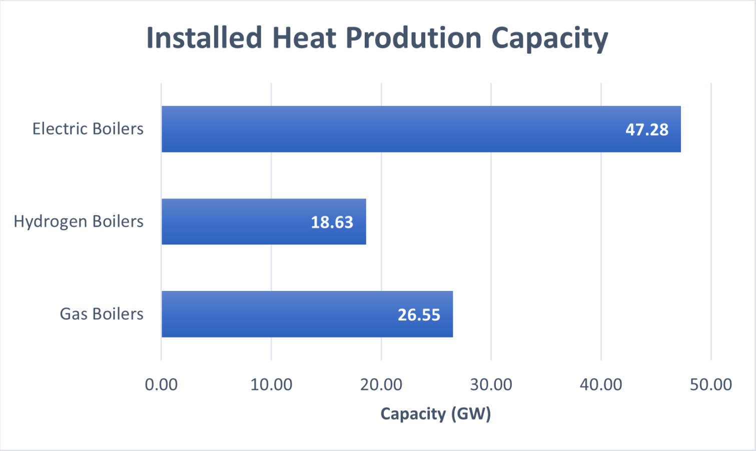

Figure 6.5: Installed heat production capacity per technology in the 2030 Iberian Energy System

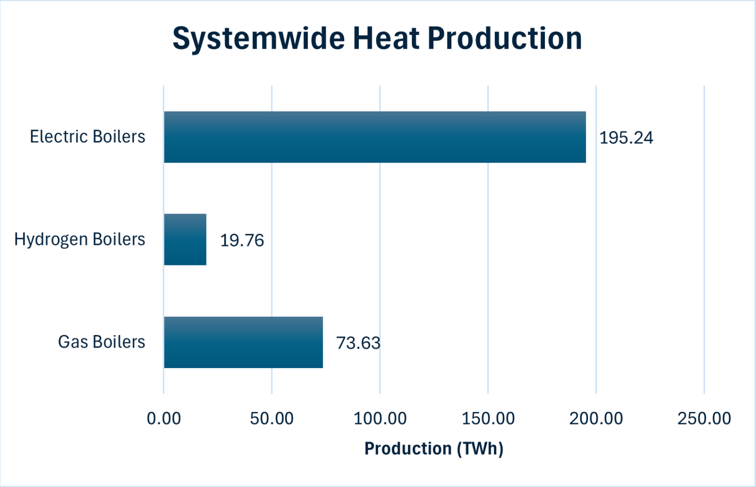

Figure 6.6: Total heat generation in the 2030 Iberian Energy System

Figure 6.7 illustrates the results of the installed storage capacity of the permitted technologies in the system, which are essential for supporting renewable electricity and hydrogen generation. These options encompass lithium-ion batteries, salt caverns, and pumped hydro-storage (PHS). Salt caverns were the most prevalent means of energy storage due to their low construction cost and favorable storage-to-energy capacity ratio. Subsequently, Li-ion batteries were succeeded by PHS. However, the chosen system approach generated very few new PHS plants mostly because of the substantial capital expenditure required, which fails to account for the long-term value of the investment, since the model depicts the system in a short-term future. In addition, since the model optimizes only based on cost minimization, it fails to consider the importance of Battery Energy Storage Systems (BESS). The elevated CAPEX for the small amount of energy a battery can store is not cost-efficient from the overall perspective of the model, failing to represent its necessity to cover short-term shortages in the electricity sub-system. Therefore, reducing its installed storage capacity.

The diagram in Figure 6.8 depicts the evolution of the stored energy in the system. The majority of the energy is stored in salt caverns in the form of hydrogen, as indicated by its installed capacity. Based on the initial assumption made during the model's construction, the system is designed to begin with a sufficient quantity of hydrogen to meet its energy requirements for the whole year. Hence, it starts and concludes at an identical magnitude, approximately 4.5 TWh of stored hydrogen. The graph's configuration fails to provoke any surprise. In winter, the levels decrease significantly due to the reduced availability of RES. Upon the arrival of spring, the levels begin to rise. It is intriguing to note that during Autumn, there are significant fluctuations in weather patterns, perhaps due to the intermittent occurrence of sunny or windy days, frequent in both of the countries being investigated. Conversely, as depicted in figure B.1, Li-ion batteries, which are not apparent in the initial picture, exhibit a distinct charging and discharging cycle during the day and night. Thus, it can be concluded that salt caverns serve the purpose of storing energy at a seasonal scale, while Li-ion batteries fulfill urgent requirements, as explained in Chapter 2.

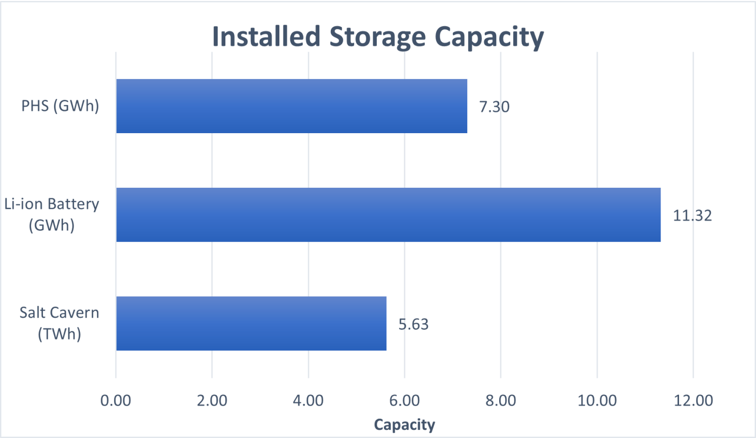

Figure 6.7: Installed storage capacity per storage technology in the 2030 Iberian Energy System

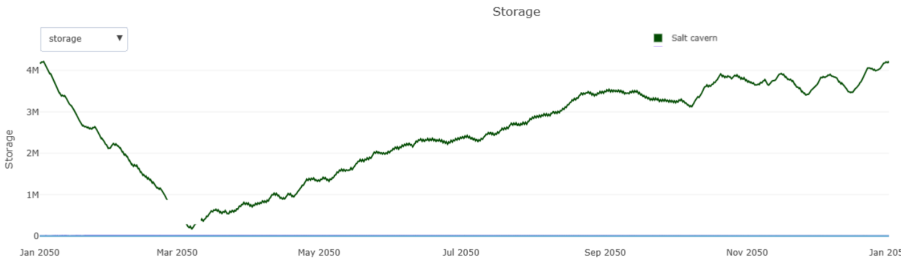

Figure 6.8: Evolution of the stored energy in the Iberian energy system over the year 2030

Regarding the transmission infrastructure, figure 6.9 depicts the results illustrating the different types of distribution grids. The high-voltage electricity lines and the onshore hydrogen pipelines connect the different inland nodes, while the new high-voltage electricity lines connect the three offshore nodes with the closest inland nodes. No offshore hydrogen pipelines were built, due to the low installed capacity of offshore wind farms which did not create sufficient energy to invest in a set of electrolyzers worthy enough. Therefore, no hydrogen pipelines were needed. Comparing the results shown in figure 6.9 to the predictions made in chapter 4, it can be seen that most of the links were implemented by the model with the exemption of a few onshore hydrogen pipelines and the set of offshore hydrogen pipelines. Additionally, it can be seen that the network of onshore hydrogen pipelines follows the same main structure as the one proposed by ENAGAS in figure 4.5 [35].

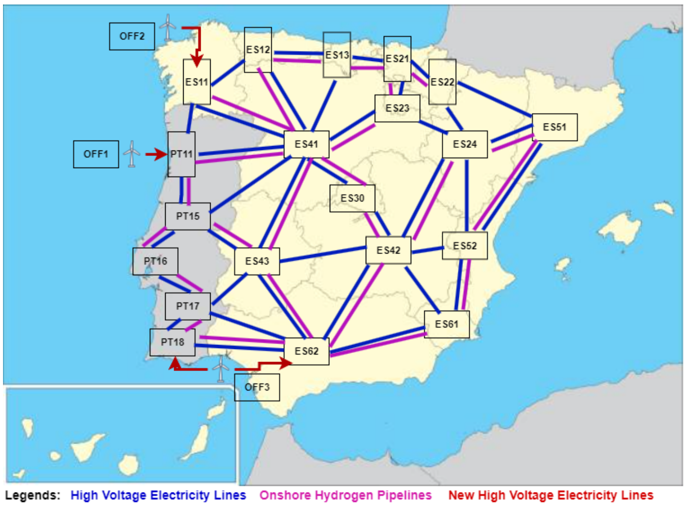

Figure 6.9: Final transmission network of the base case of the 2030 Iberian Energy Mix

6.1.2. System Behavior

To comprehensively interpret the aforementioned findings, it is important to possess an in-depth understanding of the system's general dynamics. To do so, first, an analysis of the electrification and hydrogenation process of the system will be performed. Secondly, to visually comprehend the effect of the system coupling, a specific range of time throughout the analyzed year was selected. The selected time frame was from November 24th to December 5th, because of the disparity in renewable electricity production resulting from variations in sunlight exposure and wind availability during those specific days. In addition, to gain an overall picture of the weather effect on renewable electricity production, the overall yearly capacity factors will be exposed.

System Coupling Analysis

By comparing the obtained results for installed capacities and production for the electrical and hydrogen-based technologies, with the target capacities and production rates established by the Spanish and Portuguese governments in the year 2030, the amount of electrical and hydrogen-based energy used to satisfy the heat and electrical sectors for the established scenarios will be obtained. This system's aspect is of great importance to explain the degree to which the model established the system coupling process of the 2030 Iberian energy system, as well as necessary to explain the disparities found between the installed capacities for RES and electrolyzer capacities between the model results for this year and the established objectives by the Spanish and Portuguese governments, which do not thoroughly study the system coupling process in their energy transition plans.

In 2022, taken as a benchmark to build the model, the electricity demand reached 296.5 TWh between Spain and Portugal [101] [132]. Out of this total, in Spain, 78.29 TWh were satisfied by using natural gas. In addition, nuclear generation accounted for 55.39 TWh. Finally, the renewable generation in 2022 was 114.56 TWh [133], summing to 248.2 TWh. On the other hand, Portugal had an electricity demand of 48.27 TWh. From this total, 17.47 TWh were produced from gas or similar, and 30.8 TWh from renewables. The total for renewables includes renewable sources not included in the model. Nevertheless, it is assumed for the ease of the analysis. On the other hand, the combined heat sectors from Spain and Portugal rendered a natural gas demand of 207.22 TWh for the industry and residential heat sectors. Additionally, the electricity consumption for the heat sector was 47.62 TWh [37]. This led to a total demand of 254.88 TWh in the heat sector as shown in chapter **??**. Finally, in 2022, hydrogen consumption was 16.98 TWh, directly used to satisfy the industrial hydrogen requirements, since it is still not used for electricity or heat production in other sectors. Therefore, the total energy consumption in the 2022 Iberian Peninsula energy system was 568.37 TWh. Based on the efficiencies of gas boilers, and electric boilers (56%, 75%, and 95% respectively), this consumption needed 670.63 TWh of available energy. Figure B.3 combines the energy consumption of Spain and Portugal into one, for the year 2022, to understand the overall system consumption behavior and use it as a reference.

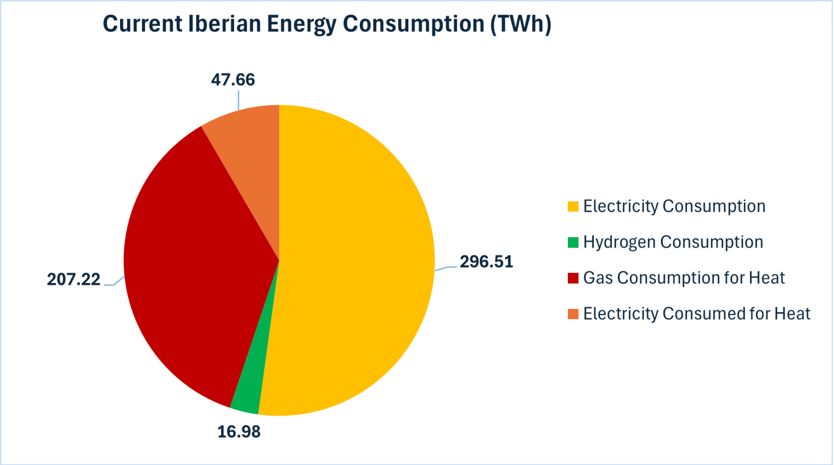

Figure 6.10: Characterization of the Iberian energy consumption in the year 2022

After obtaining the results obtained for the base case scenario, it can be seen that the degree of system coupling changes. The total energy energy consumption was 643.43 TWh, while the total energy necessary to meet this value was 654.93 TWh. It is surprising to see that even though the total energy demand in the system increased by 13.5% between the 2022 and 2030 cases, the total required energy decreased by 15.7 TWh. The discrepancy between one and the other is mainly caused by the increase in the use of electric boilers, accompanied by hydrogen boilers to generate heat. This generates an efficiency advantage (95% for electric boilers and 80% for hydrogen boilers) over the use of gas boilers (75%). Nevertheless, the reduction was expected to be even bigger. These results show a great advancement in the objective of increasing the system efficiency for both Portugal and Spain compared as stated in Chapter 4, achieving a 44% and a 32.5% increase respectively, compared to the 2007 scenario. Figure 6.11 depicts the consumption behavior for the different energy carriers in the overall energy system.

Comparing this figure to figure B.3, it can be seen that the relevance of nuclear and gas electricity production loses importance. Conversely, these losses are compensated with a significant renewable production increase, which covers the elimination of the non-renewable electricity production, as well as the integration over the heat sector, by reaching a share of 56% as shown in figure 6.13. Furthermore, part of this electricity is transformed into hydrogen to be stored and then reused when the heat sector requires extra energy to meet the requirements and to replenish the initial hydrogen stored quantity (4.5 TWh). This hydrogen can be produced through the electrolysis process which uses the surplus of renewable electricity, or by the use of the SMR + CCS process, which requires natural gas as a feedstock. Figure 6.12 depicts the division of the hydrogen consumption per sector. Nevertheless, it was unclear from the results whether blue or green hydrogen was used to satisfy a specific part of the hydrogen requirements in the different sectors.

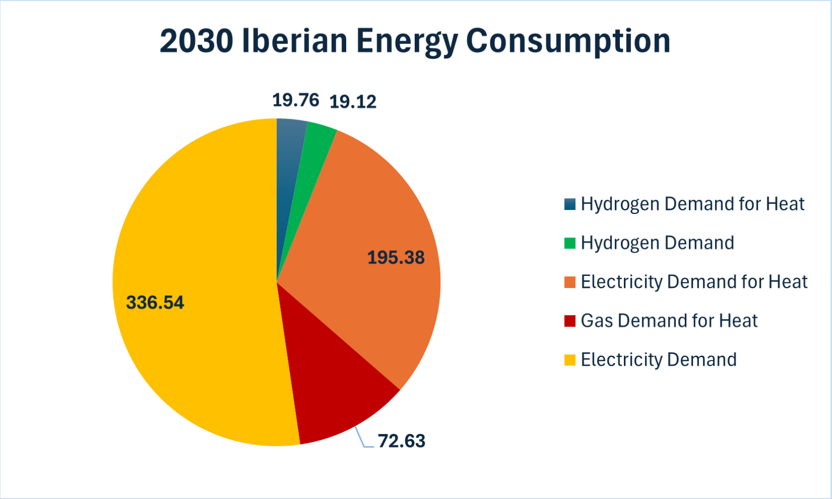

Figure 6.11: Results of the system coupling effect on the overall energy consumption in the 2030 Iberian energy system

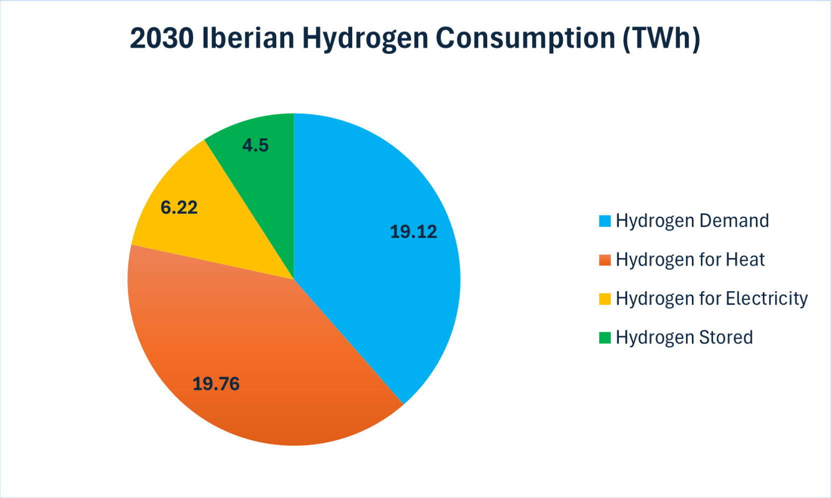

Figure 6.12: Hydrogen Consumption per available source in the overall 2030 Iberian Energy System divided by shares, according to figure 6.4

By specifically looking into the heat sector, figure 6.13 depicts the effect of the sector coupling process in the sub-system in the year 2030. As mentioned before, the system was dominated by using natural gas to satisfy the heating requirements in the year 2022 (77% of the total heat consumption). Nevertheless, the results obtained for the base case scenario suggest differently. With the integration of the hydrogen and electricity sectors into the heating sector, the gas share is reduced to 31%. Conversely, with the implementation of electric and hydrogen boilers, the sector electrification reaches 57%, and the substitution of natural gas for hydrogen rises from nothing to 12%.

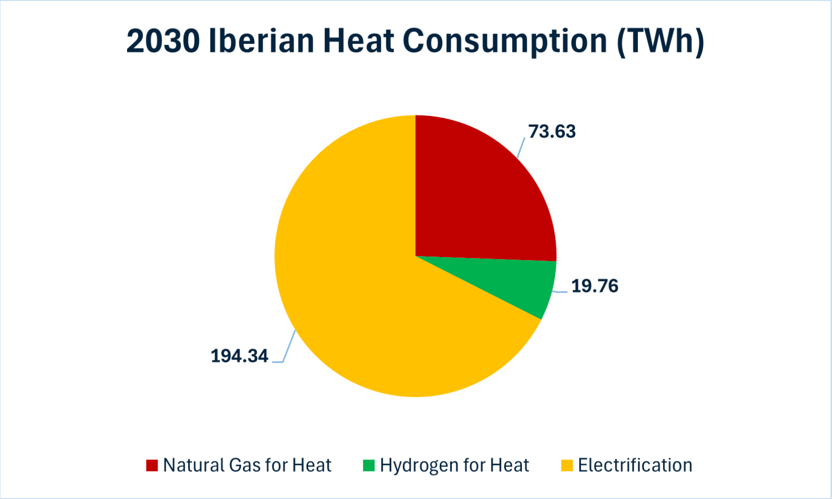

Figure 6.13: Results of the system coupling effect over the heat sector in the 2030 Iberian energy system

In conclusion, the reason why the values for the installed capacity of solar PV and onshore wind energy are much higher than the ones stated in the energy transition strategies from Spain and Portugal for 2030 is the electrification process of the overall energy system, where the combination of renewable electricity and hydrogen overrun the use of fossil fuels for heat purposes, as well as reducing its importance in the electricity generation. Therefore, these processes require much more renewable production and thus, renewable capacity to reach the electricity requirements not only of the electrical sector but of the overall system.

Time-Frame Analysis

As depicted in figure 6.14, the initial fixed point occurs on the night of November 26th, when renewable energy sources (RES) production is limited. This is primarily attributed to the low capacity factors for both wind and solar energy. More precisely, the solar power generation is 0 MWh, whereas the onshore wind power generation totals 22 GWh for the entire installed capacity in the system. The current demand is around 33 GWh. Thus, the system primarily depends on the generation of electricity through hydroelectric power plants (11000 MWh), and CCHT plants (18000 MWh) which create electricity from hydrogen, as depicted in figure 6.15. Alternatively, nuclear and CCGT facilities are utilized to offset the limited availability of renewable energy sources (RES) over this period. In some other moments throughout the year, CCGT plants cover the lack of RES and hydrogen in the system. However, the production is limited, since the model was confined to not building new nuclear reactors or CCGT plants, following the initial approach indicated in the PNECs [10] [108]. Furthermore, it is noteworthy to mention that when there is a limited supply of renewable energy, electric boilers have a minimal electricity consumption to fulfill the heat demands. Thus they are substituted by other available technologies, as depicted in figure B.4.

In contrast, the second marked point in figure 6.14, which takes place on December 3rd during the day, indicates a particular hour when the availability of renewable energy sources (RES) is significantly higher compared to the one before. Currently, power generation using renewable energy RES is substantial. Solar photovoltaic farms specifically produce 66000 MWh, whilst onshore wind farms create approximately 62000 MWh. The current demand at this particular time of the year is 44000 MWh. Therefore, renewable technologies solely provide all of the necessary electricity. Consequently, the generation of electricity from hydroelectric, nuclear, CCGT, and CCHT power plants is minimal. The excess electricity is then utilized to meet the heat demand by employing electric boilers. This is seen in figure 6.14 by the purple curve in the negative range of the graph, representing consumption, and in figure B.4. The excess electricity is used to satisfy a major part of the heat requirements. In addition to the utilization of electricity for heating purposes, the system consumes additional electricity by using electrolyzers to transform it into hydrogen (negative numbers in the graph). The produced green hydrogen is then stored in salt caverns, as depicted in the third highlighted point in figure 6.15.

Regarding hydrogen, figure 6.15 demonstrates that its generation is heavily dependent on SMR + CCS plants when the availability of RES is minimal. Due to the limited capacity of renewable electricity generation during unfavorable weather periods, the production of green hydrogen is likewise limited. Regarding hydrogen imports, the system does not rely on it to cover the lack of renewable electricity generation. Instead, it shows a constant import behavior through time. This is an indicator of the use of imports to recharge the stored hydrogen used when necessary. Salt caverns are more significant in the overall hydrogen usage during periods of reduced hydrogen consumption, which occurs when there is ample renewable electricity output, as shown in the second pinned point. This is done to avoid further costs of production generated by SMR + CCS plants or imports. Additionally, when the electricity surplus is high enough to cover all the heat requirements by using electric boilers, salt caverns usually charge. This is depicted in figures 6.15 and B.4. Notably, periods of reduced activity in the hydrogen sub-system align with periods of abundant availability of renewable energy sources (RES).

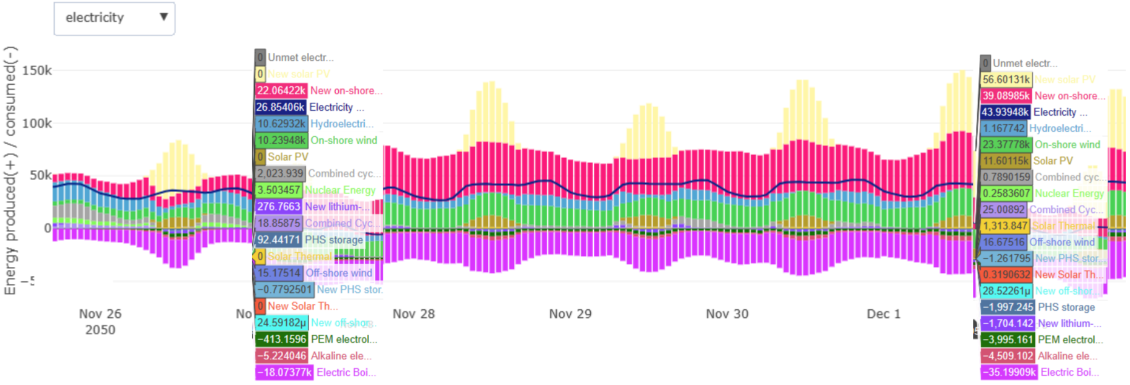

Figure 6.14: Electricity consumption, production, and demand over the selected time in the BC scenario

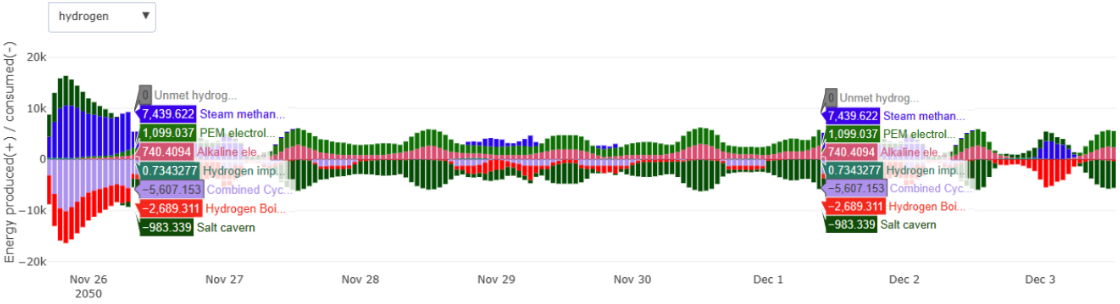

Figure 6.15: Hydrogen consumption, production, and demand over the selected time in the BC scenario

Capacity Factor

Figure 6.16 depicts the yearly capacity factors of the renewable technologies in the system, which are closely consistent across all of the developed scenarios presented in the rest of the chapter. The highest capacity factor recorded in the system belongs to the offshore wind, based on its great electricity production for its minimal installed capacity, while the lowest is given to CCHT plants, due to its lower efficiency and its low use based on its high installed capacity.

Electricity Production Technologies

The findings indicate that in 2030, the non-renewable installed power capacity consisted of 29.15 GW of CCGT and 7.11 GW of nuclear reactors. The input installed capacity in the model corresponds to these figures, as the model cannot increase this capacity. Hence, the values represent the installed capacity of CCGT and nuclear reactors in Spain and Portugal in the year 2030 [133] [39]. The findings on electricity generation indicate that Spain and Portugal may reduce the merit order of CCGT plants in response to potential carbon tax regulations outlined in ”The Iberian Power and Renewable Market Forecast” authored by Aurora (2022) [13]. In practical terms, it appears that CCGT facilities will continue to play a significant role in the medium-term future since the model still relies on producing electricity through gas when the availability of RES is minimal. Nevertheless, it is complemented by CCHT plants, which consume the hydrogen generated in the system. Conversely, the findings indicate that Spain will maintain its reliance on nuclear energy to supply steady electricity generation, as indicated by the model’s outcomes. However, this contradicts Spain’s plans, as the country aims to gradually eliminate nuclear energy by 2035. Specifically, the objective is to remove 2 out of the 7 operational gigawatts (GW) by 2030 [108]. However, this is implausible considering the existing delays in the process and the current significant dependence on nuclear energy, which ranks as the second most prominent technology for power generation in 2021 [103] [133].

In 2030, the Iberian energy system saw a rise in renewable capacity with 66.56 GW of onshore wind, 118.16 GW of solar PV, 1.42 GW of solar thermal, and 0.03 MW of offshore wind. A cumulative

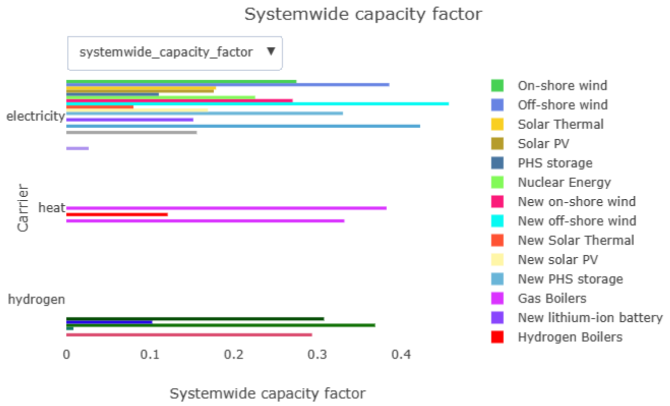

Figure 6.16: Average capacity factors of each of the renewable technologies for the different energy carriers

capacity of 101.32 GW for offshore wind, 139.06 GW for solar PV, 2.31 GW for solar thermal, and 0.025 GW for offshore wind energy was obtained for 2030, based on the initial capacities shown in Chapter 4. In general, the numbers for installed renewable capacities are higher than the combined estimated renewable capacity outlined in the energy transition policies of both Spain and Portugal for the year 2030, as indicated in sub-sections 4.1 and 4.1.2, which means that the estimation made by both governments might still rely on the possibility of building more CCGT plants.

Hydrogen Production and Conversion Technologies

The results from the 2030 Iberian energy system model indicate that there will be a total installed capacity of 18.55 GW for SMR + CCS plants, which will produce blue hydrogen. Additionally, there will be 3.22 GW of PEM electrolyzers and 3.44 GW of alkaline electrolyzers, resulting in a total installed capacity of 6.66 GW for green hydrogen. These findings indicate that Spain and Portugal will rely heavily on hydrogen by investing in developing green hydrogen technologies supported by producing blue hydrogen for industrial purposes. This reliance will be particularly significant when the supply of renewable energy sources (RES) is limited or scarce, in conjunction with the substantial investment in RES. Furthermore, the findings indicate no specific preference for the type of electrolyzer. This result is driven by the superiority of PEM electrolyzers in their efficiency and longevity, overcoming the lower costs from AEL and resulting in a similar installed capacity. It is worth noting that the obtained results for the installed electrolyzer capacity closely align with the planned capacity mentioned in the original PNIEC (Spain) and PNEC (Portugal), which together amount to 5 GW (4 GW in Spain and 1 GW in Portugal), as indicated in sub-sections 4.1 and 4.1.2. However, they are far from the capacities stated in the newer drafts, which double these values. The primary factor driving the replacement of hydrogen with natural gas in the model outcomes is the extensive deployment of blue hydrogen production infrastructure, which directly substitutes the use of gas in the heating sector. However, this contradicts the strategic plans of both countries under examination, as they lack a thorough examination of this alternative.

Heat Production Technologies

In addition to electricity and hydrogen production technologies, the system develops a myriad of conversion technologies that allow heat generation through the consumption of either hydrogen or electricity. The model results indicate an installed capacity of 47.28 GW of electric boilers, 26.55 GW of gas boilers, and 18.63 GW of hydrogen boilers. These results indicate two main things. First, the system will heavily rely on renewable electricity to satisfy the heat demand in most of the year, based on the results shown in figure B.4, where gas and hydrogen boilers substitute the electric ones in very specific moments. Secondly, the system will continue to rely heavily upon natural gas as a fuel when renewable electricity generation is minimal.

Node-Specific Results

The summary of outcomes for the deployed hydrogen technologies on certain system nodes is shown in table 6.1. The results illustrate the precise installed capacity for production and conversion equipment that utilizes hydrogen as the energy carrier. The chosen nodes represent the areas in the Iberian Peninsula with elevated population levels and/or increased industrial activity or where the installed renewable energy sources (RES) capacity is significant. Table 6.1 displays the ideal nodes for several hydrogen-related technologies (PEM, AEL, SMR + CCS, CCHT, and H_2 boilers). The table uses bold letters to highlight the node with the highest installed capacity.

MW	**ES30**	**ES51**	**PT17**	**ES21**	**ES52**	**ES42**	**ES13**
AEL	5.80	7.34	**1372.22**	861.55	2.81	746.76	344.08
PEM	6.46	7.58	275.18	4.59	**1421.63**	708.67	603.04
SMR + CCS	**14684.75**	491.20	970.50	293.41	1.15	0.52	0.56
CCHT	**6330.85**	3407.65	2947.05	1640.90	455.48	455.44	1140.49
H2 Boilers	**7612.91**	1203.22	557.29	715.38	1940.52	1654.15	704.13

Table 6.1: Summary of the installed hydrogen technologies in the most important nodes of the system

The findings indicate that nodes exhibiting greater heat and hydrogen demand, which aligns with nodes characterized by heightened industrial activity and increased population densities, exhibit the most substantial installed capacities for SMR + CCS plants. This is because this technology offers great flexibility in the hydrogen production sub-system. It enables the immediate production of hydrogen by using natural gas, which is readily available in all regions. In contrast, producing green hydrogen requires a significant installed capacity of renewable energy sources. The ES30 node in Madrid has the most installed SMR + CCS capacity. This is logical, considering its significant industrial activity and the fact that it has the highest population index in the system. This event establishes Madrid as the most suitable location for installing CCHT plants and H_2 boilers. This is because there is a need to convert the large amounts of blue hydrogen produced into other forms of energy and vice versa to meet the other two demand categories.

ES52 (Valencia) and PT17 (Lisbon) are the second and third nodes with the most installed capacity for hydrogen technology. Surprisingly, ES51 (Catalonia), the node rated second in population density and industrial activity, as well as high RES installed capacity, does not show big numbers for any of the hydrogen production technologies. This results from the closeness to other nodes, which can provide and store the region with the necessary hydrogen. This can be seen in the high values for CCHT and H_2 boilers. Furthermore, Valencia appears to be the most suitable location for installing PEM electrolyzers, with ES42 (Castilla La Mancha) being the next best option. Regarding alkaline electrolyzers, Lisbon seems to be the optimal location, probably due to its close proximity to salt cavern structures and the sea, in terms of receiving imports. Figure 6.17 illustrates these findings for a better understanding.

To clarify why the nodes with the largest SMR + CCS capacities do not have the highest installed capacity for green hydrogen production technologies, it is important to consider that the generation of clean hydrogen using green methods necessitates the usage of renewable electricity. The installed capacities of RES in the examined nodes are presented in table 6.2. Regions with greater installed capacity for PEM electrolyzers tend to align with nodes where the installed renewable energy source (RES) capacity is higher. This correlation can be attributed to more available land and favorable weather conditions in these regions. Madrid (ES30) is the only exception, as it possesses the greatest amount of newly erected solar PV farms. However, the explanation aligns with the requirement that this node necessitates this capacity to supply the energy sub-system directly.

The findings indicate that the capacity of hydrogen technologies is influenced by the hydrogen, heat, and electricity needs of different regions and the proximity to storage facilities (salt caverns). In addition, the availability of renewable energy sources (RES) and electricity generation from these sources in each location plays a crucial role in determining capacity. This is important because blue hydrogen can adequately meet the demands. It should be noted that PEM electrolyzers are preferred over Alkaline electrolyzers in the nodes with a bigger industry. A clear example is Valencia and Lisbon. The reason

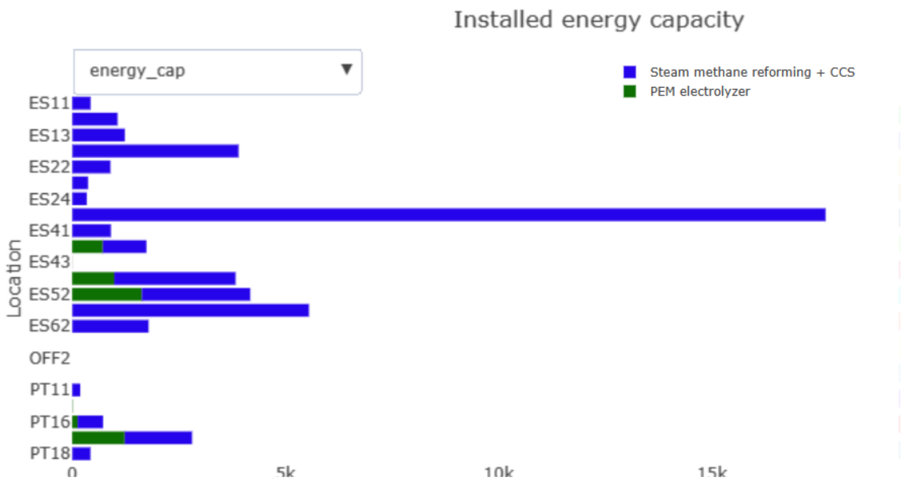

Figure 6.17: *Installed capacity for PEM electrolyzers and SMR + CCS over the system nodes*

MW	**ES30**	**ES51**	**PT17**	**ES21**	**ES52**	**ES42**	**ES13**
Solar PV	63.00	296.00	427.30	51.00	**423.00**	349.00	10
New Solar PV	20005.34	**20054.34**	6298.21	7839.63	14334.01	2517.85	3781.27
Wind Onshore	0.00	1369.00	129.50	154.00	1243.00	**4706.00**	35
New Wind Onshore	**16350.84**	13090.87	4355.08	3661.82	9936.39	7.22	1677.00

Table 6.2: Summary of the main installed renewable energy sources in the most important nodes of the system

for this is the shorter ramping times and greater energy efficiency provided by PEM electrolyzers compared to AEL. The properties of PEM electrolyzers enable them to produce with greater flexibility and rapidly adjust to changes in demand and the availability of renewable energy sources (RES) within the system, compared to alternative options [153]. Consequently, the system prioritizes PEM electrolyzers over the more developed AEL, with high industrial activity. On the other hand, AEL is highly present on those nodes where this need for flexibility is not required, and the hydrogen is destined to be stored in salt caverns, as is the case for ES13 and PT17.

To provide additional evidence of this result, while referencing tables 6.1 and 6.2, it is evident that all of the chosen nodes exhibit a greater capacity for PEM electrolyzers in comparison to ES30 or ES51. ES30 represents the node with the highest industrial activity and population density levels and, consequently, the node with the highest energy consumption. Because of this, ES30 has less spatial capabilities to build all of the necessary equipment to generate green hydrogen. Therefore, this hydrogen is produced through SMR + CCS plants or brought from other regions. Madrid exhibits close and direct connections with areas characterized by abundant space and favorable conditions for generating additional renewable energy supply. Consequently, sustainable electricity and hydrogen generation is delegated to these sites. This can be seen in figure 6.18.

The installed hydrogen energy storage capacity is only developed in specific places where the nodes meet the essential geographical criteria to construct these structures, as seen in figure 6.19. This energy storage technology's installed capacities are significantly higher than other technologies, as illustrated in figure 6.7. This indicates that the system will prioritize hydrogen storage over electrical storage, as it incurs smaller storage losses, requires less investment, and has longer lives, as demonstrated in chapter 2. Based on these characteristics, salt caverns are also preferred due to their capacity for seasonal storage. In addition, this is also influenced by the significant potential that Spain and Portugal possess to develop these structures. The results indicate that the areas with a larger installed electrolyzer capacity possess salt cavern structures or are close to them. Consequently, the primary purpose of electrolyzer hydrogen generation is to convert surplus electricity for subsequent storage inside the system. Conversely, it is noteworthy that the nodes without storage are more prevalent in the hydrogen import and the implementation of CCHT technologies, which are utilized to supply

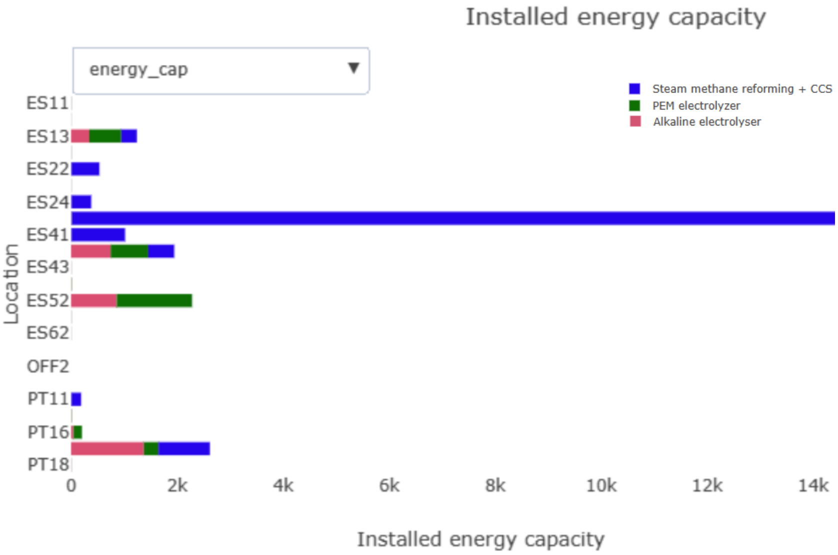

Figure 6.18: Optimal allocation of hydrogen technologies in the BC scenario

additional electricity to the system as required. This also applies to ES51, which exhibits low installed hydrogen production capacity despite high energy requirements. This is due to the proximity to other regions that possess the space, weather conditions, and storage facilities that feed this node with the necessary hydrogen. This is observed by its high installed capacity for CCHT and hydrogen boilers. This relation can be seen in figure 6.19.

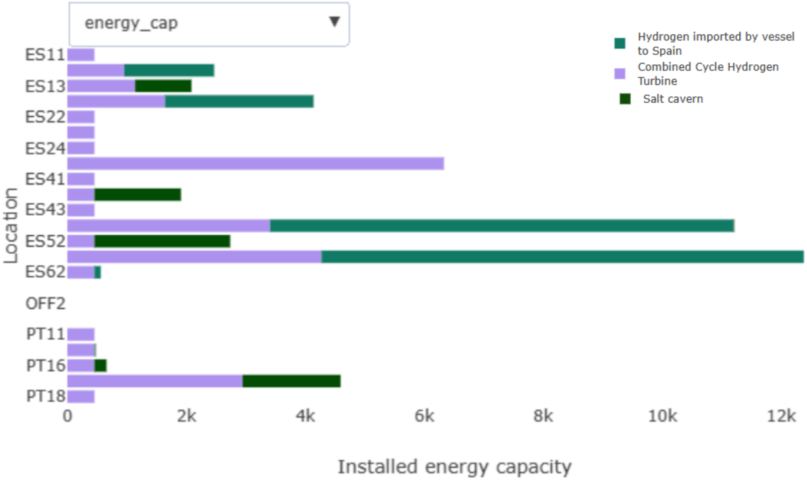

Figure 6.19: Optimal allocation of salt caverns and CCHT, together with hydrogen imports for all of the system nodes

6.2. Sensitivity Analysis

The scenario matrix consisted of four distinct scenarios designed to examine various potential combinations of capital costs for renewable energy sources (RES) and green hydrogen production technologies. These scenarios were analyzed by varying the electrolyzer and renewable energy associated CAPEX. In this manner, the influence of hydrogen technologies and renewable electricity generation technologies on the system will be extracted and examined.

The objective of the scenario matrix was to perform a sensitivity analysis by varying two different parameters, which led to the creation of four different scenarios, namely, SC1, in which both the electrolyzer and RES CAPEX parameters had the highest reduction. Secondly, SC2 presented an optimistic reduction for RES CAPEX and a pessimistic value for the electrolyzer CAPEX. Then, SC3 presented a pessimistic reduction in the CAPEX for RES and an optimistic value for the electrolyzer CAPEX. Finally, SC4 was pessimistic for both parameters. In addition, the PNIEC scenario was included to be used as a benchmark to compare the results obtained with the expected system situation by the year 2030 from Spain and Portugal.

6.2.1. System-wide Results

Overall System Total Costs

As mentioned before, the model solver is based on an optimization tool, which, in this case, was used for overall cost minimization. This optimization was performed under the same conditions for each scenario, except for the selected fixed parameters, which constrained the minimization process differently. Therefore, the results for the overall system costs of each of the scenarios presented some variation too.

Table 6.3 helps visualize the effect of capital expense variation of renewable energy sources and electrolyzers on the overall total system-wide costs. The base case scenario, used as a reference to see the differences between the rest of the programmed scenarios where some parameters are varied, shows a total cost of 37.6 billion €. The only analyzed scenario under this value was SC1, which had lower capital expenses for electrolyzers and renewable energy sources. The rest of the scenarios' total costs were slightly higher than the base case and were closer to each other. This demonstrates that, although the installed capacities of renewables require the highest investment due to the overall final installed volumes, the electrolyzer costs have a greater impact on the overall costs since renewables depend on them due to participating in the mitigation of the variability of renewable energy sources. This means that the Iberian Energy System's overall cost is more sensitive to the electrolyzer capacity than the RES capacities, caused by its influence over the system.

Scenario	**BC**	**SC1**	**SC2**	**SC3**	**SC4**	**PNIEC**
Total Cost (Billions of €)	37.6	34.6	38.2	38.7	38.9	43.2

Table 6.3: Summary of the overall system-wide total costs per created and analyzed scenario

Installed Renewable Electricity Generation Capacity

Figure 6.20 and table 6.4 depict the installed renewable capacity per formulated scenario, ranging from 273.16 GW to 195.68 GW. Hydro-power is not included in the visualization since the model was not allowed to create a bigger capacity due to the extended construction times and the high involved capital expenditure, which would lead the model not to choose this option, as was the case for pumped hydro-storage (PHS), which was allowed to increase its capacity. Nevertheless, it is included in the total installed capacity shown in table 6.4. Unsurprisingly, the scenario that shows the highest renewable installed capacity is the scenario set at the low capital expense bounds for RES and electrolyzers (SC1). On the other hand, the scenario with the lowest installed capacity, excluding the PNEC scenario, in which final capacities for these technologies were introduced as inputs, was the scenario set at the highest capital expenses bounds both for RES and electrolyzers (SC4), displaying an installed renewable capacity of 259.86 GW. In addition, these results also demonstrate that despite the uncertainty regarding the associated capital expenses of renewable energy sources and hydrogen production technologies, the system will install similar amounts of renewable energy capacity to satisfy the different demands.

Figure 6.20 also depicts the differences in the installed capacity of solar PV and onshore wind, the two main installed renewable sources, between the scenarios. The scenario presenting the highest solar PV capacity is SC3, which presented high costs for RES and low costs for electrolyzers. Conversely, SC2 presented the highest installed capacity for onshore wind energy. Slightly higher than the value retrieved for SC1. The explanation behind this phenomenon is that the model prioritizes solar PV in scenarios where the capital expenses of renewables are at the pessimistic value (highest). In contrast, onshore wind is prioritized when there is a cost reduction. This results from the main optimization objective of reducing overall costs to meet the set energy requirements. With a cost reduction, apart from installing more renewable capacity, the model selects wind over solar due to higher capacity factors and, thus, more energy efficiency. Conversely, at higher costs, the model chooses to reduce the costs by reducing the overall renewable capacity, cutting 10 to 15 GW of installed wind energy, relying on a slightly higher solar capacity, and increasing hydro-power and non-renewable sources. On the other hand, the electrolyzer capital expenses do not affect the solar PV/wind onshore ratio.

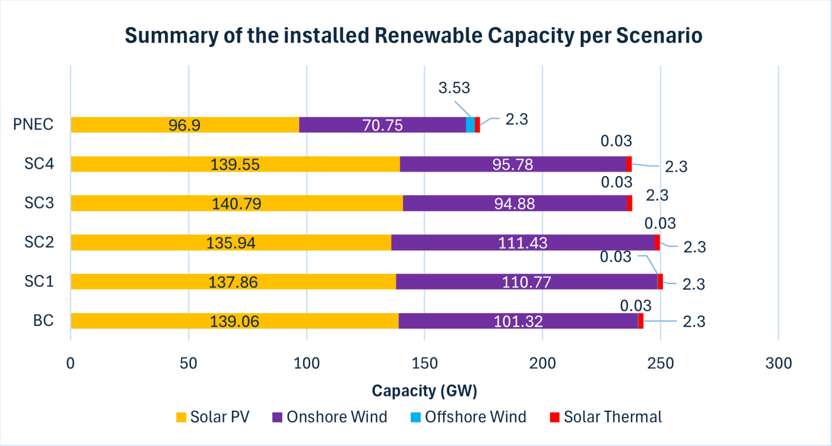

Figure 6.20: Summary of the optimal installed renewable capacity per defined scenario in the analysis

Scenario	BC	SC1	SC2	SC3	SC4	PNEC
Total RES capacity (GW)	264.91	273.16	271.9	260.2	259.86	195.68

Table 6.4: Total Optimal Installed Renewable Capacity per Analyzed Scenario

Overall Electricity Production

Figure 6.21 depicts the differences in renewable electricity production between the base-case scenario and each of the scenarios belonging to the scenario matrix. This figure illustrates that the two scenarios with the highest reduction in the RES CAPEX display the highest installed renewable capacity, as it is logical. If these scenarios (SC1 and SC2) are compared, it can be concluded that SC1, caused by a higher reduction in the associated capital costs to electrolyzers, increases the overall renewable generation capacity and electricity production in the system. Nevertheless, the effect is less sharp than expected since the difference in installed capacity is small, as seen in figure 6.20.

On the other hand, the smaller reduction in RES CAPEX renders a bigger decrease in the installed renewable generation capacity and overall electricity production, which barely varies based on the established electrolyzer CAPEX compared to the comparison between SC1 and SC2. The biggest variation is observed with the PNEC scenario, in which renewable electricity production is highly decreased, caused by the smaller renewable installed capacity obtained through the data extracted from the PNIEC and the PNEC [105] [10].

Figure 6.22 depicts the differences in the non-renewable electricity production between the base-case scenario and each of the scenarios belonging to the scenario matrix. It is important to remark

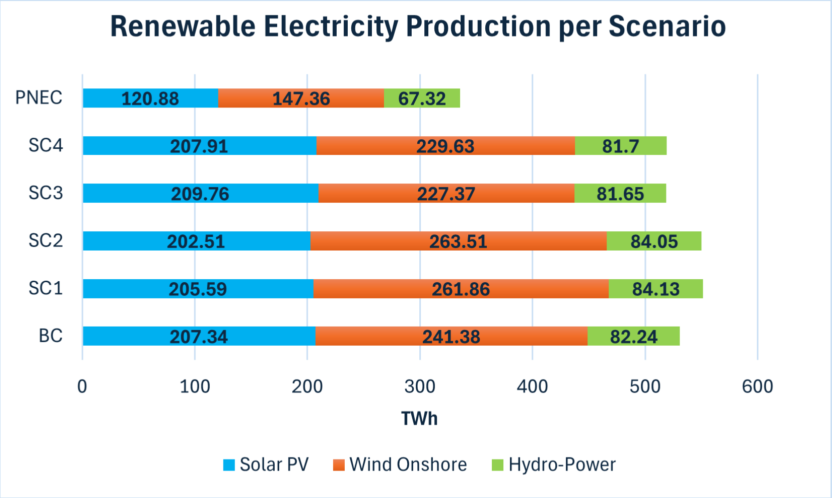

Figure 6.21: Summary of the renewable electricity production per scenario

that the installed capacity for non-renewable generation sources was kept constant for all of the different produced scenarios. The graph illustrates a minor variation in the electricity produced through CCGT plants, meaning the system will rely on natural gas to establish constant electricity production throughout the year. Nevertheless, nuclear electricity production is affected to a major degree between the optimistic and pessimistic scenarios regarding the RES CAPEX. This demonstrates that, based on cost minimization, the system will rely more on natural gas than nuclear energy. The biggest difference is observed between all the scenarios compared to the PNEC scenario. The non-renewable electricity production skyrockets due to the smaller presence of installed renewable capacity in that system. The non-renewable sources need to compensate to supply the required electricity to the system.

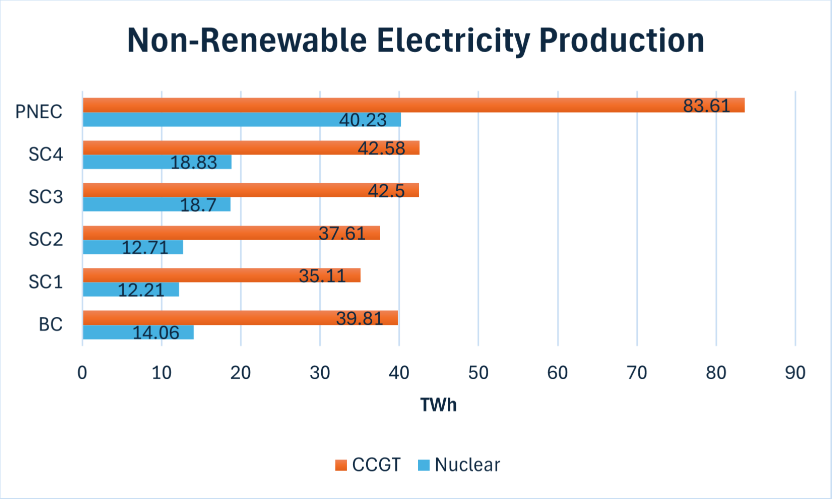

Figure 6.22: Summary of the non-renewable electricity production per scenario

Based on the figures 6.21 and 6.22, it can be seen that overall electricity production in SC3 and SC4 scenarios is smaller than the electricity generation in SC1 and SC2. This is a result of the higher presence of renewable capacity, which leads to overall greater electricity production and, thus, a higher degree of electricity substitution for non-renewable energy sources in the three different included energy sectors, which leads to a higher degree of the system's electrification. This is proven by observing figures 6.27 and 6.26, which depict the installed heat capacity per scenario and the overall heat production. In the two scenarios with higher renewable electricity production, the system displays a higher capacity and production of heat by electric boilers. On the other hand, the two other scenarios display a higher reliance on gas boilers and, thus, a decreased degree of electrification.

By specifically looking into SC4, which displays the highest overall system costs as seen in table 6.3, it can be observed that the overall electricity production is slightly reduced compared to the other scenarios, including the PNEC case. This proves that an overall increase in the capital expenditure of the technologies that produce renewable energy (both hydrogen and electricity) directly affects the overall electricity production and, thus, affects the system's degree of electrification and sector coupling.

In addition, this graph seems to suggest that the variation in the capital expenses for electrolyzers does not heavily affect the overall electricity production since SC1 and SC2, as well as SC3 and SC4, vary this parameter without creating any significant effect on the overall electricity production or the ratio between renewable and non-renewable production.

Installed Hydrogen Production Capacity

Three possible technologies' installed hydrogen production capacity (SMR + CCS, PEM, and AEL) was one of the main system variables to study based on the different fixed parameters. By observing figures 6.23 and 6.24, the overall effect of the established parameters over the installed hydrogen production capacity can be observed. The optimistic case for the electrolyzer's capital expenditure displays a higher installed hydrogen production capacity overall. On the other hand, at its lower bound, the hydrogen production capacities decrease. This can also be observed in figure 6.21, in which the scenarios with lower installed capacity for renewables match those presenting a decreased installed capacity for hydrogen production. In addition, in figure 6.27, the scenarios with lower hydrogen production capacity match those with lower capacity for hydrogen boilers.

Regarding the installed capacity for blue hydrogen generation, figure 6.23 illustrates this parameter for each of the analyzed scenarios. The variation between the scenarios where the model was let to decide the overall installed capacity of new hydrogen and renewable energy technologies does not vary much. The optimal installed capacities range between 17.63 to 22.59 GW. The scenario that presents a great difference is the PNIEC scenario, in which capacities were equaled to the previewed installed capacities by the Spanish and Portuguese governments. In this case, the renewable installed capacity suffers a great decline compared to the other cases. Nevertheless, the hydrogen requirements needed to satisfy the hydrogen demand and for heat and electrical purposes do not change. Therefore, the model compensates by creating a greater amount of blue hydrogen capacity to compensate for the lower presence of renewable electricity to feed the system-wide heat requirements through electric boilers and to generate hydrogen through electrolysis. This demonstrates that the SMR + CCS capacity is highly sensitive to the overall renewable installed capacity.

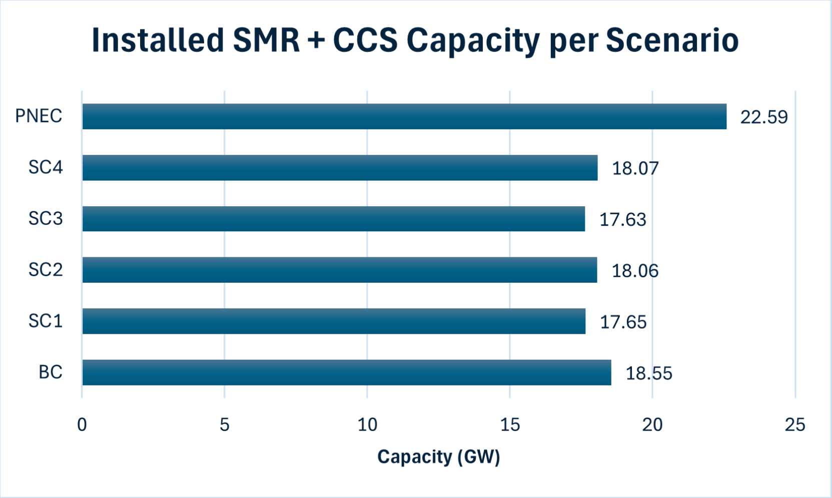

Figure 6.23: Summary of the optimal installed SMR + CCS capacity per defined scenario in the analysis

Regarding the installed capacity for green hydrogen generation, table 6.5 illustrates the total amount for each scenario. In addition, figure 6.24 illustrates the variation between the capacity installation of each electrolyzer type for each defined scenario. This figure helps establish a relation between the dominance of the electrolyzer type based on the variation in the capital expenses of these technologies and the capital expenses of renewable energy sources. As mentioned, the optimal installed capacity for green hydrogen technology ranges between 5.68 and 7.05 GW, demonstrating a higher sensitivity to uncertainties.

The sensitivity of green hydrogen installed capacity is high considering the variations in the chosen uncertain parameters about these technologies. To further understand this dependence it is necessary to analyze the installed capacity of each type of electrolyzer individually. The alkaline electrolyzer capacity ranges from 1.28 to 5.61 GW of installed capacity. On the other hand, the PEM electrolyzer ranges from 0.89 to 4.94 GW. When the cost of electrolyzers is at the expected future value, like in the base case scenario, the ratio of alkaline/PEM electrolyzers is almost 1, meaning the model does not create a preference. On the other hand, when the cost of the electrolyzer is increased, the model selects an alkaline electrolyzer over PEM electrolyzers. Finally, the model chooses PEM electrolyzers as an over-the-counter option when reducing capital expenses. Overall, even though the model does not highly vary the total installed capacity for electrolyzers between the scenarios, it creates a significant effect between the internal proportions.

Moreover, the installed hydrogen capacity is also sensitive to changes in the installed renewable capacity, which decrease and increase with a rise or a reduction in their capital expenses. By comparing the installed capacities of SC1 and SC3, where the capital expenses for renewables vary but are similar for electrolyzers, the system displays a higher installed capacity in SC1. This is due to the higher volume of renewables, which promotes using green hydrogen technologies instead of their counterparts. In addition, the model prefers PEM electrolyzers over alkaline electrolyzers in both options. This seems to be caused by the higher technical advantages brought up by PEM electrolyzers over AEL to be more responsive to sudden changes in heat and electricity requirements, as well as the fact that in these two scenarios, the electrolyzer costs are reduced, making PEM electrolyzers more cost-efficient in the cost minimization process.

A similar behavior is seen when comparing SC2 and SC4, where the electrolyzer costs are at their highest bound, with different capital expenses for renewables. In this case, the installed capacity of electrolyzers is reduced compared to the other two scenarios caused by the higher bound in their CAPEX. However, in contrast to the other two scenarios, varying the RES capital expenditure seems less effective when the electrolyzer CAPEX is high. This might be caused by a lower needed bound to fulfill the system's hydrogen requirements based on the different demand inputs. Nevertheless, this will affect the overall system costs as seen in table 6.3.

Both the decrease in capital expenses of electrolyzers and the lower installation of renewables improve the appeal of PEM electrolyzers, despite their greater cost compared to Alkaline electrolyzers, owing to the better technological features. As a result, these two elements have a dual effect on the energy system. They increase the installed capacity of renewables and enhance the production of green hydrogen due to the improved efficiency and ramping rate of PEM electrolyzers.

Finally, by looking into the PNEC scenario, it can be seen that the overall green and blue hydrogen production capacity obtained in the rest of the scenarios matches the planned green hydrogen capacity established by the Spanish and Portuguese governments, ranging between 5.5 and 7 installed GW. Nevertheless, the data matches with the original PNECs from Spain and Portugal. The updated versions, which state 16 GW of installed electrolyzer capacity, are far from the results.

Scenario	BC	SC1	SC2	SC3	SC4	PNEC
Total Electrolyzer Capacity (GW)	6.66	7.05	5.68	6.22	5.72	6.5

Table 6.5: Total Optimal Installed Electrolyzer Capacity per Analyzed Scenario

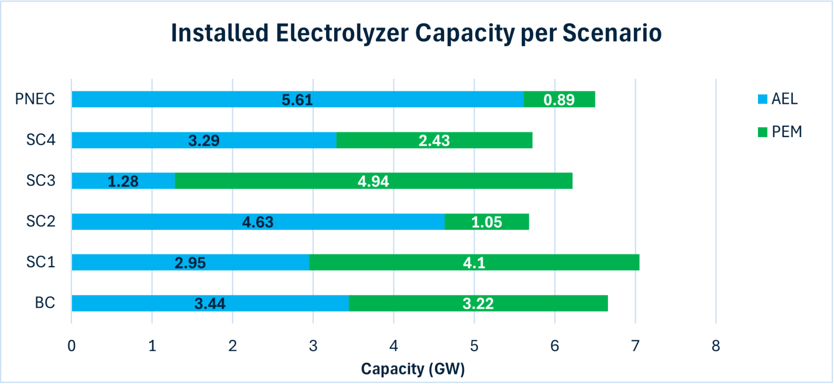

Figure 6.24: Summary of the optimal installed electrolyzer capacity per defined scenario in the analysis

Hydrogen Production

Figure 6.25 depicts the differences in the system's hydrogen production between the base-case scenario and each of the scenarios belonging to the scenario matrix and the PNEC scenario. The figure illustrates that the scenario with the highest hydrogen production is SC3 and the base case, followed by SC1, SC4, PNEC, and SC3 scenarios. In addition, SC3 produces the highest amount of hydrogen through PEM electrolysis. On the other hand, SC2 produces the highest hydrogen through AEL electrolysis. Finally, the PNEC scenario proves to have the highest reliance on imports and blue hydrogen production.

Two different factors cause the reason that SC3 presents the highest hydrogen production. First of all, the bigger reduction in the capital expenditures of electrolyzer technology boosts its installation in the system, as seen in figure 6.24. In addition, the installed capacity in SMR + CCS does not vary much, even though there is a higher installed electrolyzer capacity. Thus, the system has a higher capacity to produce hydrogen. Nevertheless, the same explanation applies to SC1. Therefore, to explain why SC3 has more production than SC1, it is necessary to remark that the lower renewable electricity production, caused by the slight increase in the RES CAPEX, leads the system to rely more on hydrogen to fulfill the system's heat requirements, as seen in figure 6.27, where SC3 presents one of the highest hydrogen boiler production output.

On the other hand, SC2 presents the lowest hydrogen production output over the set of produced scenarios. The rationale behind this outcome is opposite to the one explained before. First, the smaller reduction in capital expenses associated with electrolyzers reduces its installed capacity and, thus, its production, as seen in figure 6.24. On the other hand, SC2 presents a higher capacity and production of blue hydrogen. However, it is not enough to reach the SC3 levels. This is also caused by the higher reliance of the system on renewable electricity production to fulfill the system's heat requirements, as seen in figure 6.27. In this case, a higher installed renewable generation capacity and a bigger electricity production compensate for the lack of hydrogen.

Interestingly, the effects of parameters in SC2 and SC3, which combine an optimistic and pessimistic view, display a greater impact than in the all optimistic (SC1) and all pessimistic (SC4) scenarios. This further demonstrates the strong correlation between renewable electricity sources and electrolyzer technologies. When the capital expenditures of these technologies align, hydrogen production establishes itself close to what is expected in the PNEC. Oppositely, when the cost view of these technologies differs, the cases display extreme scenarios.

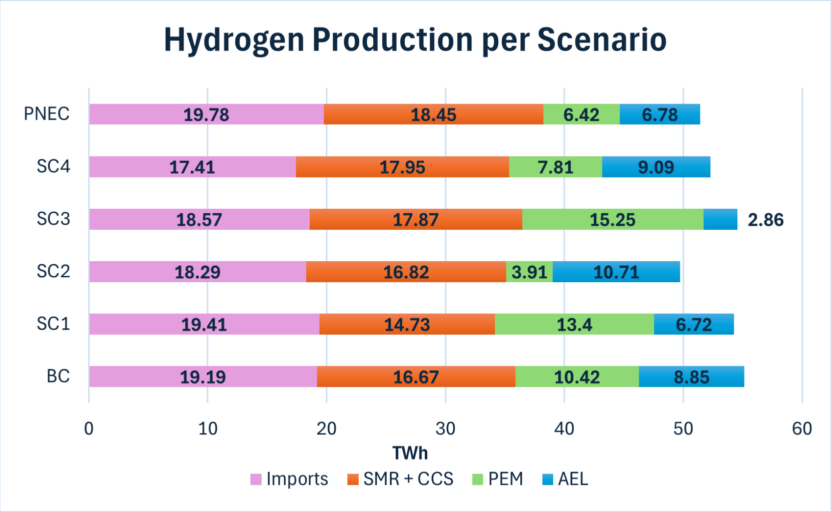

Figure 6.25: Summary of the hydrogen production per defined scenario in the analysis

Installed Heat Production Capacity

Figure 6.26 depicts the installed heat production capacity per formulated scenario, ranging from 91.6 to 92.56 GW (SC1 and BC or PNEC). The variation between the heat production capacity between the scenarios is the slightest between all of the analyzed variables of the system. This is caused by the fact that the heat energy vector in this model is only used to fulfill the system's heat requirements, which do not change throughout the scenarios.

The minimal change observed between the installed capacities in heat production technologies is attributed to the difference in efficiencies between the predominant technologies in each scenario. SC1 presents the lowest value out of all the options. The system relies heavily on electric boilers to generate heat due to the boost in the installed renewable electricity generation capacity and the overall electricity production. On the other hand, the base case and the PNEC scenarios display the highest installed capacity of gas boilers, which is the least efficient option out of all available technologies. Thus rendering a slightly higher overall installed capacity.

SC1 and SC2 trivially present the highest installed capacity for electric boilers due to the optimistic reduction in the CAPEX of RES. This effect is seen in a minor way in SC3 and SC4 since the CAPEX of RES is under the pessimistic case. On the other hand, SC3 presents the highest installed capacities for hydrogen boilers, caused by the decreased dependence on electricity for heat purposes and the optimistic situation for the cost of electrolyzers imposed in this scenario.

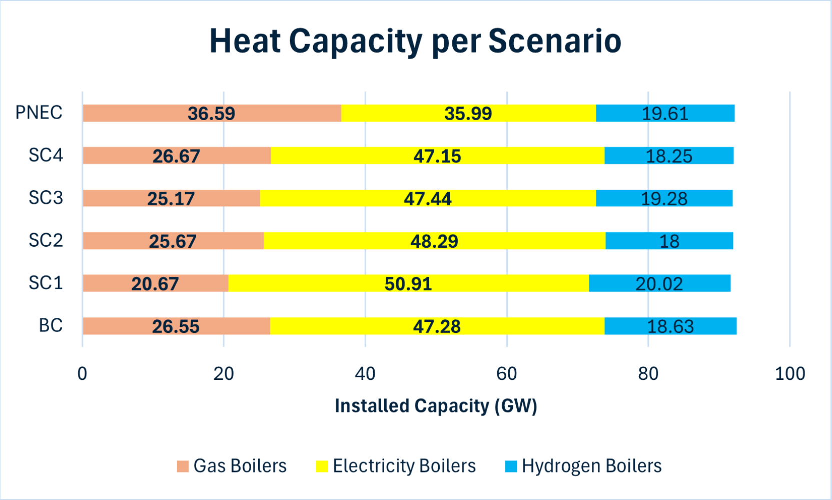

Figure 6.26: Summary of the optimal installed heat production capacity per defined scenario in the analysis

Heat Production

Figure 6.27 displays the share of heat production per energy vector included in the study. The overall heat production is always constant for all scenarios since it is the only energy vector that cannot be converted in this model. Based on the outcomes of figures 6.21 and 6.22, some of the behaviors retrieved from figure 6.27 can be explained. Since SC1 and SC2 depict the highest electricity production amounts caused by a higher installed renewable capacity, the dominance of electric boilers in the heat sector is higher. Conversely, when the electricity output is decreased, so does the heat output of electric boilers. Then, the model compensates by relying mainly on gas and hydrogen boilers at a lower scale. However, the hydrogen-generated heat does not vary enough to make clear conclusions. In addition, the system will rely more on blue hydrogen to meet the heat requirements satisfied by hydrogen renewable electricity production when the electrolyzer capacity is lower, as seen in figures 6.24 and 6.23 .

The base-case, SC1, and SC2 scenarios have the highest heat production through electric boilers. This is due to a higher installed renewable electricity generation capacity. Nevertheless, the effect of the electrolyzer's capital expenses is noticeable since the heat production by electric boilers in SC2 is smaller than in the base case, even though the reduction in the RES CAPEX is higher. In this scenario, the small reduction in heat production through electricity is compensated by the gas boiler's output increase. This can also be proven by comparing the SC3 and SC4 scenarios, which share the same CAPEX for RES but differ in the electrolyzer one, and SC4 shows a smaller output. Finally, for the PNEC case, the system relies heavily on gas boilers to fulfill the heat requirements, almost at the same level as the electric boilers. This is due to the big difference in the installed RES capacity.

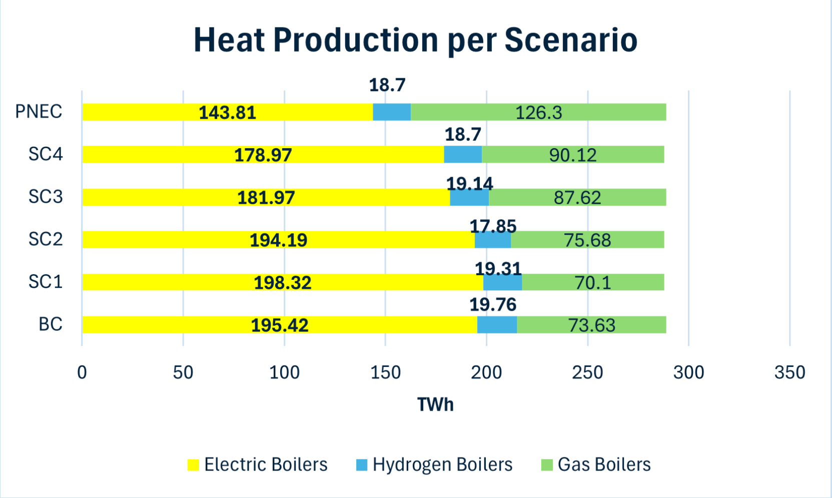

Figure 6.27: Summary of the heat production per defined scenario in the analysis

Installed Storage Capacity

Figure 6.28 depicts the varying total ideal storage capacity built for salt caverns in different scenarios, ranging from 1.96 to 5.63 TWh. The data demonstrates that salt caverns are sensitive to fluctuations in both capital costs of electrolyzers and renewable energy sources. If the capital expenses of the electrolyzer are set at their higher bound, the importance of salt caverns diminishes in the energy system due to the substitution for batteries and the lower hydrogen production in the scenario. In contrast, if the capital expenditures of electrolyzers are moderate or minimal, the optimization leads to a significantly higher storage capacity being installed for salt caverns, accompanied by a higher hydrogen relevance in the system. By specifically looking into SC4 and PNEC scenarios, it seems that under increased non-renewable energy production, the system strongly decreases the necessity for hydrogen storage.

The analysis of the PHS and battery-installed capacities is not included due to the lack of importance given by the model of these technologies, given the objective function of the optimization problem. As mentioned, the model does not consider BESS's high importance in establishing a responsive energy storage system.

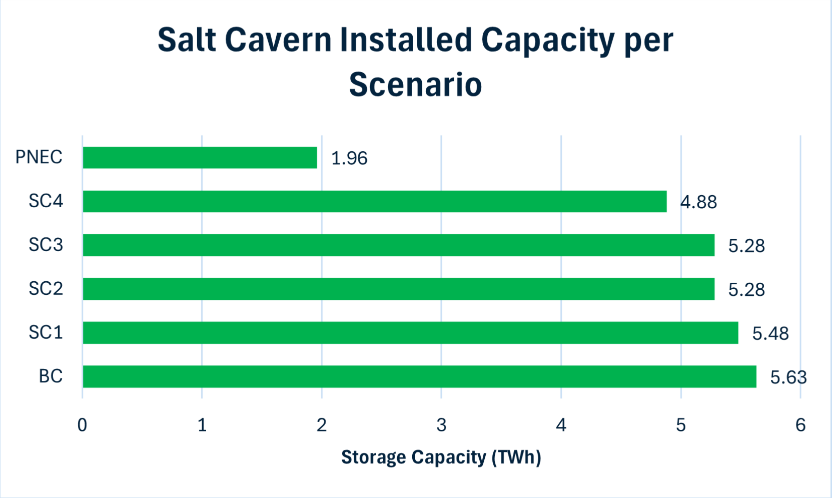

Figure 6.28: Summary of the optimal installed salt cavern storage capacity per defined scenario in the analysis

7

Discussion

This research paper focused on analyzing the impact of generating an intensive system integration between the different sub-sectors of the Spanish and Portuguese energy systems and the integration of new hydrogen technologies into the system regarding the objectives established for 2030, according to the Spanish and Portuguese PNECs. In section 7.1, the results obtained in Chapter 6 will be compared to the proposed benchmark, composed by the Spanish PNIEC and the Portugues PNEC's objectives regarding installed renewable capacity, energy efficiency improvements, installed hydrogen production capacities and others. Then, in section 7.2, the results will be interpreted into the real situation considering all of the different components of the system first, from my perspective, and secondly, after performing expert consultation. Finally, in section 7.3, the significant discrepancies between the results and the interpretation will be used to create a set of policy recommendations. Sections 7.4 and 7.5 compile the limitations of the research and the possible future paths to dig deeper into the research topic.

7.1. Model Validation

As mentioned in the introduction of this research, it is crucial to validate the results obtained from a model to ensure that the discussion will produce relevant, realistic, and robust outcomes. The assumptions taken to produce the model have been validated by the use of literature in Chapter 4, as well as the data-gathering process reviewed through the use of further literature. The last step of the validation process consists of comparing the input-output model with the input-output transformations of the real system in the study. This will be performed by re-introducing the data from the benchmark case, composed of the objectives in both PNECs, together with other relevant reports elaborated by energy consulting companies, followed by an expert consultation, which will be performed later in this chapter.

The main objectives stated in the Spanish PNIEC, which follows the European objectives established in the ”Fit for 55” and ”RepowerEU” statements, consisting of the energy transition objectives looking to 2030, involve a 32% reduction in the greenhouse gas emissions compared to the values retrieved from 1990, a 48% of renewable energy over the final gross energy consumption, a 44% improvement in the energy efficiency of the system using 2007 as a reference, and 81% of renewables in the final electricity generation mix, and a 34% of electrification in the overall economy, and 22 GW of electricity storage capacity [105].

In addition, the Spanish government expects 214 GW of electricity installed capacity, of which 160 GW are renewable and the rest non-renewable. The renewable capacity will be composed of 62 GW of wind energy, composed of 58 GW of onshore wind and 4 GW of offshore wind, 76 GW of solar PV capacity composed of utility-scale and self-consumption, 4.8 GW of solar thermal, 27 GW of CCGT, 16 GW of hydro-power, and 9,5 GW of PHS as the primary electricity generation sources. Nuclear energy is expected to be phased from 7 to 3 GW by 2030. Regarding the installed capacity of electrolyzers, the Spanish government expects to reach 11 GW by 2030 without specifying the type. Nothing is stated about the expected capacity for blue hydrogen [105].

On the other hand, the main objectives stated in the Portuguese PNEC, which follows the European objectives established in the ”Fit for 55” and ”RepowerEU” statements, consisting of the energy transition objectives looking to 2030, involve a 55% reduction in greenhouse gas emissions compared to the values retrieved from 1990, 47% of renewable energy over the final gross energy consumption, a 32.5% improvement in the energy efficiency of the system using 2007 as a reference, and 85% of renewables in the final electricity generation mix, and a 65% reduction in energy dependence [10].

In addition, the Portuguese government expects to reach 47 GW of installed renewable energy generation capacity. 21 GW of wind energy, composed of 10 GW of onshore wind and 11 GW of offshore wind, 20.7 GW of solar PV capacity composed of utility-scale and self-consumption, 2 GW of solar thermal, 1.2 GW extra of hydro-power capacity, as the main electricity generation sources. Regarding the installed capacity of electrolyzers, the Portuguese government expects to reach 5 GW by 2030 without specifying the type. Nothing is stated about the expected capacity for blue hydrogen [10].

By comparing the base-case scenario and the PNEC scenario, as seen in table 7.1, composed of the expected installed capacities by Portugal and Spain in 2030, stated in 2021, it can be seen that the model installs almost 70 GW more. This is important to note, meaning the system can transition much faster based on the built model conditions. The disparity does not validate the result itself. However, the difference is caused by not considering the spatial limits needed to build such a large amount of renewable capacity and the model’s ability to couple the sub-systems without limitation. If these constraints were imposed, the total RES capacity would be lower.

Scenario	BC	PNEC
Total RES capacity (GW)	264.91	207 (updated)

Table 7.1: Comparisson between the installed renewable capacity between the benchmark and the base-case

These disparities are also found when comparing the results obtained for the installed capacity per renewable energy source between the benchmark and the base-case scenario, as seen in table 7.2. Again, the values obtained in the model results for solar PV and wind onshore sources exceed the targets established in the benchmark by a reasonable amount. On the other hand, the targets for solar thermal and wind offshore are higher than the model results. The reason behind the higher installation of the first two mentioned RES is the same as explained before. The model tries to minimize the costs, and by increasing this capacity, it reduces the overall electricity and heat production costs through the electrification of the thermal sub-system. The disparity between the benchmark and the base case in the other two RESs is also caused by the optimization process. Both of these technologies are less cost-efficient than their counterparts. However, in the actual situation, the establishment of solar thermal and offshore wind has a rationale, which consists of diversifying the energy generation system to provide higher production security based on different weather patterns.

Installed RES Capacity by 2030 (GW)	**Solar PV**	**Solar Thermal**	**Wind Onshore**	**Wind Offshore**
Benchmark	98	6.8	70	14
Base Case	139.06	2.3	103.32	0.03

Table 7.2: Comparison between the benchmark and the base case scenario for the installed capacity per renewable energy source

Finally, figure 6.24 depicts the installed electrolyzer capacity per scenario. The model displays similar values for the overall installed electrolyzer capacity between the benchmark and the base case scenarios, which validates the model output regarding this technology since the model could freely impose the optimal capacity. However, these values differ from the updated national targets for electrolyzer capacities, which are not included in the PNEC run scenario. Nevertheless, these new targets have not been approved yet and seem to be unrealistic [105].

7.2. Analysis of the System from a Wider Perspective

The Spanish and Portuguese governments established some objectives regarding the total installed renewable capacity for 2030, amounting to 160 and 47 GW proposed through the PNIEC and PNEC [105] [10]. The results for the total system-wide cost shown in table 6.3 demonstrate that the established targets are not optimal, given the same energy demand in 2030. This is mainly caused by the target imposed in the PNEC scenario on solar and wind onshore energy, which leads to a higher production of electricity by using combined cycle gas turbines and nuclear reactors, as well as a higher production of heat by using gas boilers, which leads to much higher operational costs expenses, composed by fuel and CO_2 costs, and to a lower energy efficiency, which causes the necessity to increase the necessary amount of energy. In addition, the National Plans for the Energy Transition establish a combined total installed offshore capacity of 3.5 GW, compared to the almost negligible installed capacity of the rest of the scenarios. This capacity highly increases the overall system-wide costs caused by the high necessary investment and maintenance costs related to this renewable technology. Thus, these results also demonstrate that, without a limitation over the available surface destined for creating renewable energy generation infrastructure, offshore wind energy is not optimal regarding the overall system costs.

Although some cost parameters have been varied, the optimization model suggests that, for the specific built model, in which the three energy carrier sectors were allowed to closely interact and transform into each other to satisfy the energy requirements most optimally, the system requires at least a minimal renewable installed capacity of 259.86 GW, for the studied parameter variation. This requires a minimal introduction of 179.68 GW of renewable capacity to reach a future energy system dominated by renewables, together with the introduction of hydrogen to reach a more efficient energy system and a reduction in the importance of non-renewable energy sources. Thus, investing in large increments of renewable energy capacity is not a bad decision, even in the worst possible scenarios concerning the cost of installing new technologies.

As mentioned in Chapter 6, the model built for representing the Iberian Energy System in 2030 was allowed to create a greater degree of interplay between the different energy sectors compared to the current situation. This meant making available the selection of three different types of boilers, one per energy carrier, to be used for the generation of heat necessary both for the residential and industrial sectors. The reason behind introducing a higher degree of interplay was to analyze to what extent the energy system would become more efficient by replacing natural gas-based technologies, which are not the most efficient for hydrogen or electricity-based technologies, which present higher efficiency levels. Moreover, the objective extended to observing the degree of electrification when the selected parameters were varied. The results presented a much higher-than-expected percentage of electrification compared to the objective established in the PNIEC, reaching almost 65% compared to the established 34%. Nevertheless, this value is not fully realistic since it does not include all of the different sectors of the economy.

Based on the results, the original electrolyzer's planned capacity seems achievable for 2030, given the planned capacity for renewable energy sources as seen 6.24. However, the updated targets are far beyond the results obtained in the model simulations, reaching double the values. It is important to note that the uncertainties regarding electrolyzers' technical specifications and those related to capital expenses must be reduced to achieve the desired capacities successfully. Nevertheless, the installed capacity could overcome the planned amount if policymakers adopt specific policies, such as limiting or eliminating blue hydrogen technology or starting a phase-out process for nuclear and natural gas-based energy production.

Another important remark taken from the results shows that the effect of the installed electrolyzer capacity on the overall electricity production is much bigger than the effect of the variation of RES capital expenditure on the overall hydrogen production, meaning that the overall system is much more sensitive to changes in hydrogen production technologies, despite the great disparity between the installed capacities compared to renewable energy sources.

This research also provides meaningful outcomes regarding the sensitivity of installed renewable hydrogen production capacities concerning variations in the uncertainties regarding hydrogen technologies. Based on the result, it can be seen that the installed capacity for SMR + CCS plants is less sensitive to variations in hydrogen uncertainties compared to green hydrogen technologies. On the other hand, blue hydrogen seems to be more sensitive to variations in renewable installed capacity compared to green hydrogen technologies.

The study results demonstrate that the 2030 Iberian energy system will still rely on natural gas consumption to meet the energy requirements of all the system's sectors. Significantly when the availability of renewable energy sources declines. Nevertheless, even though the inclusion of CCS technology into the steam methane reforming process significantly reduces the greenhouse gas emissions generated, it is necessary to realize that storing space for CO2 emissions is limited and not fully efficient in the long run. Consequently, placing a significant emphasis on blue hydrogen production may not be the optimal solution to the decarbonization process.

7.2.1. Initial Interpretation of Results

Based on the main extracted conclusions stated above and by using the gained knowledge from the benchmark case and the used literature involving the predictions for the Iberian Energy System in 2030, the results can be interpreted from the real-case perspective of this system.

Technical Implications

The technical implications of the result include all of the problems arising from a technological perspective. The main two encountered discrepancies between the real system and the model results, including the benchmark objectives in this process, were the role of hydrogen in the 2030 Iberian Energy System and the uncertainty regarding the technological development of the involved technologies. Other implications include the lack of grid capacity and the uncertainty regarding implementing offshore wind farms.

Based on the results, the role of hydrogen in 2030 takes the expected shape based on the literature. It acts as an additional energy vector, capable of storing the surplus of energy produced through renewables by the electrolysis process, complementing natural gas to fulfill the heat requirements of both the industrial and residential sectors and enabling a smoother sector coupling process. However, the model establishes the role at a higher degree than expected. In the scenarios with a higher reduction in the electrolyzer CAPEX, hydrogen gains great importance by reducing the electricity production through CCGT plants and the heat production through gas boilers. This seems unrealistic, given that currently, there are no functional electrolyzer plants in the Iberian Peninsula.

Secondly, the model assumes that the technological readiness of hydrogen-related technologies and the RES will achieve the predictions from the literature. This concerns the associated technology costs and the technical specifications such as lifetime or efficiencies. However, there is great uncertainty about the future specifications of these technologies, especially the ones surrounding hydrogen production and conversion and offshore wind, which could render completely different results in the system if the predictions are not accurate.

Another important discrepancy between the system and the model concerns the electricity network among both nations. In the model, the grid capacity and the detailed network structures were not considered since they were left out of the scope of the study. However, in the real system, grid capacity is one of the significant issues regarding the expansion of renewables due to the necessity of coping with all the extra electricity that cannot be easily stored yet.

Financial Implications

The financial implications concern all of the discrepancies between the system and the model from an economic perspective. The main discrepancies encountered include the lack of infrastructure and investment incentives to generate the system changes proposed by the model results.

The model expects growth of approximately 120 GW of installed renewable capacity compared to the current installed capacity in the system and a difference of roughly 70 GW compared to the objectives established by both nations regarding the year 2030. The substantial differences led to the conclusion that the system cannot achieve such an expansion, given the lack of infrastructure and financing, especially for windmills, which take between 4 and 8 years to be constructed. The numbers could be slightly more realistic for solar PV, but they are still impossible. This was also encountered with the model's high electric boiler capacity, given that the current system has no large-scale electrical heating systems installed.

Regulatory Implications

The regulatory implications of the result involve the problems arising from an institutional and bureaucratic perspective, which were not considered in the model but are a component of the real system. The two main regulatory implications that could make the results seem unrealistic are the bureaucratic processes required to establish new renewable energy generation areas and ecological-related issues.

As mentioned, a windmill technically takes 4 to 8 years to build. However, in Spain and Portugal, acquiring a license and performing a study is necessary before proceeding with the construction. If the licensing process is slow, this adds more construction time. This makes achieving the capacities obtained from the result and even those stated in the benchmark more challenging and unrealistic.

Another issue regarding the construction of renewable energy generation installations concerns ecological issues. For example, in Spain and Portugal, the areas where windmills can be built are limited due to the danger they generate to protected species of birds. Ecological institutions limit the construction areas by studying the flying trajectories of these birds, reducing the available construction areas and slowing down the construction process. Thus, it is difficult to reach the expected and obtained capacities for wind energy due to the lack of space.

Social Implications

The social implications of the result include all of the problems arising from a social perspective that were not considered in the model. Based on the literature, the main encountered difficulty from this perspective involves the likelihood of inhabitants accepting the construction of the necessary structures to generate renewable electricity or hydrogen near their residential locations.

Windmills, in particular, generate the most significant complications due to their size. People who live in the countryside, where these structures are usually placed, are against allowing the construction process due to the noise windmills produce when functioning and the disturbance of the nature surrounding the areas, which affects the visual attractiveness of the area. This further limits the areas allowed to be used and increases the construction times even further, making the obtained results even less realistic.

7.2.2. Interpretation of Results after the expert consultation

Once the main conclusions of the implications of the results over the dimensions not considered in the model were extracted, it was necessary to validate the study further. To do so, an expert consultation process was performed. This consisted of interviews proposed to three experts who are currently deeply involved in the sector and the energy transition process from different perspectives. The first interviewee was Javier Revuelta, Senior Principal at AFRY, working as an Energy & Social Transition Leader. The second interviewee was Ana Isabel Barillas, Managing Director for the Iberia and South America department at Aurora Energy Research. José Truzman, Chief Financial Officer at Jenner Services (AMP Energy), was the last interviewee. The set of questions proposed for the interviews is presented in Appendix C. The implications stated below are based on the expert's answers.

Technical Implications

Currently, the installation rate of solar PV in Spain is approximately 7 GW per year, while onshore wind is 1 GW per year. To achieve both the benchmark objectives, which are even smaller renewable installed capacity values compared to the ones obtained in the model. The values could be achieved for solar PV by increasing the construction rate to 12 to 13 GW per year. However, this is highly difficult because of the lack of infrastructure and a capable workforce to reach this construction time. For wind energy, the objectives are completely unrealistic given the current construction rate, which is lower than solar due to all the infrastructure required to build a wind farm. From an optimistic perspective, the rate could increase to 2 to 3 GW per year, which is still insufficient to reach the obtained onshore wind capacities in the results. This objective could be achievable for the year 2040 instead. However, in the next decade, most of the wind farms constructed in Spain and Portugal during the first decade of the 21st century must undergo renovation to reach the end of their lifetime. This further complicates the achievement of the capacity obtained in the model results for 2040.

Another significant barrier to the massive deployment of renewables obtained from the model results and for the objectives stated in the benchmark is the development of the electricity grids. The current energy transition plans assume that the electricity grids will develop at the same rate as RES. However, that assumption is unrealistic given the greater amount of factors to consider in its expansion.

The same problem is encountered regarding the massive installation of electric boilers to generate greater electrification and system coupling levels. There is no proposed project to generate such a massive substitution of gas boilers for their electric counterpart, making it unrealistic to achieve a 65% share of the installed boiler capacity as obtained in the model results. In addition, there is no capacity to produce such a change in the next 6 years, even if the project starts immediately. In addition, using electric boilers for some industries is impossible due to the incapacity to reach the necessary temperatures for the desired activities. Hydrogen, in the long run, has a higher chance of substituting the use of fossil fuels for this purpose.

Regarding the installed capacity for the production of green hydrogen, neither the results obtained nor the objectives established by both governments are realistic for different reasons. First, given that there is currently only 25 MW installed in Spain for the production of green hydrogen, reaching 11 GW is impossible in 6 years, given the nation's capabilities and the technology readiness of these components. In addition, the transport of hydrogen through the current network is limited to 5% of the overall mixture, further limiting its integration into the system.

Financial Implications

The biggest financial problem regarding the massive expansion of renewables is the uncertainty regarding the future price of electricity. The average electricity prices in the Iberian Peninsula have been at historical lows in the past months. The great renewable electricity production creates a massive problem from the investors' perspective. If the current RES capacity generates such a decrease in prices, the prices might reach 0 €/MWh in the future, generating no benefit for the energy sellers. Therefore, investing in renewables would not be worth it from an investing perspective. This effect could directly collide with the necessity to currently invest in renewables to achieve the established objectives, making it difficult to incentivize investment.

The biggest barrier to developing and integrating hydrogen in the energy system is not technical but financial. Even if the national objectives could be achieved (higher than the ones obtained in the results), given the expected prices for green hydrogen, there would not be enough demand to cover all of the possible green hydrogen production, and it would be impossible to generate that necessary demand in such a short time. The demand will directly depend on the prices that industries are willing to pay for the produced green hydrogen. If it is established at low prices, the generation of green hydrogen would not be financially beneficial, making the business unsustainable.

Regulatory Implications

One of the main regulatory issues of the massive increase in renewable electricity generation is the lack of rules to secure a return on investment for RES, given that the prices are low. The government must find a way to regulate this situation and mitigate the price reduction caused by the increase in renewable electricity generation to keep the incentive on the investment in renewables and be capable of achieving the massive expansion targeted for 2030 and onwards.

Secondly, as mentioned, before starting the construction of any energy generation facility, it is necessary to obtain the necessary licenses to start the project. In addition, the project has to be within the regional limits established by the ecological institutions, taking care of the environment of the selected areas. This is becoming a significant issue since institutions keep pushing to expand these areas, eliminating the possibility of building parks in spaces where the best weather conditions can be achieved. In the last three years, the Spanish government established an auction system to achieve the permit to be connected to the electricity grid and thus build a functioning renewable energy generation site. The capacity ready to be auctioned amounts to 100 GW. However, none of that capacity has been auctioned in this period, generating a more significant concern regarding the objective's achievement for 2030, as well as more significant problems for the companies investing in renewables due to the elongated time needed to build the facility, and thus delayed profitability of the project.

Social Implications

Regarding the social implications, the biggest issue concerns the neighboring areas to the spaces where the renewable energy facilities are projected to be built. More and more, the people surrounding these areas are posing problems in establishing new renewable energy generation technologies due to modifying the areas where they live. They state that the visual appeal of their environments is being affected and claim financial compensation, making the projects even less attractive, given all of the already mentioned financial and regulatory implications affecting the financial attractiveness of these projects.

7.3. Policy Recommendation

The analysis of the obtained results, which was validated through the comparison to the benchmark case, as well as by integrating the implication of the aspects of the system that could not be simulated in the model and the expert consultation, has been presented. The main discrepancies between the real possibilities for the system's evolution towards the year 2030 and the predictions made by both the model results and the national objectives established in the energy transition plans of both Portugal and Spain will enable the proposal of a set of policy recommendations.

The main discrepancies between the answers obtained through the analysis of the real system and the model results entail the difference in the predicted installed renewable capacity for electricity and heat generation, the system's available storage capacity, and the high reliance on blue hydrogen technology. As mentioned, the model's objective is to satisfy the energy requirements in each energy sub-system (thermic, hydrogen, and electricity) cost-efficiently without considering many factors that limit the desired massive renewable expansion. The model was allowed to freely install renewable capacity and connect it to the other sectors without boundaries, leading to a very optimistic view of the system in 2030. Nevertheless, achieving those results, in reality, will not be possible mainly due to the lack of infrastructure and technology to reach those construction rates, the lack of incentives to invest in renewables given the effect of a dominated market by renewables causing low profitability, and other regulatory and social concerns that slow down or could completely modify the development of renewable projects, which could never be precisely considered by using this model.

Based on this, it can be seen that the priorities of the model regarding the system's evolution in 2030 differ from the government's vision and the sector experts, which also differ in many points from the national plans. Given the most significant discrepancies between the three different perspectives of the Iberian Energy System in 2030, the following set of policies is proposed to try to align the objectives into a realistic point of view, given the system's real constraints:

- Creating **Power Purchase Agreements (PPAs)** between energy producer and consumer to fix the electricity price at a value where the producer retrieves benefit from the project, and the consumer is willing to pay. Like this, the government maintains an incentive for further investment in renewables and thus continues with the established progress.
- Investing in the quick and robust **expansion of the Spanish and Portuguese internal electricity grid** to cope with the massive expected renewable increase in their energy mix. Without sufficient grid capacity, the expansion of renewables will not generate any impact on the system except an economic loss for the investors in the project.
- Negotiating an agreement between the Iberian Peninsula and France to establish a **more significant trade volume and feed electricity to the rest of the European countries**. Given the high

capacity for renewable generation in the peninsula, this would benefit the EU by receiving the energy that their renewables cannot produce due to weather conditions, as well as the Spanish and Portuguese energy producers, which, with a higher volume of renewables, will be less capable of generating profitability in their borders.

- Setting the established objectives for the **installed electrical storage capacity to the maximum priority**. By installing such a significant storage capacity (22 GW), the system will require of less installed renewable capacity to satisfy the demand for electricity at every moment. In addition, this will lead to a higher variation of electricity prices, creating a higher incentive to invest in renewables. Furthermore, the system will have the necessary time to gradually integrate green hydrogen technology without creating great disruptions.
- **Limiting the allowed capacity for producing blue hydrogen**. Based on the literature, carbon capture and storage technology has been studied for the short term. Nevertheless, in the long run, a massive amount of space will be needed to store all the CO_2 produced through this process if the governments highly rely on this option. In addition, the reliance on blue hydrogen might delay the development and deployment process of green hydrogen technology due to the lack of investment and the consolidation of the opposite technology.
- Establishing financial incentives to promote the substitution of the current network of gas boilers to **electric boilers or heat pumps** among the citizens for the electrification of the residential sector, which has the potential to increase the energy system's efficiency highly. The objective should be established towards 2040 rather than 2030 since the nations do not possess the financial or infrastructural capacity to generate such a change in the next 6 years.
- **Reducing the regulatory pressure** imposed on the companies willing to invest and develop new renewable electricity generation facilities. This involves reducing ecological institutions' power over the limitation of key spaces and reducing the capital needed to receive the permits and approval to build the projects. In this way, the projects will be developed at a faster pace, giving smaller companies the chance to compete in the energy production market, which makes it more competitive.

7.4. Limitations

The model built in Python, using the Calliope framework, has presented the opportunity to gain meaningful insights into the development of the Spanish and Portuguese energy systems for the year 2030. Nevertheless, as with every model-based analysis, the research methodology presented some limitations.

One of the most relevant limitations concerns the Calliope framework. This tool resolves energy system optimization problems using linear programming, which only allows for establishing linear relationships between variables. In reality, systems can also present non-linear relationships, as is the case for the electrolyzer learning curve, in a system that desires to study the impact of hydrogen on an energy system.

Regarding the data gathering, the retrieved capacity factors were values recorded for 2019. They were not adapted to the year 2030 since it is impossible to be fully certain about the weather patterns in the future. In addition, the data used for energy demand was also assumed to have an overall increase of 13.5%. Nevertheless, further factors could affect the evolution of demand through the years and reach, overcome, or stay behind the selected value for the energy demand.

Regarding the previously made assumptions, the electricity and gas grid capacity was not limited to a maximum capacity, as is the case in reality. Transmission networks have a maximum capacity of electricity and hydrogen they can transport at once, limiting the system's overall response times. This is currently one of the biggest problems regarding the dominance of renewables in the system. Additionally, the defined regions in the system were not limited, considering the space to construct renewables and the rest of the system's technologies. Finally, an infinite storage capacity for CO_2 was assumed. Nevertheless, this requires further facilities and extra space, making it more difficult to depend on blue hydrogen technologies. Finally, this analysis was performed as if the Iberian Peninsula presented island characteristics. There is an existing connection with France, the neighboring country.

In addition, the EU is planning on a shared European hydrogen transition network to allow countries with higher availability of renewables to help those who suffer from this phenomenon.

Finally, all of the financial, technical, social, and regulatory aspects that could not be included in the model create a great limitation to represent reality through the model. As mentioned, all of these processes slow down the required time to create renewable infrastructure, which is neglected in the model. In addition, the interactions between the actors involved in the process are not considered. From the financial and technical perspective, the capacities to generate infrastructure, available workforce, and spatial limits are also not included in the model.

7.5. Future Research

The present study has provided valuable insights into the impact of fluctuations in capital expenditures of electrolyzers and renewable energy sources on the prospective integrated energy systems of Spain and Portugal. However, conducting additional research has the potential to enhance the findings by exploring other uncertainties, which would lead to a more comprehensive understanding of the implications of hydrogen integration and the intricate process of sector coupling.

One potential avenue for future research involves exploring additional uncertainties related to hydrogen technology and examining the system's sensitivity to alterations in technical parameters, such as efficiency or non-linear features. This would enhance the realistic aspect of the analysis. By undertaking this action, a more profound and comprehensive understanding of the impacts of hydrogen system integration may be gained. This will result in a more precise delineation of the governing principles and thus facilitate a more seamless transition process.

Furthermore, a larger set of scenario combinations can be generated by expanding the defined scenario matrix to include additional parameters and increasing the number of cases for each parameter. This can provide additional insights into the interaction between the selected factors. By adopting this approach, the analysis of the system will closely align with reality, as even a slight alteration of a single parameter could result in a very different conclusion.

Another intriguing approach would be to thoroughly examine and enhance the current transmission networks in the system. This study did not take into account any capacities. However, transmitting electricity from one area to another is essential when designing and constructing a new power plant. If a particular electricity line becomes overloaded, the power plant cannot market its generated energy. The system can be analyzed for various installed capacities of renewable energy, hydrogen, and storage by keeping the previously investigated parameters fixed and determining the present transmission capabilities.

8

Conclusion

The main research objective of this Master Thesis was to create an important advancement in the current understanding of the interaction between the integration of green hydrogen technology into an energy system and the effect it generates on the deployment of renewable energies, together with the interplay between the different energy sectors. To do so, the research aimed to acquire important insights into the influence of the uncertainties surrounding the future of renewable energy technologies on the integrated energy system in the Iberian Peninsula, composed of Spain and Portugal, and focusing on the year 2030, a target year established to achieve established decarbonization targets. Moreover, based on the results, the objective was extended to suggesting possible policy measures to tackle the several coordination issues, technical, social, and financial, linked to the disruptive change caused by green hydrogen infrastructure.

The study was conducted utilizing the Calliope multi-scale energy systems modeling framework, which brings up great advantages and some disadvantages in modeling energy systems. Calliope displays a high degree of flexibility by enabling the incorporation of any kind of energy source, new technologies, and different policy scenarios. Furthermore, Calliope allows the integration of many different sectors, to capture the interplay between the components of energy systems. This allows for a comprehensive analysis of the consequences that arise across other sectors when one is modified, as well as the identification of parameter sensitivities, synergies, and trade-offs. Nevertheless, Calliope has its limitations. To cope with the intricacy of computational complexity, Calliope utilizes simplifications and assumptions that may not comprehensively encompass the complexities of real-world energy systems, which could impact the precision and practicality of its outcomes. An example is the establishment of only linear programming, which cannot analyze non-linear behavior present in energy systems. Furthermore, the model predominantly emphasizes techno-economic factors and may not comprehensively integrate social, behavioral, and political factors, requiring further external analysis.

By conducting an in-depth sensitivity analysis of the research results, the main research question: ”To what extent will the new technologies related to hydrogen production pathways accelerate the deployment of Renewable Energy Sources?” has generated great insights. The results suggested that variations in the uncertainties regarding hydrogen production, conversion, and storage technologies generated significant influence in the overall system. In specific, the capital expenses of green hydrogen production technologies exerted a significant effect in the overall deployment of renewable energy sources. Furthermore, the overall system energy consumption showed sensitivity to variations in the deployed green hydrogen capacity, by reducing the overall energy consumption whenever the green hydrogen production was at its highest levels, caused by the promotion of renewable electricity sources.

The study’s findings highlight further advantages gained by reducing the required capital investment for electrolysis technology. This decrease, in return, would encourage investments in PEM electrolyzers, rather than in the older and alternative option, due to presenting better technical characteristics. This type of electrolyzer plays a crucial function in promoting the implementation of renewable energy sources and stimulating investments in salt caverns, by improving the security of supply when there are imbalances in the electrical or heat sectors. Therefore, greater adoption of these technologies would consequently substitute the reliance on fossil-based hydrogen and energy, leading to a significant decrease in carbon emissions and expediting the shift towards a low-carbon economy, which are part of the established objectives for the year 2030.

Another meaningful insight gained from the analysis is the effect of the presence of blue hydrogen technology in the system. When the CAPEX of electrolyzers is at its high bound, the system increases the installed capacity of blue hydrogen to compensate for the decreased green hydrogen capacity. The same effect is observed vice-versa. Based on this outcome, we could assume that the real system does not need the presence of blue hydrogen. However, based on the current cost specifications, blue hydrogen presents a great cost advantage over its green counterpart. In addition, it would be unrealistic to think that by 2030, the production of hydrogen through the Steam Methane Reforming process would disappear, since the system will still rely on natural gas for the production of cheaper hydrogen, to gradually integrate it in the system, while the technology development process of electrolysis continue.

Conversely, the electrification process of both the electrical and heat sectors, together with the expected increase in the total energy demand, and the limitation of energy production by non-renewable sources showed the biggest effect regarding the installed capacity for renewable and green hydrogen technology. The decrease in the need for energy production, caused by a higher overall system-wide energy efficiency led the system to rely more on renewable electricity, and thus in green hydrogen. The higher the installed capacities for these technologies, the bigger the energy efficiency improvement. Therefore, it is highly likely that the sector coupling process might lead to the reduction of the capital expenses for renewable energy sources and green hydrogen technologies.

Based on the study's findings, it is clear that lowering the capital expenses of electrolyzers by promoting their technological development or introducing financial incentives to promote investment can significantly contribute to the system-wide adoption and integration of green hydrogen infrastructure. Furthermore, the promotion of investment in renewable electricity sources will create the same effect. On the other hand, using resources to develop blue hydrogen infrastructure or impeding the installation of conversion technologies that link the different sectors in the energy system may hinder the progress toward establishing a sustainable energy system. Thus, it is advisable to implement a policy framework that limits the generation of blue hydrogen, as this will promote the use of green hydrogen infrastructure and accelerate the transition process by deploying bigger volumes of renewables.

Furthermore, this research also emphasizes on the importance to compare the obtained results of an energy system modeling process to the real system. As mentioned throughout the discussion, the model neglects many of the infrastructural and financial issues related to the massive deployment of renewables and the electrification process, leading to more optimistic results compared to what the reality is. In addition, the regulatory and social interactions between the different stakeholders in the system were not included either, which creates another difference between model and reality. Therefore, although the model has created great insights to study the relation between the different technical components in the system, it is important to include this further analysis when taking action.

This study is also focuses in the crucial role that policies play in creating incentives that help the system transition towards the governments' established objectives. This includes the electrification process and the required installation of energy storage facilities and the integration of green hydrogen infrastructure to reach the massive deployment of renewable energy sources within the Spanish and Portuguese Energy Systems. Policymakers should actively formulate measures that not only promote the widespread use of hydrogen as a feedstock in the industrial sector but also successfully tackle the challenge of being used as the intermediary to coordinate the efforts of the different energy sectors to meet their energy requirements. Through this approach, policymakers may actively facilitate the shift towards a low-carbon economy, alleviate the negative consequences of climate change, and lay the foundation for a sustainable and ecologically sound energy future.

In summary, the study's results suggest that integrating green hydrogen technologies into the Iberian energy system can be an effective strategy to reduce carbon emissions and achieve decarbonization goals set in Spain and Portugal's energy transition. However, developing policies fostering green hydrogen production and usage, alongside cooperation between the public and private sectors, is crucial for ensuring a successful and sustainable energy transition by 2030.

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A

Iberian Integrated Energy System

A.1. Spanish Nodes

Node	**Location**
ES11	Galicia
ES12	Asturias
ES13	Cantabria
ES21	Basque Country
ES22	Navarra
ES23	La Rioja
ES24	Aragón
ES30	Comunidad Autonoma de Madrid
ES41	Castilla y León
ES42	Castilla-La Mancha
ES43	Extremadura
ES51	Catalunya
ES52	Comunitat Valenciana
ES61	Andalucía
ES62	Murcia

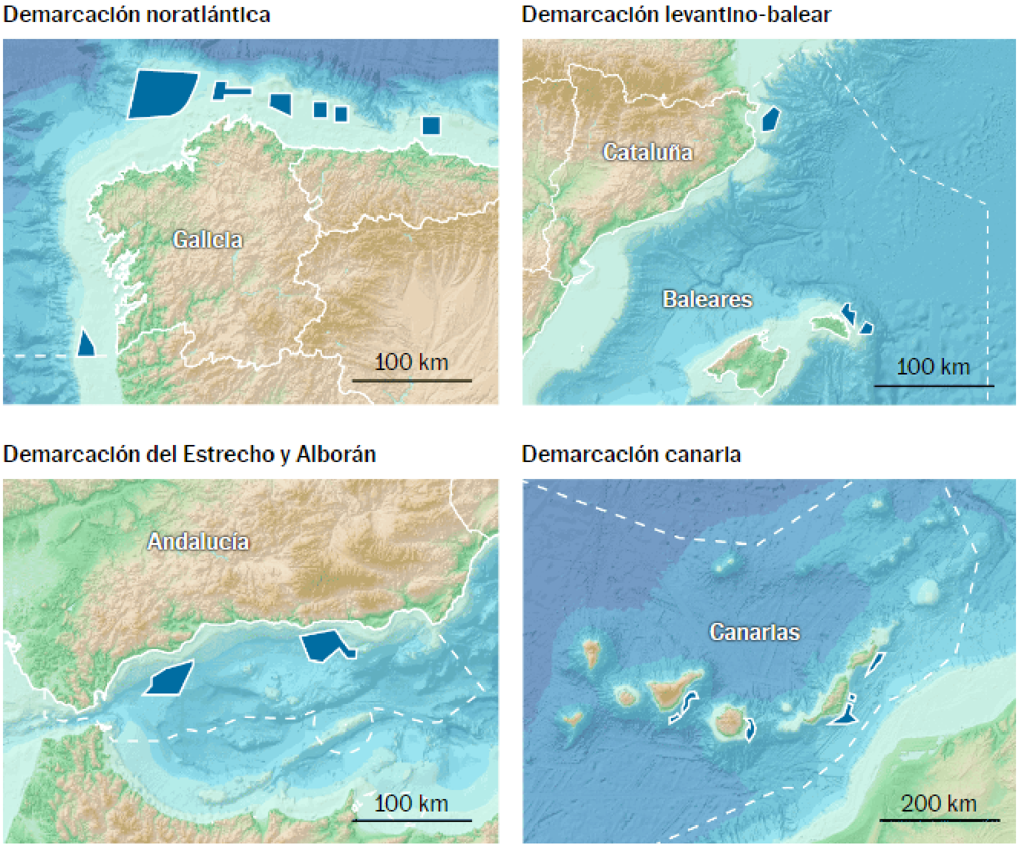
Table A.1: Selected nodes for the Spanish territory

A.2. Portuguese Nodes

Nodes	**Location**
PT11	North Portugal
PT15	Algarve
PT16	Centre Portugal
PT17	Metropolitan Area of Lisbon
PT18	Alentejo

Table A.2: Selected nodes for the Portuguese territory

A.3. Spanish Offshore Wind Farm Planning



Demarcación noratlántica

Demarcación levantino-balear

Demarcación del Estrecho y Alborán

Demarcación canaria

Figure A.1: Map of the maritime spatial planning for offshore wind farms in Spain. Extracted from the PNIEC [108]

A.4. Portuguese Offshore Wind Farm Planning

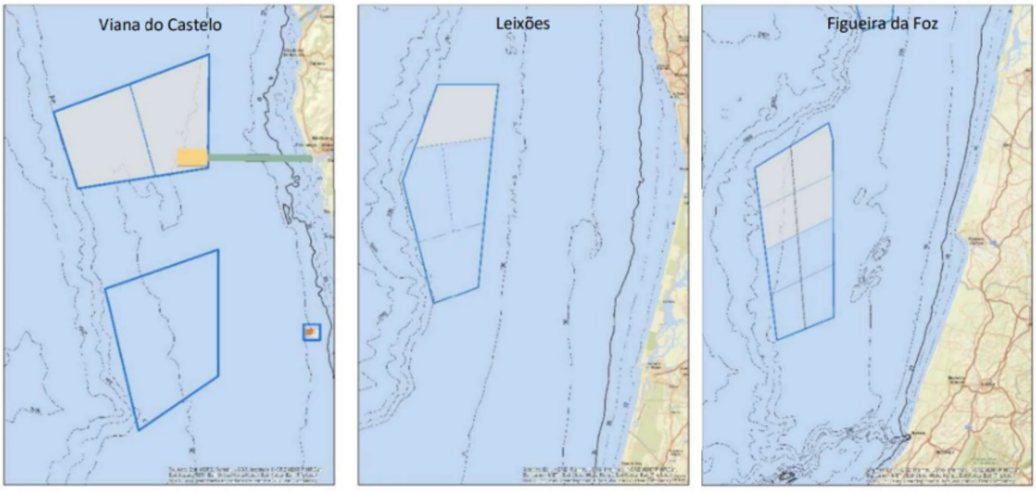


Figure A.2: Map of the maritime spatial planning for offshore wind farms in Portugal [20]

A.5. Offshore Wind Farm Nodes

Node	Location
OFF1	Viana do Castelo
OFF2	Levantino-Balear
OFF3	Alborán
OFF4	Gibraltar’s Strait
OFF5	North Atlantic
OFF6	Figueira da Foz

Table A.3: Offshore Nodes for the model with their locations

A.6. Total Installed Capacity in Spain

Energy Source	Installed Capacity (MW)
Hydro-Power	17093
Pumped-Hydro	3331
Nuclear	7117
CCGT	24562
Co-Generation	5590
Solar PV	19538
Solar Thermal	2304
Wind Onshore	29553
Coal	3223
Other Renewables	1087

Table A.4: Summary of the installed capacity in Spain including the relevant energy sources for the model [133]

A.7. Total Installed Capacity in Portugal

Energy Source	Installed Capacity (MW)
Hydro-Power (All three combined)	8221
Wind Onshore	5347
Wind Offshore	25
Solar	1892
Biomass	700
CCGT	4461
Other	28

Table A.5: Total installed capacity in Portugal per existent energy source. Source \[157]

A.8. Cross-Border Grid Connections in Spain

Figure A.3: Cross-border grid connections between Spain and its neighbour countries [72]

A.9. Maps of the current Gas Networks

Figure A.4: Map of the 2022 Spanish gas network according to Enagas [34]

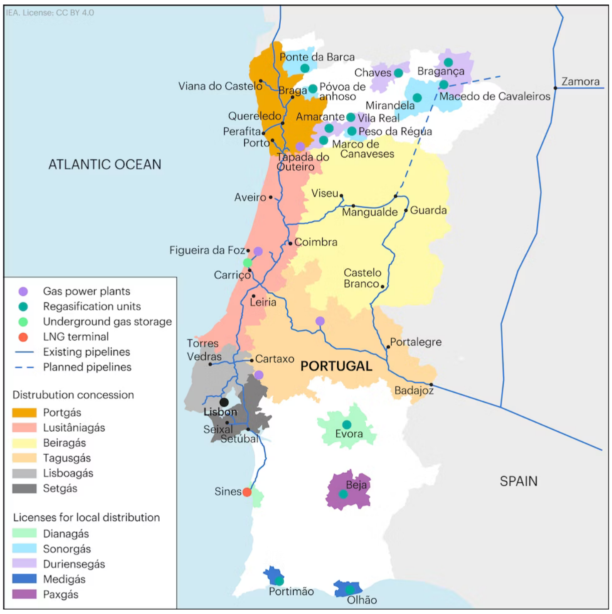


Figure A.5: Map of the 2022 gas network in Portugal [69]

A.10. Division of Electricity Demand per Sector

Figure A.6: Share of final electricity demand per sector in Spain

A.11. Data Processing

A.11.1. Industrial Hydrogen Consumption in Spain

Node	% of GDP	Hydrogen Demand (MWh)
ES11	5.60%	108,35
ES12	2.08%	40,17
ES13	1.23%	23,72
ES21	6.35%	122,87
ES22	1.80%	34,92
ES23	0.76%	14,76
ES24	3.36%	65,05
ES30	20.78%	402,04
ES41	5.15%	99,58
ES42	3.74%	72,46
ES43	1.78%	34,47
ES51	20.31%	393,10
ES52	9.97%	192,94
ES61	14.23%	275,43
ES62	2.85%	55,18

Table A.6: Summary of the final data for industrial hydrogen consumption in Spain after the data process methodology described above

A.11.2. Electricity Demand per Node in Spain

Node	Electricity Demand (MWh)	% of Demand
ES11	13,760,055	5.83%
ES12	8,839,053	3.75%
ES13	3,618,394	1.53%
ES21	15,207,498	6.45%
ES22	5,042,751	2.14%
ES23	1,597,425	0.68%
ES24	10,213,736	4.33%
ES30	27,876,683	11.82%
ES41	13,384,554	5.67%
ES42	11,704,862	4.96%
ES43	4,840,938	2.05%
ES51	44,900,259	19.03%
ES52	27,067,126	11.47%
ES61	38,792,977	16.44%
ES62	9,054,222	3.84%
Total	235,940,903	100%

Table A.7: Electricity demand per node in Spain

A.11.3. Electricity Demand per Node in Portugal

Node	Electricity Demand (MWh)	% of Demand
PT11	17,112,449	35.24%
PT15	2,690,774	5.57%
PT16	10,892,259	22.56%
PT17	13,842,501	28.67%
PT18	3,836,463	7.95%
Total	48,274,445	100%

Table A.8: Electricity demand per node in Portugal

A.11.4. Industrial Heat Demand in Spain

Node	% of GDP	January Industrial Heat Demand (MWh)
ES11	5.60%	1347.07
ES12	2.08%	499.39
ES13	1.23%	294.98
ES21	6.35%	1527.64
ES22	1.80%	434.16
ES23	0.76%	183.51
ES24	3.36%	808.79
ES30	20.78%	4998.80
ES41	5.15%	1238.18
ES42	3.74%	900.87
ES43	1.78%	428.58
ES51	20.31%	4887.57
ES52	9.97%	2398.92
ES61	14.23%	3424.59
ES62	2.85%	686.10

Table A.9: Summary of the final data for industrial heat demand in Spain after the data process methodology described above

A.11.5. Industrial Heat Demand in Portugal

Node	% of GDP	May Industrial Heat Demand
PT11	35.24%	367,57
PT15	5.57%	58,14
PT16	22.56%	235,34
PT17	28.67%	299,08
PT18	7.95%	82,89

Table A.10: Summary of the final data for industrial heat demand in Portugal

A.11.6. Residential Heat Demand in both Nations

Node	Ratio 1st hour	Annual Heat Demand (MWh)	Heat Demand 1st hour (MWh)
ES11	0.00030043	3022854.93	1026.20
ES12	0.00025014	1127311.89	318.65
ES13	0.00037624	659888.06	280.55
ES21	0.00051662	2489325.36	1453.22
ES22	0.00069529	755576.387	593.64
ES23	0.00064246	361924.989	262.75
ES24	0.00045179	1514860.81	773.37
ES30	0.00020343	7744205.65	1780.23
ES41	0.00046761	2668413.14	1409.99
ES42	0.00022155	2336804.75	1010.33
ES43	0.00038262	1179067.73	509.78
ES51	2.6546E-05	8925612.99	267.74
ES52	2.1186E-05	5897500.36	141.18
ES61	0	9623033.43	0.00
ES62	3.9563E-05	1746968.78	78.10
PT11	0.00033361	2234416.35	842.33
PT15	0.0001072	353406.51	42.81
PT16	0.00039283	1430590.16	635.03
PT17	0.00019041	1818075.13	391.19
PT18	0.00026775	503881.29	152.46

Table A.11: Summary of the process followed to obtain the residential heat demand for Spain and Portugal

B

Results

B.1. Base Case

B.1.1. Short Tem Storage State

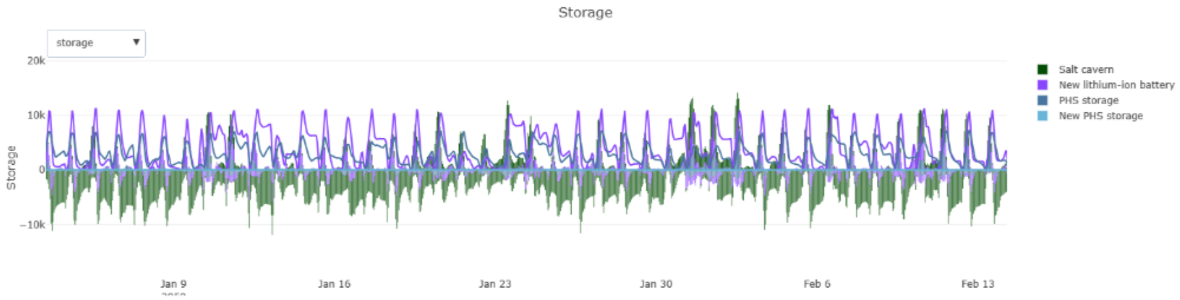


Figure B.1: Short Term Storage State of the system where the daily fluctuations on batteries are visible

B.1.2. 2022 Iberian Electricity Production and Heat Consumption Shares

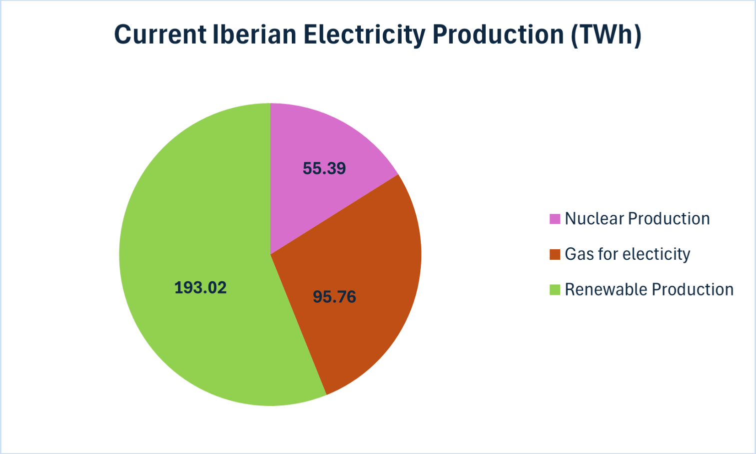


Figure B.2: Characterization of the Iberian electricity production in the year 2022

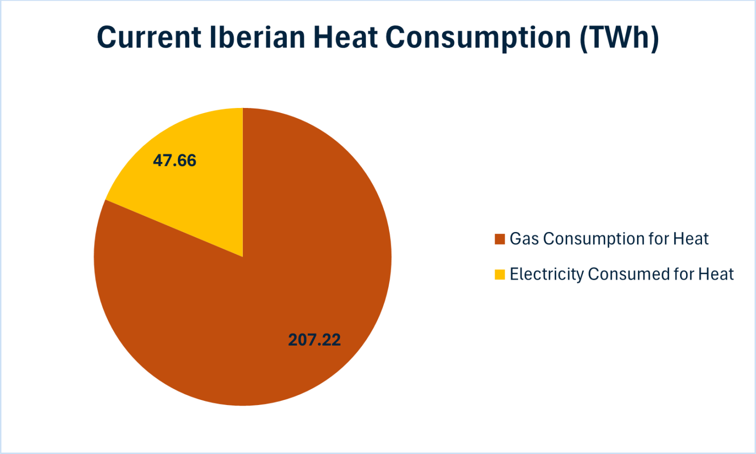


Figure B.3: Characterization of the Iberian heat consumption in the year 2022

B.1.3. Heat Mix

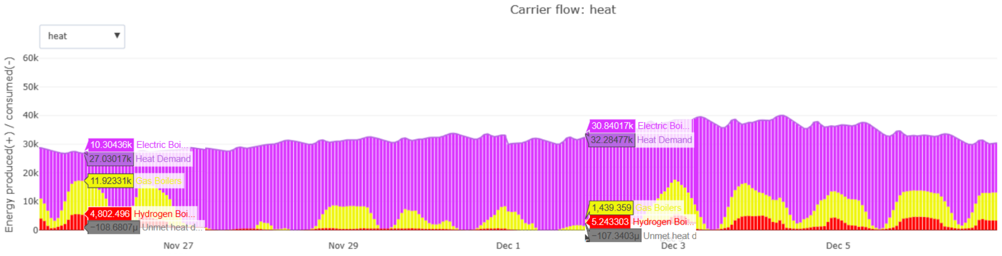


Figure B.4: Heat production and heat demand over the selected time in the BC scenario

B.1.4. Scenario 5 (PNIEC)

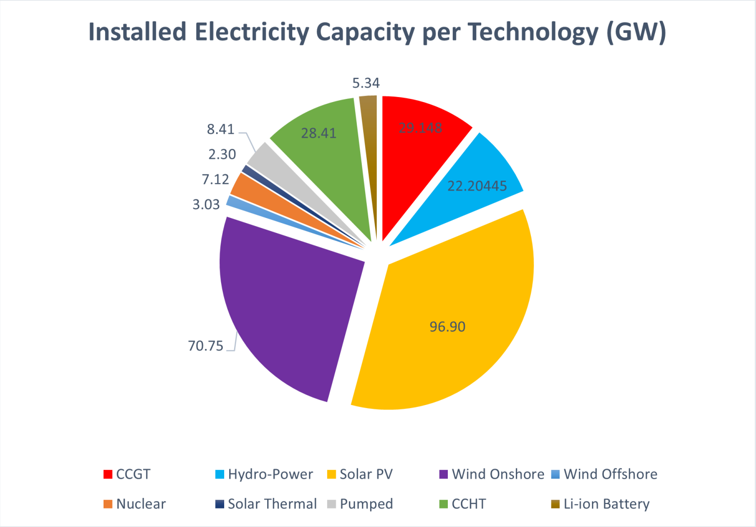


Figure B.5: Electricity Capacity Per Technology in the PNIEC Scenario

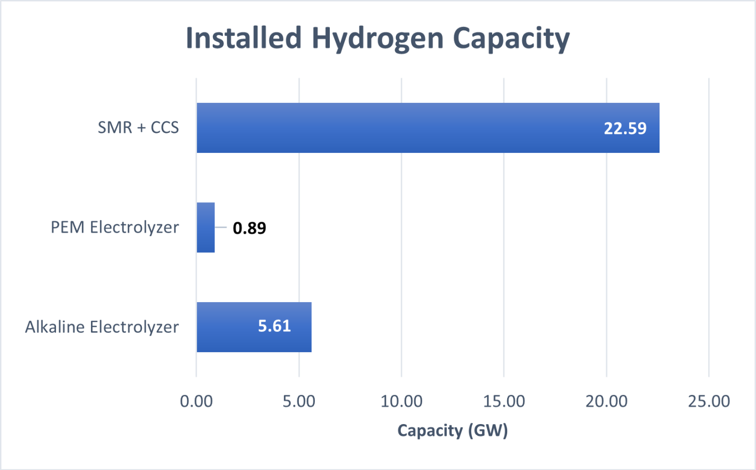


Figure B.6: Hydrogen Capacity Per Technology in the PNIEC Scenario

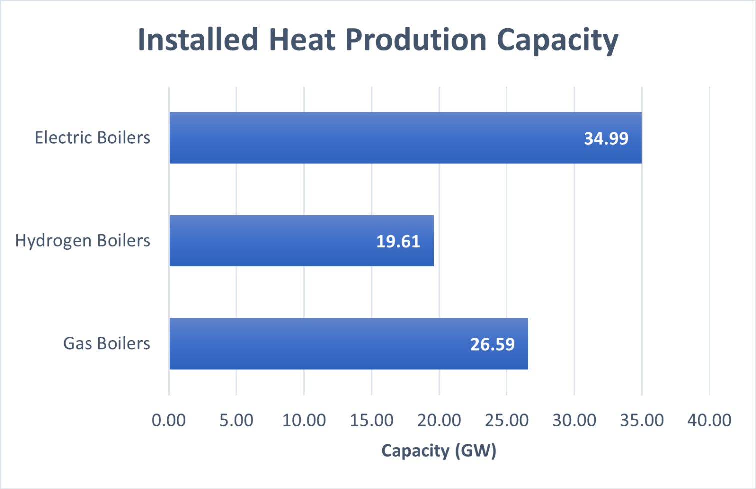


Figure B.7: Heat Capacity Per Technology in the PNIEC Scenario

C

Interviews

C.1. Questions Prepared for the Interviews

In the PNIEC, 4 GW of electrolyzers are originally estimated in Spain and 2 GW in Portugal. The adapted version mentions 11 GW only in Spain. Do you believe this is a realistic and achievable goal? How much do you estimate could be achieved by the year 2030?

In my model results, due to the interconnection created between the electric and thermal systems, there is a high electrification of the system accompanied by a significant expansion of renewables. Specifically, around 40 GW more than expected by 2030. Do you think the system could support this type of expansion by the year 2030? If not, will reliance on natural gas continue, or could hydrogen begin to replace it in the thermal sector?

Regarding the necessary infrastructure for hydrogen integration, do you think it would likely use existing gas pipelines, or will new conduits need to be built for hydrogen transportation?

The PNIEC indicates that 80-90 GW of renewables will be achieved by 2030. Is this objective realistic, given the current state of the system? What social and economic barriers do you think could limit this objective?

Do you think electrifying the thermal system could be realistic in terms of the necessary infrastructure transformation by 2030? If not, how long would it take to achieve the efficiency improvement mentioned in the PNIEC?

Do you believe oil companies will adapt to the change in the energy system? If not, will they delay the transition to renewable energy?

Do you think implementing offshore wind energy is realistic, given the installation and maintenance costs it entails, rather than continuing with onshore wind?

Do you think the electricity and gas market dynamics will change with new technologies? In terms of new institutions or actors participating in the system as agents.

What policies do you think maybe hindering or could hinder the energy transition and hydrogen integration into the system as one of the primary energy vectors?

In my model, I decided that the creation of new infrastructure requiring the use of fossil fuels could not be increased. Is this presumption realistic? Or do you expect the creation of more combined-cycle plants and gas boilers?