UNIVERSIDADE DE LISBOA

FACULDADE DE CIÊNCIAS

DEPARTAMENTO DE ENGENHARIA GEOGRÁFICA, GEOFÍSICA E ENERGIA

The Portuguese energy system in 2030

Rita Maria da Silva dos Santos Costa

Mestrado Integrado em Engenharia da Energia e do Ambiente

Dissertação orientada por Professor Doutor Miguel Centeno Brito e coorientada pelo Doutor Rui Nogueiro Gomes Morais Borges

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Resumo

Com o objetivo de mitigação das alterações climáticas, os países definiram metas para a diminuição das emissões de gases de efeitos de estuda (GEE). A aprovação do Acordo de Paris em 2015 definiu os objetivos necessários para a limitação do aumento da temperatura global abaixo dos 2 ºC e reunir esforços para que este aumento seja ainda inferior a 1.5 ºC.

Por esta razão, as nações signatárias elaboraram estratégias para redução de gases de efeito de estufa a médio e a longo prazo. Estes esforços para redução de emissões com fim à neutralidade carbórnica têm em perspetiva metas mais exequíveis a médio prazo, ou seja para 2030, e que nos levam a um fim estipulado para 2050.

Esta dissertação foca-se no estudo dos cenários a médio prazo de 2030, através da simulação dos sistemas de energia destes países com base nos dados estimados, que estão descritos nos documentos dos planos nacionais de energia e clima de Portugal e de Espanha. Utilizou-se uma ferramenta de modelação de sistemas de energia que nos permite simular os vários setores de um sistema de energia e interligações entre diversos modelos de sistemas.

O objetivo destes planos é a definição de metas atingíveis a médio prazo que contribuam para a diminuição das emissões dos gases de efeito de estufa (GEE) através de estratégias de descarbonização do setor da energia que passam essencialmente pelo aumento da produção de energia por fontes renováveis, e que vêm a substituir as tecnologias de geração de energia com origem em combustíveis fósseis. Essas mudanças, no entanto, devem garantir a robustez e a flexibilidade dos sistemas de energia, e devem ser um mix de tecnologias que muda progressivamente com a integração de energia renovável e o surgimento de novos vetores de energia, como o hidrogénio, considerados importantes por contribuírem para a descarbonização e diminuição da dependência energética do país.

Os resultados obtidos neste estudo evidenciam se as medidas contempladas nos planos de 2030 contribuem para atingir os ambiciosos objetivos definidos para 2050, quais são os maiores desafios para atingir estas metas, e o que poderá ter de ser diferente. A simulação dos sistemas de energia de Portugal e de Espanha tendo em conta as várias tecnologias de energia renovável, tecnologias de armazenamento, consideração de *phase-out* de centrais de produção utilizando recursos não renováveis, a introdução do hidrogénio e estratégias de otimização da rede, permitem uma visão geral e um pouco mais perto da realidade, de como os vários setores – como a produção de eletricidade, a cogeração, o setor industrial, os transportes, entre outros – se influenciam entre si e como por consequência, influenciam os sistemas exteriores.

Os sistemas de energia atuais, nomeadamente os sistemas de Portugal e de Espanha têm uma percentagem relevante de geração de energia renovável quando olhamos para o panorama europeu e mundial. No entanto, observa-se um aumento muito significativo na quantidade de energia renovável produzida a cada ano, prevendo-se penetrações de geração renovável variável muito perto dos 100%, com o objetivo de atingir esse valor absoluto num futuro que podemos considerar bastante próximo. Os sistemas de energia com estas percentagens de produção renovável, apresentam desafios muito diferentes dos sistemas atuais. Por esta razão, este estudo dá ênfase a alguns fatores que achamos relevantes nos sistemas de energia de Portugal e de Espanha neste novo paradigma energético.

O grande desafio passa pelo balanço de consumo e produção de energia, quando temos grandes percentagens de produção variável devido aos recursos renováveis como o solar e eólico, apresentarem um pequeno grau de previsibilidade de produção.

A complementaridade entre várias tecnologias de produção renovável que utilizam diferentes recursos renováveis, como o conhecido exemplo entre a complementaridade da produção solar com a produção eólica, contribuem para uma menor flutuação das curvas de produção de um sistema.

Uma estratégia que se tornará mais relevante no futuro será a própria complementaridade entre sistemas. Diferentes sistemas de energia apresentam diferentes curvas de consumo, tal como diferentes curvas de produção de energia. A diferente disponibilidade de recursos endógenos consequentemente resulta em diferentes perfis de produção. A linha de transmissão aqui ganha um papel na complementaridade entre sistemas de energia criando um balanço entre os sistemas por meio de exportações e importações, onde o consumo de um sistema é suprimido pelo excesso de produção renovável de outro sistema. Neste futuro, a gestão, aumento e até criação da capacidade da linha de transmissão que liga os vários sistemas energéticos da Europa ganha uma maior importância.

Neste trabalho também se estudou a influência do hidrogénio como vetor energético, de forma a perceber como influência os sistemas de energia, produzido através de eletrólise de água acoplado a centrais solares fotovoltaicos e eólicas. O efeito da introdução do hidrogénio nos sistemas faz-se sentir essencialmente no aumento da produção das centrais a gás natural pela realocação de energia solar e eólica para o efeito, e na redução da necessidade de bombagem de água por ser o hidrogénio um vetor energético que proporciona flexibilidade ao sistema.

De acordo com a capacidade instalada para 2030 segundo os respetivos planos para Portugal e Espanha, os modelos indicam maiores percentagens de renováveis na eletricidade e na energia primária superiores que nos dados estimados.

A conclusão central deste estudo está relacionada com o papel da capacidade da linha de transmissão entre Portugal e Espanha e entre Espanha e França, na prespetiva dos sistemas de energia de 2030. O aumento de produção renovável em ambos os sistemas resultam em maior potencial de exportação, e consequentemente, é necessário um aumento da capacidade da linha de transmissão para transportar todo o excesso de energia.

Os modelos criados neste trabalho indicam que a capacidade da linha de transmissão estimada segundo os planos para 2030 no sentido de Portugal para Espanha, está de acordo com os valores obtidos, mas que a capacidade no sentido de Espanha para os sistemas externos (França), está subestimada. O foco é então no reforço acima das expectativas da interligação entre Espanha e França, permitindo o fluxo de exportações em horas de produção solar, típicas do perfil de produção renovável da Península Ibérica.

No entanto, devido ao consumo e produção de Portugal e Espanha serem muito semelhantes por se encontrarem em locais geograficamente semelhantes, influenciados pelo mesmo ambiente e condições, estes sistemas apresentam muito pouca complementaridade. Os resultados obtidos remetem também à Peninsula Ibérica com um perfil de consumo e produção próprio relativamente aos sistemas externos (Europa), e à relevância do aumento da interligação no sentido da Europa (França).

Portanto, o valor do excedente de eletricidade do ponto de vista interno entre Portugal e Espanha tem pouco valor, mas numa perspetiva de complementaridade de regiões da Europa, vai de encontro à atual conjuntura em que o reforço de interligações é considerado crucial para manter a resiliência dos sistemas energéticos, tornando-os mais independentes de combustíveis fósseis por meio de trocas de energia renovável.

Neste trabalho não foram tidos em conta fatores económicos sendo que o foco foi uma análise técnica, mas não desprezando que a visão económica influência diretamente decisões de operação que não estão necessariamente ligadas à opção tecnicamente mais eficiente de produção de energia. Este facto determina diretamente as trocas de energia entre sistemas (importações e exportações) tal como o armazenamento. Por vezes as importações e exportações ocorrem devido a valores de custo de energia superiores ou inferiores aos custos de produção.

Palavras-chave: transição energética, sistemas de energias em 2030, interligação entre sistemas, sistema de energia da Peninsula Ibérica

Abstract

This dissertation focuses on the study of the national energy and climate plans for 2030 in Portugal and Spain, through a tool for modeling energy systems.

These plans define achievable medium-term goals that contribute to the reduction of greenhouse gas (GHG) emissions, through decarbonization strategies in the energy sector that essentially involve increasing energy production from renewable sources that come to replace energy generation technologies based on fossil fuels. The objective of this work is to simulate and analyse the operation of electricity systems of both countries based on the objectives defined in the mentioned plans.

The results obtained in this study show whether the measures of the 2030 plans contribute to achieving the ambitious goals defined for 2050, what are the biggest challenges to achieve these goals and which may have to be different.

The main conclusions drawn from this study focus on the importance of increasing the capacity of the transmission line in relation to what is estimated in the plans defined for 2030 mainly in Spain. The simulations indicate that for the characteristics of the systems according to estimates made for 2030, the capacity of the transmission line from Portugal to Spain is adequately dimensioned for the energy flows obtained, however, in the direction of Spain for the outside systems (France), it was concluded that the capacity of the line needs to be about double that estimated.

This study allowed an analysis not only of the systems in Portugal and Spain individually, but also from the prespective of Iberian Peninsula with a own consumption and production profile in relation to external systems (Europe), emphasizing the importance of increasing interconnection towards Europe (France).

Keywords: energy transition, energy systems in 2030, interconnection between systems, Iberian Peninsula energy system

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List of abbreviations and nomenclature

AEL – Alkaline Electrolyzer

CCS – Carbon Capture and Storage

CEEP – Critical Excess Electricity Production

CHP – Combined Heat and Power

CSHP – Combined Solar Heat and Power

CSP – Concentrated Solar Power

DGEG – Direção Geral de Energia e Geologia

DSM – Demand Side Management

EU – European Union

EEEP – Excess Exportable Electricity Production

FCEV – Fuel Cell Electric Vehicle

GHG – Greenhouse gases

IPMA – Instituto Português do Mar e da Atmosfera

MIBEL – Mercado Ibérico de Eletricidade

MIE – Mercado Interno de Energia

PEM – Polymer Electrolyte Membrane

PNEC 2030 – Plano Nacional de Energia e Clima 2030

PNIEC 2030 – Plan Nacional Integrado de Energía y Clima 2030

PP – Power Plant

PTG – Power To Gas

PV – Photovoltaic

REE – Red Eléctrica de España

REN – Rede Energética Nacional

RES – Renewable Energy Sources

RNC 2050 – Roteiro para a Neutralidade Carbónica 2050

SOEL – Solid Oxide Electrolyzer

TSO – Transmission System Operator

VRES – Variable Renewable Energy Sources

V2G – Vehicle to grid

1 | Introduction

1.1 Context

To address the challenges of climate change, countries have defined targets to decrease greenhouse gas (GHG) emissions. The approval of the Paris Agreement in 2015 defined three major goals to limit the increase of the global temperature below 2 ºC (above pre-industrial levels) and pursue efforts to maybe get this temperature increase even below the 1.5 ºC[1].

For this purpose, Portugal and Spain, as well as the other signatory nations, prepared middle and long-term GHG reduction strategies. Portugal developed the Roadmap for carbon neutrality in 2050: a long-term strategy for carbon neutrality in the Portuguese economy in 2050 (RNC 2050)[1]. This effort to lower GHG emissions requires a definition of goals more feasible on a middle-term scale for 2030. Consequently, based on the goals established in the RNC 2050, the National Energy and Climate Plan 2030 (PNEC 2030)[2] appears in Portugal as a tool for climate policy and energy strategy for the decade between 2021 and 2030 toward 2050 objectives[2]. Similar documents were developed for Spain, such as the Long-term decarbonization strategy 2050: a long-term strategy for a modern, competitive and climate-neutral Spanish economy in 2050[3]and the middle-term plan for 2030, analogous to the PNEC 2030, the National Integrated Energy and Climate Plan 2021-2030 (PNIEC 2030)[4].

These plans and agreements are all based on the decarbonization of the power sector, and the consequent increase of renewable energy in the energy systems, since a large share of emissions (approximately 27%)[5] is due to the electricity generation from the combustion of fossil fuels. The objectives set in PNEC 2030 and PNIEC 2030 require the incorporation of more renewable energy sources, an increase of energy efficiency and the promotion of interconnections (c.f. Table 1.1).

Table 1.1 – Main goals to be achieved by Portugal and Spain by 2030.

	Emissions	Energy Efficiency	Renewables in final energy use	Renewables in electricity generation	Electrical interconnections
PNEC 2030[i]	-45% to -55%[ii]	35%	47%	80%	15%
PNIEC 2030[iii]	-23%[iv]	39,5%	42%	74%	15%

To adequately contribute to the objectives of the Paris Agreement, the European Union (EU) must achieve carbon neutrality (net emissions equal to zero) by 2050. Achieving carbon neutrality implies the total decarbonization of the energy system and urban mobility in parallel with different management of resources and land use. [2] Table 1.2 presents the main objectives defined by Portugal and Spain in their respective long-term strategies. At this stage, the countries included in the Paris agreement have the electrification sector entirely with production from renewable sources and predict a 90% reduction in emissions. Although certain objectives must be met, Portugal and Spain have energy systems with different production and consumption

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[i] Governo Português. “Plano Nacional de Energia e Clima 2021-2030 (PNEC 2030)”, 2019.
[ii] Reduction in emissions when compared to 2005. [2]
[iii] Instituto para la Diversificación y Ahorro de la Energía, “Plan Nacional Integrado de Energía y Clima 2021-2030”, 2020.
[iv] Reduction in emissions when compared to 1990. [4]

characteristics (namely the fact that the Spanish system is larger), and therefore the prospect of renewables in the final energy use is higher in Portugal which also foresees a lower energy dependence than Spain[1,3].

Table 1.2 – Main targets to be achieved by Portugal and Spain by 2050.

	Emissions	Renewables in final energy use	Renewables in electricity generation	Energy dependence
RNC 2050[v]	-90%[vi]	86% to 88%	100%	13%
Spain Strategy for decarbonization 2050[vii]	-90%[viii]	97%	100%	< 20%

The main drive in these plans is the continuous reduction of carbon emissions for electricity production and the replacement of fossil fuels with electricity in the other sectors of the economy, or, in other words, the electrification of the economy.

Energy production will be based on endogenous renewable energy sources, and that will be achieved with significant investments in the renewable capacity, in particular, wind energy and solar PVs (which has vast growth potential in both countries) with a major reduction, or even the elimination, of energy produced by fossil fuels, including coal, fuel oil and natural gas[1].

These changes, however, must guarantee the robustness[ix] and flexibility[x] of the power system and must be a mix of technologies that changes progressively with the integration of renewable energy and the emergence of new energy vectors, such as hydrogen, which is seen as giving an important contribution for decarbonization and decrease of the country's energy dependence [6,7].Hydrogen may prove to be decisive to reach this energy transition, as it promotes the flexibility of the system by being a form of (renewable) energy storage, facilitating the integration of an enlarged renewable capacity in the energy system[8].

Furthermore, the industrial sector is one of the most responsible for consumption and emissions in an energy system, which means that it is necessary to decarbonize this sector while managing to meet its thermal needs, such as high-temperature processes [9,10]. Green hydrogen could be the main energy vectors to be implemented in industrial processes. [3] The transformation of the industry will be a decisive factor in achieving the decarbonization targets and therefore, in this work, special importance is given to the role of hydrogen in the future of power systems.

Green hydrogen is obtained by electrolysis using renewable electricity as the energy source. According to RNC 2050, 5% to 8% of the electricity will be used to produce hydrogen in Portugal. This vector is gradually gaining expression in Portugal and is expected to achieve 4% in the final energy consumption by 2050[1].

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[v] Governo Português. "Roteiro para a neutralidade carbónica em 2050 (RNC 2050): Estratégia de longo prazo para a neutralidade carbónica da economia portuguesa em 2050", 2019.

[vi] Reduction in emissions when compared to 2005[1].

[vii] Ministerio para la Transición Ecológica y el Reto Demográfico, "Estrategia de descarbonización a largo plazo 2050: Estratégia a largo plazo para una economia española, moderna, competitiva y climaticamente neutra em 2050", 2020.

[viii] Reduction in emissions when compared to 1990[3].

[ix] Robustness of the power system is the ability of the system to resist to disturbances maintaining the reliability of operation[6].

[x] Flexibitly of the power system is the capability of the system to change demand and supply in order to create a balance between the at all times. Variable renewable energy can increase the need of flexible load because their energy production change in a inpredictable way[7].

In support of the plans for 2050, both Portugal and Spain have developed strategies related to the production of hydrogen as it is considered a pillar to sustain the energy transition. Portugal has developed the National Hydrogen Strategy (EN-H2) which has a medium and long-term vision of the projects that will be promoted for the introduction of hydrogen in the energy system. [11]

In summary, EN-H2 defines that the hydrogen that will be produced is intended for consumption in the Portuguese system itself, but also export. It is also expected that in 2030 the introduction of hydrogen will promote its injection into the natural gas network, reducing natural gas imports. [11]

In Spain, hydrogen is also one of the *magnitudes* of the strategy for the total decarbonization of the energy system by 2050, as one of the necessary developments in the industrial sector such as developments in storage technologies, energy efficiency measures, renewable fuel, and digital transformation. [3] The document similar to the EN-H2 but applied to the Spanish energy system is the *Hoja de Ruta del Hidrogéno: Una apuesta por el hidrogeno renovable* (The Hydrogen Roadmap: A commitment to renewable hydrogen) which also defines medium and long-term objectives for the decarbonization of the industrial sector as already mentioned, of the mobility, electricity and storage.[12]

The main objectives defined by these hydrogen implementation strategies for the time horizon of 2030 in Portugal and Spain are illustrated in Table 1.3 to allow us to understand the dimension of the projects and the influence that this energy vector will have on these systems.

Table 1.3 – Main objectives of hydrogen strategies complementary to the 2030 plans for Portugal and Spain.

	In final energy use	In the consumption of road transport	In the consumption of the industry sector	Installed capacity in electrolysers
Portugal[xi]	5%	5%	5%	2 GW
Spain[xii]	NA[xiii]	150-200 buses + 5000-7500 vehicles FCEV[xiv]	25%	4 GW

The Portuguese and the Spanish power systems are electrically, economically and legally integrated under the Iberian Electricity Market (MIBEL) [13]. The MIBEL, launched in 2007 with the expectation that the harmonization of requirements between the two electricity systems would bring improvements to the consumers [14], resulted in the establishment of an Iberian electricity market and consequently in a contribution to the European Internal Energy Market (MIE).

Thus, to study the energy transition in Portugal, or Spain, ought to take into consideration the integrated Iberian power system. The Iberian power system is also connected to North Africa (interconnection between Spain and Morocco), and the rest of Europe (interconnection between Spain and France). The European power system is a set of interconnections between systems in central Europe, the Scandinavian countries, Eastern Europe, and the British Isles. The interconnection between power systems is becoming even more important nowadays because of

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[xi] República Portuguesa, "EN-H2 Estratégia Nacional para o Hidrogénio", May. 2020.

[xii] Ministerio para la Transición Ecológica y el Reto Demográfico, "Hoja de Ruta del Hidrogéno: Una apuesta por el hidrogéno renovable", Oct. 2020.

[xiii] The Spanish Hydrogen Roadmap does not provide any value on hydrogen in final energy use.[12]

[xiv] On the Spanish Hydrogen Roadmap, a percentage of hydrogen in road consumption is not provided, but it is said that a fleet of at least 150-200 autobuses at FCEV and at least 5000-7500 light and heavy goods vehicles at FCEV are expected for 2030.

the increase in electricity dependency and the constant growth of demand, increasing the security of supply. [15]

1.2 Motivation and Objectives

This work will focus only on the electricity part of the energy systems and, because of that and aligned with the strategies of the decarbonization plans, it will consider the increase in capacity of renewable energy in the systems, new technologies associated with this transition, energy efficiency optimization measures, and increase in interconnections.

The increase of renewable capacity in the electricity mix reduces energy dependency but also introduces variability in power generation: wind energy and solar PV will constitute most of the renewable installed capacity by 2030, in both Portugal and Spain [16], and these resources have hourly, daily, and even seasonal variations that translate into variations in power generation. In consequence, the problems associated with the variability of these sources will be felt on both sides of the border.

Therefore, the main objective of this work is to understand the impact of the future Iberian energy system on the Portuguese energy system considering the following:

i) Regional-scale modelling of the integrated Portuguese and Spanish electricity systems, considering the interconnection Portugal-Spain in the future. Both countries will face the same challenges concerning variable renewable generation but, due to the different time zones, there may be a better match between generation and consumption.

ii) Evaluation of the interconnection capacity needs between Iberia and the rest of Europe, as imports/exports of energy across the Pyrenees as a possible way to minimize fluctuations due to variable generation.

iii) The addition of new technologies such as hydrogen seems to be a promising energy vector in terms of non-dispatchable renewable energy storage.

Models of the Portuguese and Spanish electricity systems in 2030 are developed using EnergyPLAN to simulate these systems working in isolation and combination, taking into account the plans defined by both countries for 2030. As the main objective is to understand how the Iberia will work as a whole and how Portugal and Spain will influence each other, the MultiNode add-on tool of EnergyPLAN was used to calculate the balances and exchanges of electricity between the two systems.

The interest in this study on the interconnection of the two systems reinforces the benefits of increased interconnection between energy systems. The import of energy from systems with excess clean production and at lower costs, and the creation of reserve sharing that allows the systems to be supported in an emergency, are examples of these known benefits. In this study we will explore another potential benefit, linked to the exchange of renewable energy between the two systems where there is excess of this generation at certain times, avoiding the curtailment of renewable resources through the complementarity of consumption and generation of the interconnected systems. [17]

The EU strategy to reduce emissions is to reduce the effect of variability of renewable sources to operate flexible de-centralized power systems. The main principle is that renewable energy should be all utilized when it is available thus being a priority to dispatch this type of energy within the interconnection. This applies to wind and PV generation in times that major generation occurs in low load demand.

From this EU perspective, there is a need to identify the importance of reinforcement or improvement of cross-border interconnections allied with energy storage technologies, for the EU members to share an excess of renewable generation to match the needs of other member's power systems. And so, it presents three recommendations for the reliability of these long-term plans, which are the implementation of flexibility mechanisms associated with the increase of renewable generation, as DSM, storage and hydrogen strategy, the need for future reinforcement of interconnection capacity, and energy efficiency measures in heating and cooling sectors and the transport sector.

The expansion of interconnection capacity in Europe is targeted to be 10% of generation capacity rising to 15% by 2030. This should lead to the ability to have a higher share of renewable generation in the systems, however, adverse weather could affect wide areas and can influence the availability of generation for neighbouring countries. [17]

1.3 Dissertation Structure

This dissertation is structured into 5 chapters.

Chapter 1 explains the context in which this work fits, with a focus on the Portuguese and Spanish decarbonization strategies for 2030 and 2050, as well as the motivation behind this study.

Chapter 2 explores recent works considered most relevant in this study, carried out in the field of energy systems simulation on the horizon between 2030 and 2050.

Chapter 3 explains why EnergyPLAN is used and how it works. The methods are explained and justified. The calibration models of the Portuguese and Spanish systems are first defined using known data, to proceed to the simulation of the 2030 base models of both systems as defined by the national plans.

Chapter 4 defines the base models for 2030 and studies the effect of the variation in the interconnection between these two systems, the installed capacities and the impact of the time difference between the two countries in the individual systems and the perspective of a combined system (Iberia).

Chapter 5 presents the conclusions of this study, comparing with what would be expected and what is new. The limitations of the study are discussed, identifying correlations through the study, and points that might be interesting to study further.

2 | State of the art

Due to the urgency in the decarbonization of the power sector to reduce GHG, numerous studies have appeared for different countries and regions around the world assessing the evolution of power systems into the future. These studies model energy systems considering different strategies that can be considered, regarding emergent technologies that could be used and export/import of energy to achieve the best possible match between generation and demand in a future when there will be an increase in variability in the power grid associated to the increase of renewable energy sources (RES) for energy generation.

This chapter presents a literature review about the integration of large amounts of renewable sources in power systems and the consequent challenges to achieving systems with 100% renewable generation, with a focus on studies that allow us to understand how interconnections between systems can minimize the effects of large penetrations of this type of non-dispatchable energy. The research was also carried out on existing work on the integration of hydrogen in systems with high renewable penetration.

2.1 Integration of renewable energy in power systems

Across Europe, conventional fossil fuel power plants are being replaced by power plants based on endogenous resources and renewable energies, although it is not always clear how to reach stability in the power systems with a large fraction of non-dispatchable generation.

With the non-dispatchable renewable “input” generation, such as solar or wind energy, the power system has to deal with the risk of fast generation ramps, so it has to have the flexibility to deal with variable generation, or it cannot guarantee the security of supply. Dispatchable natural gas power plants are the conventional approach to overcome this variability, providing flexibility with lower CO_2 emissions than coal-fired power plants. [18]

At load peak hours renewable generation may not be able to satisfy demand. The increase of transmission between power systems will become very important in the future for the integration of the varying renewable energies and secure the stability of the operation of the system [12] but it also increases the dependency between adjacent systems [19].

In 2013, Spiecke and Weber [18] have made scenarios until 2050, concluding that the integration of large amounts of non-dispatchable renewables requires large cross-country exchanges of power and flexible capacity. They argued that to guarantee the security of supply, good interconnection management is essential for the drastic reduction of production from natural gas plants that are now used as a backup. They also point out that, there will not only be an increase in the transmission capacity but also a change of directions of the power flow in many different geographies. [18]

This leads us to another important conclusion, which is also mentioned in more recent studies and has to do with the fact that countries with warmer climates, such as Portugal and Spain, are expected to be less affected by variability and uncertainty due to *better* weather conditions (especially for solar generation). Especially in the summer, the Iberia is expected to export energy to France because of the impact of the seasonal increase in RES (namely solar) generation. [18]

Large penetration of variable renewable energy sources can be balanced by dispatchable renewable generation such as hydropower, geothermal, biomass and concentrating solar thermal power (CSP) which can provide baseload capacity throughout the year, complemented by storage technologies. [19] The main challenge is a technical limitation: these power plants may not ramp quickly enough to keep the balance between supply and demand. Other limitations are related to weather variability, both in the short and long term; some years can be more sunny or windy than others, which means that wind energy generation or solar PV generation is uncertain even on an annual basis. Hence, it is important to study the reliability of a 100% RES power system both in the short and the long term. [19]

Zappa et al.[19] modelled several scenarios for the European power system in 2050 to answer the main question: “Could a future 100% RES European power system be supplied using European resources alone and have the same level of system adequacy as today’s power system?”. It considered the impact of uncertainties in future demand profiles and the types of technology that would be available and defined adequacy “as the ability of the power system to supply the required power and energy requirements subject to outages and operations constraints” which means that the definition of system security is the adequacy of the power system in terms of how the power system deals with sudden disturbances. [19]

Various simulations of the European system 100% based on renewable energy sources were made assuming possible future demand and RES generation including wind (onshore and offshore), PV (utility and rooftop), bioelectricity, CSP, geothermal and hydropower. These scenarios were compared with non-RES power systems including natural gas and coal generation technologies (with or without CCS[xv]), and nuclear and bioenergy with CCS. [19] Results show that we are moving towards a reality where utility PV represents the largest share of installed capacity in all scenarios although, it’s considered that this generation makes no difference in the amount of energy which can be guaranteed to be available at a given time. Another important share in production is biomass; as dispatchable capacity, it has an important role in providing for the peak and baseload in these scenarios. This type of energy production is here considered as particularly relevant in central and northern European countries, and less representative in Portugal and Spain.

Onshore wind is mainly installed in the British Isles and Baltic countries because of the favourable wind speeds, although it is also installed in central locations in Europe to minimize transmission losses. Offshore wind is mainly installed in the North and Baltic Seas. Although the potential for PV production in countries in southern Europe as consequence of the levels of solar irradiation in these areas, the study shows a greater share of utility PV in the mix of countries in northern and eastern Europe, compared to Portugal and Spain.

A particularity of this study is the amount of CSP predicted for the countries of southern Europe, being considered the largest share in the renewable mix of these systems. It concludes that a 100% renewable European power system could operate with the same level of system adequacy as the current power system, even when relying only on domestic European sources in the most

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[xv] Carbon Capture and Storage

challenging weather year. However, this reality is only possible if we take into account several assumptions, such as:

i) The expansion of generation and transmission capacity, making Europe more dependent on interconnections.
ii) The management of the integration of heat pumps and electric vehicles into the power system, as well as technologies for demand-side management (DSM) to reduce the demand in peak hours.
iii) The implementation of energy efficiency measures to prevent the uncontrolled increase of electricity demand and
iv) promote the deployment rate and management of generation and transmission capacity through the path to 2050.
v) Increase of RES generation, in particular PV, biomass, and biogas. [19]

G. Pleßmann and P. Blechinger [20] argue that to achieve the transition to carbon neutrality, coal-fired power generation is phased out after 2035. Nuclear power plants would be phased out in 2040 assuming that new capacities of these types of technologies will not be allowed, and existing ones are going to be discontinued according to their expected lifetime. The decline in these dispatchable capacities is going to be compensated in a short term by gas-fired power plant generation and, gradually, with RES technologies. Also, energy storage technologies like batteries and pumped hydro storage will contribute to the flexibility required to accommodate non-dispatchable generation. As in previous studies, they also expect an increase in energy exchange and consequently in transmission line capacity. This study quantifies the increase in electricity exchanges in the EU from 188.4 TWh in 2016 (reference year used) to 976.7 TWh in 2050, and a consequent increase in transmission line capacity in the same time interval of 79.5 GW to 362 GW. [20]

In 2018 P. Capros et al. [21], in a 2030 perspective aiming for 2050, also concludes that solar and wind generation show significant growth. Heating and cooling through heat pumps and heat production based in RES are also expected to increase significantly, although at a slower rate of deployment. The scenarios achieve a RES share of 28% in 2030 on final energy consumption.

The fuel mix shows a decrease in both coal and oil, but also in natural gas (in the longer term) in favour of electricity with renewable sources. This increase is mainly due to the electrification of the transport sector and the increased use of heat pumps. The (small) remaining oil is consumed by the transport sector that cannot be electrified (e.g. aviation), but the remaining share of natural gas is mainly consumed by the industrial sector in the cases that electrification is difficult or even not feasible in certain industrial processes. It was assumed that by 2030 there will be a "renovation" of equipment and technologies in the domestic sector, which work as energy efficiency measures that allow the reduction of energy consumption and reach the goal of 80% reduction of GHG emissions in the EU. On the other hand, the electrification of heating in the domestic sector and the EV's [xvi] in the transport sector, increases the consumption of electricity. In all scenarios, it is considered that electricity consumption increases in the projection of the years studied. [21]

Still in this study, as expected, the most relevant development in the future of the European energy system is the increase of RES penetration on the power system, doubling the installed capacity in 2030 (compared with 2015), and increasing 4 times by 2050. The share of RES generation reaches

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[xvi] Electric Vehicle

almost 50% after 2030 and exceeds 65% in 2050. Wind offshore has a huge development after 2030 while hydropower share keeps current levels. To reach that, natural gas power plants will work as essential providers of flexibility and reserve, and in a long term are going to be progressively exchanged by storage systems that also provide the flexibility of the power system. So, gas-fired technologies represent approximately 50% of installed capacity, up from approximately 35% in 2010, while representing only between 12% and 13% of total power generation. As for nuclear energy, the same view is shared as in the study mentioned earlier.

There is a huge decline of coal fuel power plants in the scenarios in this study, and limited growth in biomass generation after 2020 due to the costs and slow technical progress. [21]

Green hydrogen, using (excess) electricity from renewable sources to generate hydrogen by electrolysis, is one of the possibilities for the decarbonization of many sectors. [21] Elberry et al. [22] studied hydrogen seasonal storage for the integration of wind energy in the Finnish electricity sector system. Finland has much higher consumption in winter than in summer. In the summer, excess wind energy is of little value (often curtailed) because neighbouring countries also have excess wind energy generation.The study concluded that the addition of hydrogen as a seasonal storage technology significantly reduces CO_2 emissions and increases electricity production while decreasing generation from non-renewable technologies. [22]

For industrial purposes, hydrogen can be used directly or be synthesized into methane or liquid hydrocarbon and substitute fossil fuels where the industry sector cannot be electrified. An important point of debate about hydrogen conversion is the energy losses and costs. In the "storage sector", hydrogen is considered competitive compared with other storage technologies but also with DSM[xvii] to reach cost-effective flexibility in the energy system. [23]

A scenario analysis done by B. Lux and B. Pluger [24] shows that the production of large amounts of hydrogen requires an expansion of renewable electricity generation and has positive effects in a flexible operation due to electrolysers and storage units with the integration of VRES into the power system. Another conclusion of this study is that for a certain sale price of hydrogen, the curtailment of renewable electricity is reduced, although, for values above this optimal price, the opposite occurs, despite the increase of renewable installed capacities. So, the main conclusion is that for certain hydrogen sales prices, hydrogen is a great option to increase flexibility in systems with a high share of VRES in the generation, and while the production of hydrogen increases (such in residential, transport or industry sector) the need for hydro storage power plant and for transmission grid interconnection to deal with the integrate fluctuations of VRES, decreases. [24]

The potential for hydrogen production varies between regions. The hydrogen potential is linked to the RES potential, so in Portugal and Spain, the origin of additional electricity generation for hydrogen production is more evenly distributed between wind and solar power. [24]

[xvii] Demand Side Management: It is the alteration of consumption patterns through strategies to change consumer behavior through financial or other incentives. The main objective of DSM is to reduce consumption during peak hours and offset this consumption during off-peak, avoiding overloading the grid. This issue has gained special importance with the increase of renewable production, due to the balance between consumption and this variable (non-dispatchable) generation[23].

2.2 Portuguese power system

In this section, the studies that were considered the most relevant focusing on the Portuguese power system are presented.

In 2014, Fernandes and Ferreira [25] explored the seasonal variability of renewable generation in Portugal showing that full decarbonization of the national power system could be achieved with large installed capacities of renewables, leading to high curtailment of solar energy in the summer and wind energy in winter. Storage technologies, the complementarity between sources and the interconnection capacity were recognized as essential for 100% RES systems.

Graça Gomes et al. [26] modelled the Portuguese energy system for 2040 considering the difference in renewable generation in wet and dry years. Results highlight the need for increased hydro pumping storage capacity. The idea taken from this study is that there is an increase in hydropower production in the winter months of the wet year, which reduces the need for imports in the first months of the year. One limitation of this study is that does not consider the impact of electrification of road transport on the future electricity demand.

A techno-economic optimization done by Doepfert and Castro [27] shows that Portugal has the potential to supply enough energy for both wet and dry years with the technology mix expected for 2050. According to this study, the role of hydropower will decrease and dammed hydro with hydrogen and gas production will serve as storage and will increase de flexibility of the system with DSM and smart charging systems.

Figueiredo et al[28] explore the impact the climate variability on future power systems using Portugal as case study. Climate does not significantly impact the total energy demand, but renewable generation depends strongly on climate, so the trade of energy in interconnections depends on climate too. They conclude that the low demand scenarios modelled are associated with large exports, and on the contrary, high demands require a strong dependence on imports and that the power system is very sensitive to the level of demand as well as to the climate variability, so the interconnections, energy storage and other mechanisms to create a more flexible power system are critical to cope with future climate variability.

F. Amorim et al. [29] analyse the decarbonization pathways to 2050 with a focus on the power sector considering hourly dynamics of supply and demand and the connection between adjacent systems. This model considered projections up to 2050 in the scenarios in which Portugal is an isolated system, and the other has an interconnection with Spain (which is five times larger than Portugal).

This study was conducted in 2014 but it’s a relevant reference for this work since it models the Portuguese power sector interconnected with Spain, that have assisted the transition from fossil fuel generation to other lower emissions technologies such as endogenous VRES and natural gas as well as investments in the grid to expand the transmission line capacity.

For Portugal as a closed system, more installed capacity is required, especially in natural gas between 2030 and 2050, although, the need for natural gas, in the open system case, tends to disappear. The close system also leads to the higher installed capacity of coal. The results also show that a higher installed capacity of PV is required for the closed system. On the other hand, the open system model indicates higher offshore wind energy needs by 2050. This is explained by the possibility of exporting electricity generated by endogenous renewable sources to support the decarbonization of Spain. Figure 2.1 shows the results for the evolution of the Portuguese generation from 2005 to 2050 for the close system, and Figure 2.2 shows the same evolution for the open system, when the study considers the interconnections.

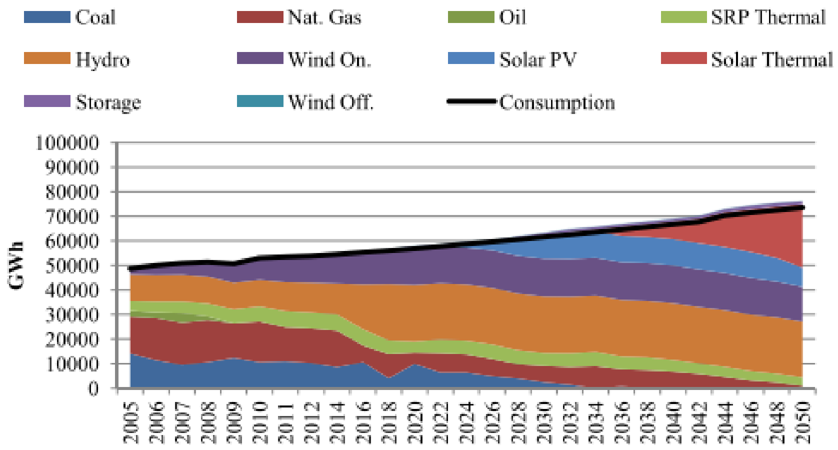


Figure 2.1 – Representation of the Portuguese evolution in electricity generation from 2005 to 2050 for the closed system. Source: F. Amorim et al.[29]

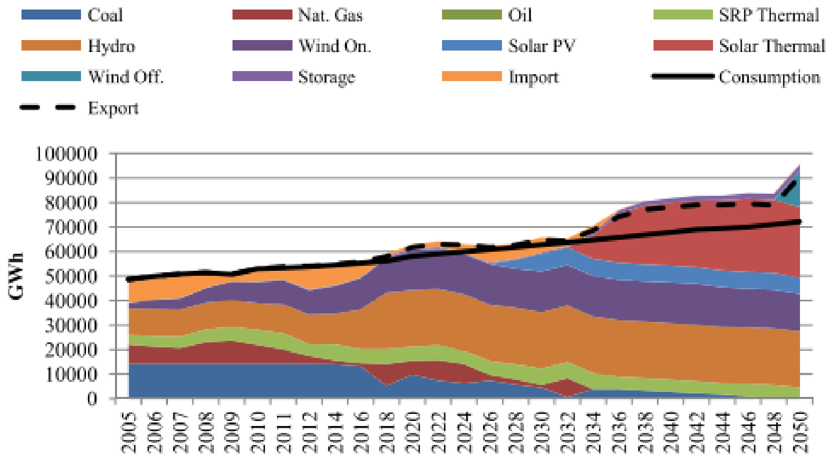


Figure 2.2 – Representation of the Portuguese evolution in electricity generation from 2005 to 2050 for the open system. Source: F. Amorim et al.[29]

In the long-term, there is more electricity generation in Portugal's open system due to the possibility of exporting electricity. According to this study, between 2018 and 2030, the generation is still significantly supported by coal and natural gas in both scenarios, and beyond 2030 the conventional power plants are gradually eliminated (we now know that the total phase-out of coal in Portugal happened during 2021). From 2032 on, the results show that Portugal becomes an exporter of electricity, which is also verified in the balances between 2018 and 2022. This occurs because of the increased production of hydropower, wind onshore and natural gas. Then, in 2040, Portugal begins to export mainly RES like hydropower, solar, and wind (onshore and offshore). Between 2024 and 2034 Portugal as an integrated system has a positive import balance and starts to be an exporter by 2034 to Spain, which leads to new investments in RES technologies (Figure 2.3).

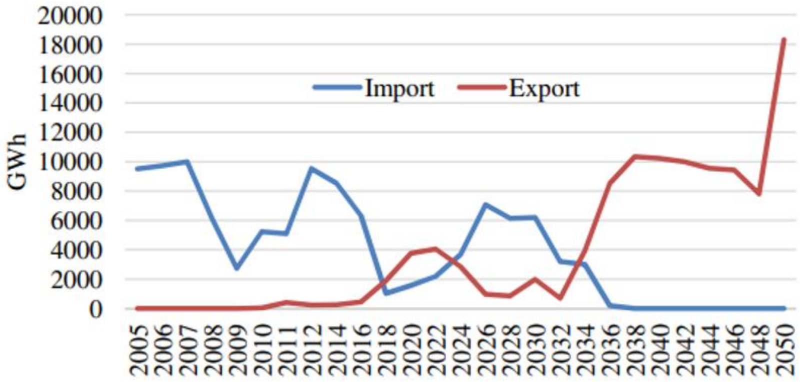


Figure 2.3 – Representation of the Portuguese annual average of imports and exports from 2005 to 2050. Source: F. Amorim et al.[29]

Regarding the need for interconnections within Iberia, it is interesting to note that an increase in interconnection capacity between Portugal and Spain is only required beyond 2050.

It is important to note that, like the study we are conducting, this reference study takes into account the fact that Portugal and Spain have different daily habits and are one hour apart in time-zone, which means that these two systems have different consumption profiles.

2.3 Spanish power system

Modelling of high penetration of renewables in Spain has also been the objective of an extensive list of references. Abadie and Chamorro [30] studied the security of electricity supply with high renewable generation. Results show that the risk of short supply is higher for higher demand scenarios with more renewable capacity installed. The modelled increase of renewable capacity is unable to compensate for the coal-fired and nuclear power plants phase-out, between 2030 and 2040.

From a storage capacity point of view, M. Bailera and P. Lisbona [31] forecasted the electricity excess and potential of power-to-gas in 2050 with high renewable generation. The most relevant outcome in this work was that for the scenarios modelled here, the authors conclude that nuclear power must be operating beyond 2050 because it is not possible to replace that base load by VRES.

For the horizon of 2030 (based on PNIEC) and focusing on the hydrogen as a system of energy storage, J.J. Brey [32] shows that the correct management of the energy network in which the VRES generation exceeds 50% is technically possible. The hydrogen is used as a storage system converting the excess of renewable electricity in hydrogen, allied to the natural gas network, in a seasonal basis. An important point of this study is that if Spain is going to become 100% renewable in power generation, the natural gas network will be discontinued and it is necessary to increase the hydrogen storage to meet the lack of natural gas, but also in transport and distribution system, and complementing the use of batteries to decrease the need of importation.

L.M. Abadie et al. [33] affirm that the risk of shortage of supply can be alleviated using hydropower as a complement of non-dispatchable renewable generation, and with pumping capacity. The results show that hydropower contributes to the system flexibility but by itself may not guarantee the security of supply during peak hours of consumption. When we consider that generation profiles of non-dispatchable renewable production are usually above the consumption in peak hours, there is less shortage of supply, but this still means that there should be an improvement of hydropower production or higher storage capacity (pumping, hydrogen storage or batteries).

All the studies mentioned above talk about important aspects to be considered in the modeling of power systems in this work, however, there are some ideas in which special emphasis is given since in this study, we are studying the effects of the interconnection between Portugal and Spain of in order to understand what role the Iberia will play in the future.

Firstly, it is important to mention what both S. Spiecke and C. Weber and G. Pleßmann and P. Blechinger say about the relevance of natural gas plants, and their role in the recent past and what will be in the medium-term future. This work will aim to predict the power systems for 2030, so we are not talking about 100% renewable systems, but with a perspective on the way to achieve it in 2050. Therefore, an important idea is that natural gas power plants will support the phase-out of other technologies (such as coal plants and later nuclear plants) because they have lower emissions, and because they provide security of supply when renewables produce below the consumption profile. The conclusions of P. Capros et al. on the future of natural gas go in the same direction, but also states that most of the natural gas that will be consumed in the long term will be in the industrial sector, in cases where electrification of processes is not possible.

Another important idea that was taken from S. Spiecke and C. Weber, is that in a future where there will be a large percentage of non-dispatchable renewables in the system, the transmission line gains relevance and will have to be increased in order to have greater power exchanges. Different countries have different consumption habits, and depending on the region, they also have different climatic characteristics. If we think of the example in Europe as a whole, a different regional distribution of renewable resources creates different profiles of renewable production, and therefore the sharing of border transmission lines can create an ease in the balance between production and consumption, giving flexibility to the interconnected systems.

This study also supports that Portugal and Spain are countries that, due to their climates, will be less affected by the variability of renewable generation, especially due to their solar and wind resources, and therefore it is expected that in the summer, the Iberia will export to France due to the high renewable production from these resources. The study that will be carried out here will basically confirm these statements for the 2030 perspective, taking into account the data we have from the plans defined for Portugal and Spain.

The study carried out by W. Zappa et al. helps to reinforce the idea that 100% renewable Europe will require the creation of more interconnections and the increase of existing ones due to the complementarity of the production profiles of different regions of Europe, and also says the European system in the future will be able to operate at the same level of adequacy than the current one.

P. Capros et al. makes some predictions, the most relevant are the large decrease in fossil fuels (including natural gas), a large increase in the installed capacity of offshore wind, however, almost no growth in the installed capacity of hydropower is expected, keeping capacity and production at the current level. This study includes hydrogen production technologies and states that hydrogen contributes to the flexibility of systems helping with the problems related to the variability of production of renewables. B. Lux and B. Pluger also consider hydrogen and speak of its application in industry for having a high calorific value and thus being able to replace natural gas in processes that depend on heat and cannot be electrified. This is the main application of hydrogen in this work. We will not consider it as storage, but rather in the industry sector (and a small part in the transport sector).

Regarding the projections made for the isolated Portuguese system and with the interconnection with Spain, F. Amorim et al. points out that for the closed system, more installed solar PV power is needed compared to the system taking into account the interconnection with Spain, and that from 2030 onwards, conventional natural gas plants are gradually being phased out. The conclusions of this study also lead us to the one of objectives of this work, and that is the evaluation of the export character that is expected from Portugal in the horizon of 2030, and also the importance of taking into account the influence of the interconnection between Portugal and Spain to make decisions on the future of the Portuguese electricity system.

The study carried out by R. Figueiredo, P. Nunes and M.C. Brito, reinforces the idea of the importance of the interconnection between the energy systems of the future due to the strong dependence that renewable technologies have on climate, but also of other measures that contribute to the flexibility of systems such as DSM, storage technologies and hydrogen strategies. These ideas are important for the work developed here mainly because we will talk about the influence of climate (availability of renewable resources), and because simulations will be evaluated considering the strategies for hydrogen.

M. Doepfert and R. Castro conclude that by 2050, a country like Portugal has the capacity to supply enough energy regardless of whether it is a wet year or a dry year. This conclusion is relevant because later we will mention the importance of characterizing a year's climate. J. Graça Gomes et al. models the Portuguese energy system in the future, also differentiating between a dry year and a wet year.

Some conclusions of studies on the Portuguese energy system are similar to those on the Spanish system. Although they are two systems with different characteristics, namely in their size, they end up having similar renewable production profiles as they share the same type of climate.

J.J. Brey concludes for the 2030 horizon, also based on PNIEC data, considering hydrogen as a storage technology and correct management of the electricity grid, that it is possible to achieve a share of VRES generation of more than 50% in the Spanish energy system. This will be a good basis of comparison for the results that will be obtained in this work.

3 | Methods

In this chapter the tools used to model the power system and the input information for the various simulations are presented. EnergyPLAN was developed to analyze the energy, economic and also environmental impacts of different strategies in energy systems [34] , and is the model used in this work to do the simulations of Portuguese and Spanish power systems in the present and the near-term perspective (2030).

Since the main purpose of this work is to understand how the power systems of Portugal and Spain are going to work interconnected, the MultiNode add-on tool of EnergyPLAN is used to explore balances and exchanges of electricity between the two systems.

3.1 EnergyPLAN

The EnergyPLAN is a computer model created in 1999 by the Sustainable Energy Planning Research Group at Aalborg University for energy systems analysis carried out in hourly steps for one year, which can be run using two strategies: a technical simulation or a market-economic simulation. This work is focused on the technical simulation strategy using the 15.0 version. The main purpose of this tool is the design and planning of national energy systems, but also has been applied at a local/region level as well as at the European level. This model emphasized the analysis and simulation strategies between combined heat and power production (CHP) and VRES, including a wide range of technologies. [35] It performs a deterministic analysis on an annual basis, it is modeled in Delphi Pascal and is free but not open source since the code cannot be edited. [34]

EnergyPLAN is an input/output model, in which the inputs are demands, VRES and central power plants capacities with the respective efficiencies, and simulation strategies that influence import/export and excess electricity products. The outputs are the energy balances and annual energy productions, fuel consumption, CO_2 emissions and values of import/export of energy. If we consider a market-economic analysis, this includes the input of costs and the output of costs associated with the exchange of electricity. The EnergyPLAN shows a diagram on the front page that illustrates the principle of the energy system and the components involved in the calculation of the hourly balancing of the electricity (Figure 3.1). For this application, since the study is focused only on the power systems, the system simulation only takes into account the electricity interactions. [35]

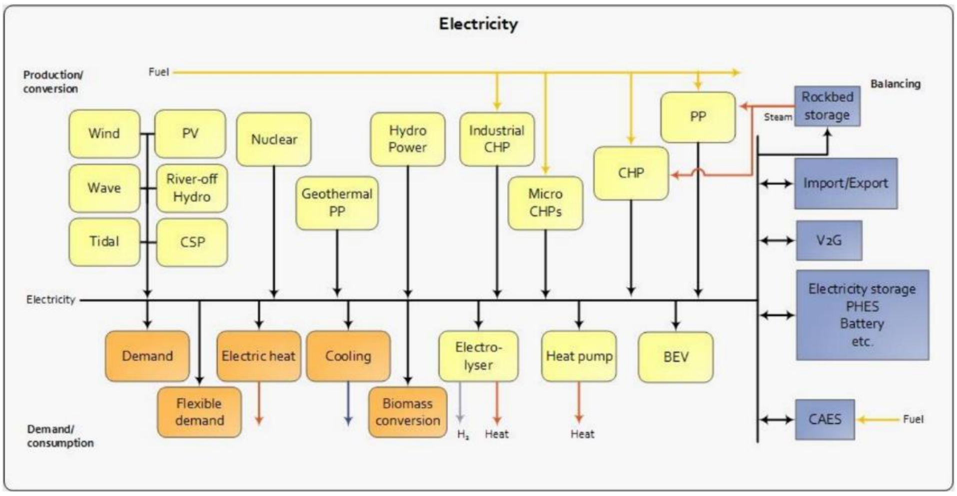


Figure 3.1– Schematics of the EnergyPLAN model applied to the power system. In yellow we have the energy production units, represented in blue are the technologies or strategies for excess production, and in orange are the outputs. [35]

One of the great advantages of using EnergyPLAN is the integration of fluctuating power from VRES into the power system having the possibility to describe current technologies that are present in the system, as well as technologies that are expected to be used or grow in the future. The possibility to vary between options makes it easy to compare different scenarios made for a system. This factor together with the focus on the integration of renewables in the system makes this model suitable for creating future models of energy systems. [34]

3.1.1 MultiNode

The MultiNode add-on tool was developed as a central part of J. Z. Thellufsen PhD project “Energy System Analysis of Multiple Systems”. The concept behind this is electricity links through cables between systems that can be of all kinds of sizes and can link between 2 and 28 different systems[36].

This add-on allows us to use the simulations of systems made in EnergyPLAN, change them to create balances with the systems that were introduced, and re-run these new systems in EnergyPLAN. The balances calculated with MultiNode are made by identifying the amount of exportable electricity and the potential for electricity import every hour. MultiNode identifies a potential import demand as hours with a lack of sufficient renewable capacity and hours with power plant production, which means that MultiNode is focused on the optimization of renewable energy in the systems. Then, the tool tries to link the exportable electricity with the import needs. In hours with import needs and available export, each system will try to fulfil its import needs as much as possible. Each energy system will get access to the electricity available for import on the grid based on a merit order.

After utilizing as much of the exportable electricity in each of the energy systems as possible, an import/export balance is created for each energy system and the yearly net export is identified. Together, the balance and the net export identify each system’s interaction with the grid. Finally, the MultiNode add-on tool runs each of the selected energy systems once again, now with the information regarding import and export. Based on these simulation results the MultiNode has the option of summarizing the combined systems.

3.2 Calibration Models

Before the simulation of an power system in a future scenario, it is convenient to model this system for the present, allowing us to compare the values obtained by the model with those already known for this power system in a certain year, and therefore, evaluate the quality of the model. Given the conditions for that year, the model calculates balances that lead to data that we can consider sufficiently approximate, or not. If it is, we say that the use of this model to model this system is trustworthy to carry out a future simulation in which we will not be able to make a direct comparison.

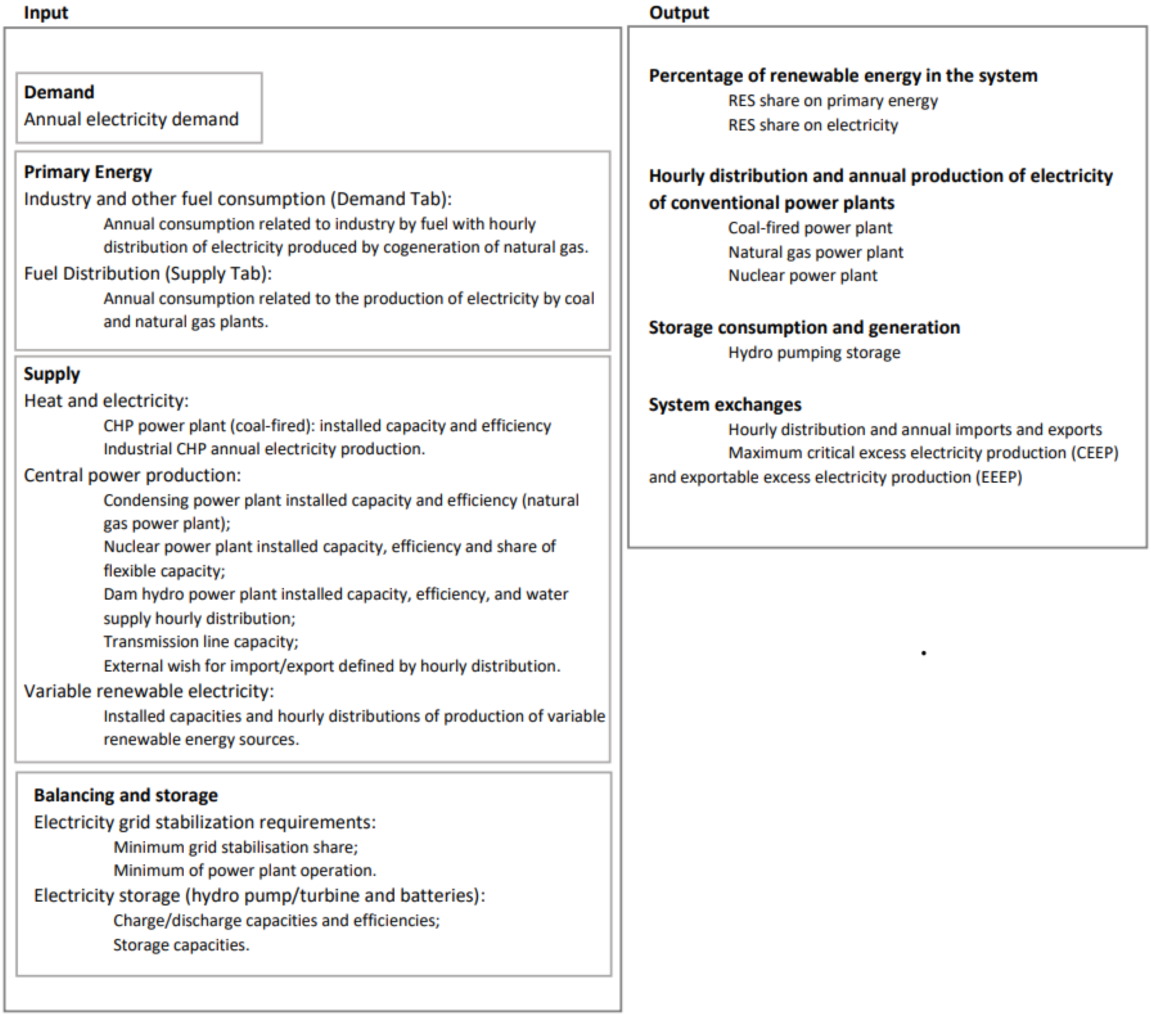
To validate the method, both Portuguese and Spanish systems were modelled for the years 2017 and 2018. These years were chosen as current reference years because we have access to more detailed data and to get an idea of the relevance of annual seasonality for hydropower production since 2017 is an example of a dry year and 2018 a wet year.

This analysis takes to account only mainland Portugal and Spain since the objective is to study the interconnections between these two countries and what will be the role of the Iberia in terms of electricity exchanges with the rest of continental Europe. It thus does not consider the non-peninsular systems of both countries, as they have no impact on how these systems are influenced by their interconnections.

3.2.1 Portugal

EnergyPLAN divides the energy system into three main sectors: electricity, heat and transport. In this work, only the electricity sector is studied. There are three tabs where inputs relating to the power system are introduced: demand, supply, and balancing and storage.

The model approach for the present reference years is the same for the Portuguese and the Spanish systems and is schematized in Figure 3.2. This allows understanding of the type of inputs given for these models and the output obtained.



Input

Demand
Annual electricity demand

Primary Energy
Industry and other fuel consumption (Demand Tab):
Annual consumption related to industry by fuel with hourly distribution of electricity produced by cogeneration of natural gas.
Fuel Distribution (Supply Tab):
Annual consumption related to the production of electricity by coal and natural gas plants.

Supply
Heat and electricity:
CHP power plant (coal-fired): installed capacity and efficiency
Industrial CHP annual electricity production.
Central power production:
Condensing power plant installed capacity and efficiency (natural gas power plant);
Nuclear power plant installed capacity, efficiency and share of flexible capacity;
Dam hydro power plant installed capacity, efficiency, and water supply hourly distribution;
Transmission line capacity;
External wish for import/export defined by hourly distribution.
Variable renewable electricity:
Installed capacities and hourly distributions of production of variable renewable energy sources.

Balancing and storage
Electricity grid stabilization requirements:
Minimum grid stabilisation share;
Minimum of power plant operation.
Electricity storage (hydro pump/turbine and batteries):
Charge/discharge capacities and efficiencies;
Storage capacities.

Output

Percentage of renewable energy in the system
RES share on primary energy
RES share on electricity

Hourly distribution and annual production of electricity of conventional power plants
Coal-fired power plant
Natural gas power plant
Nuclear power plant

Storage consumption and generation
Hydro pumping storage

System exchanges
Hourly distribution and annual imports and exports
Maximum critical excess electricity production (CEEP) and exportable excess electricity production (EEEP)

Figure 3.2 – Present EnergyPLAN model approach.

The first tab is about system consumption. Annual electricity consumption is entered along with the hourly consumption profile for that year. This consumption includes the import balance, which can be a positive or a negative value, depending on if the system had an import or export character.

The primary energy is defined in two separate tabs. One is in the consumption section and is related to the annual consumption of each fuel in the production associated with the industry sector, among other productions. In this part, it is possible to define the annual consumption of coal, fuel oil, natural gas, biomass, and hydrogen, as well as associate an hourly distribution to the natural gas consumption.

For the modelling of the Portuguese system, the primary energy is associated with cogeneration. It is possible to make this approximation of electricity production by cogeneration with the industrial CHP in EnergyPLAN because according to annual energy balances provided by the DGEG for 2017 and 2018, the industrial sector is responsible for almost all the processes involving heat and electricity production so we can consider the production of electricity by the industry as the production of electricity by cogeneration. [9,10]

The primary energy associated with production by conventional power plants, CHP, and boilers, is defined in the supply tab under *Fuel Distribution*. Here, an annual consumption by type of fuel (coal, fuel oil, natural gas, and biomass) is also defined for each plant that was considered in the model. We can define fuel consumption as variable or fixed, knowing that when selecting a fixed consumption, the value that was entered is the exact value that the plant will consume, but if a variable consumption is considered, the fuel is consumed proportionally with other fuels which are also selected as variables. [37]

Modelling the Portuguese power system for the present means that the primary energies already defined are referred to as two types of power plants that were introduced in the model: coal-fired and natural gas power plants. In the *Supply Tab*, the user enters the installed capacities and efficiencies of these two types of plants, as well as the annual production of electricity by cogeneration (as industrial CHP).

Dammed hydropower power plants are also included in this tab, as their production is dispatchable. The production by hydropower dams is defined not only by these values but also by an hourly distribution of the water supply for that year.

The production of variable renewable energies is defined in the model by introducing the installed capacity, the annual production and the hourly distribution that describes the production of a certain technology. In the variable renewable energies tab, we can define several technologies: wind, offshore wind, solar PV, CSP solar power, tidal, wave power and run-of-river hydro.

The installed capacities and annual productions are known and obtained through data provided by DGEG, and the hourly productions were provided in the TSO load diagrams. The introduction of these parameters in the model means that the production of the VRES is completely defined by the user and will create an annual production that depends on the installed power and the associated distribution that is introduced.

Also, in this central power plant tab in EnergyPLAN, it is possible to introduce a transmission line capacity and an hourly distribution that represents exchanges with an external system. The definition of these two parameters is a crucial part of the modelling of the systems in the present since we know the imports and exports that happened for those years and know that these influence productions to satisfy the import and export needs.

The exchanges that Portugal makes with external systems are quite easy to analyze and model since it is only interconnected with Spain. The simplicity of the Portuguese system in this aspect makes it easier for us to introduce into the model a time profile of imports and exports that occurred because we can directly use the ones given in the load diagrams provided by the TSO. [38,39,40]

The last parameters that we must enter into the model are in the *Balancing and Storage Tab*. In this section, we describe storage capacities, grid stabilisation requirements and system regulation strategies.

The transmission line capacity that was defined in the *Supply Tab* limits the connection that the system has with an external system. The system calculates an hourly distribution of exports, and based on the transmission capacity, the model identifies a Critical Excess Electricity Production (CEEP) when the export exceeds the line capacity and an Exportable Excess Electricity Production (EEEP) that passes through the defined interconnection. The sum of these two is the total system exports.[37]

It is not possible in a real system to have an excess of critical energy because it can cause a drop in the supply of electricity, therefore, this CEEP value is calculated according to different system regulation strategies to use this excess or to avoid it. The model gives us nine possible strategies, and it is possible to choose more than one by giving them an order of priority. These strategies include reducing variable renewable production, CHP production, boiler production, reducing power plant production in combination with variable renewable production, increasing the production of synthetic fuels through CO_2 hydrogenation, and the partial loading of nuclear giving some flexibility to this technology to reduce or increase production when needed. [37]

In EnergyPLAN, production by variable renewable technologies is fully introduced by the user, and since the balances calculated by the model give priority to renewable production, this production is maintained or decreased in case consumption is lower than production. When the system's consumption per hour exceeds the variable renewable production, and this cannot satisfy the load, non-renewable production enters. However, the operation of conventional power plants is not that simple because we cannot have them operating and shutting down in short periods.

Unlike variable renewables, the user enters only the installed capacities and efficiencies of the plants, so the hourly production calculation is defined by the model based on demand and with certain technical aspects characteristic of each type of power plant. An example is the combined cycle power plants that do not work below a defined minimum because their efficiency decreases as they depend on a heat process. Therefore, we can specify in this tab a *Minimum PP* as the minimum production that power plants can reach.[37]

In the modelling of the calibration systems, by having access to the TSO load diagrams we can add the hourly distributions of the coal power plants and the natural gas power plants and look for the minimum operating capacity of the resulting distribution. This value will be the most appropriate to consider as a minimum operating capacity as it gives us the lowest operating power observed in the year in question. In the Portuguese case, as there was a large renewable production capable of satisfying consumption in certain periods, we observed that the coal and natural gas power plants went off simultaneously, which is why the *Minimum PP* in the Portuguese calibration models are considered zero. We will see later that the same did not happen in Spain.

It is considered in the EnergyPLAN that an energy system is composed of five types of grids: the electricity grid, the district heating and district cooling grids, and the gas and hydrogen grids. We are doing technical modelling of the power system so we are only going to consider the electricity grid, and for that reason, although no load flow analysis is carried out on the electricity lines, or an assessment of grid stability taking into account the grid frequency, inertia and reserve, we can define the amount of hourly electricity production that must be additionally produced from certain production units, to provide stabilization to the grid. [41] This ensures that in certain hours of lack of production or peak consumption, there is sufficient dimensioning of power plants to increase their production in case of need. In this study, we considered 10% of grid stability for all the calibration models.

So, this means that in addition to the definition of a minimum operation of the exchanges, a percentage of operation necessary to guarantee the stability of the network is specified. This introduced value defines the total percentage of electricity coming from large plants, like dam hydro, nuclear, coal and natural gas power plants, which is used as a stabilization capacity. It is also possible for VRES to provide grid stability if indicated in the tab where they are defined, but in this study, we considered that only conventional power plants are covered for this purpose.

However, the hypothesis of considering VRES for the stability of the grid is something relevant to take into account when modelling future power systems. [37]

When it comes to electrical storage it is possible to introduce two types of technologies. In the calibration models, we only consider hydropower pumping technologies, so the charge input is pumping, that is, the conversion of electricity into potential energy. The discharge input is the capacity of the turbine that converts the gravitational potential energy into electricity again, and both have their respective efficiency associated. The total storage capacity of hydro pumping is also defined. [37] This storage capacity in practical terms will be the combined reservoir capacity available for storage in all dams with pumping technology. This should not introduce an error in the annual storage amount as it is limited by the pumping installed capacity.

Throughout this explanation of how it is made the modelling of the Portuguese calibration system, it was mentioned that each unit of production or storage is introduced in the model, and the known average efficiency for this type of technology is associated.

Table 3.1 – Efficiencies associated by default for the various technologies that were considered in the calibration models and future models of the Portuguese and Spanish power systems. [42,43,44,45,46,47]

	Efficiency [%]
Coal-fired power plant	38
Natural gas power plant	52
Nuclear power plant	35
Dam hydro	90
Hydro pumping storage	80
Hydro turbine storage	90
Electrolysers	73

Table 3.1 shows all the efficiencies that were considered in the calibration models for both Portugal and Spain, as well as in the future, that will be explained and analyzed later in this study. Considering these efficiencies by default gives a similar methodology for modelling the systems, however, there will be an exception in the efficiencies of coal and natural gas power plants in the calibration models in Spain, which will be explained in the section regarding the definition of the Spanish calibration model.

3.2.1.1 Portuguese Calibration Models Results

To validate the modelling of the Portuguese power system, the values obtained by EnergyPLAN and the data provided by DGEG and REN (TSO), were displayed side by side and the percentages of deviation of the data obtained to the real values observed in those years were calculated (Table 3.2).

The best way to introduce consumption was by adding the export balance to the electricity consumption and introducing this total amount of electricity consumption in the model together with the external need through the hourly distribution of imports and exports. By defining the exchanges in this way, more reliable production values of the power plants were observed than introducing the export balance as fixed imports and exports in the *Demand Tab*.

Table 3.2 – EnergyPLAN input for 2017 and 2018 Portuguese calibration models: Electricity demand, import balance and primary energy. [9,10,48,49,50]

[TWh/year]	2017 real values	2017 EnergyPLAN output	Deviation [%]	2018 real values	2018 EnergyPLAN output	Deviation [%]
Electricity Demand	49.60	-	-	50.90	-	-
Import Balance[xviii]	-2.68	-	-	-2.66	-	-
Total Electricity Demand	52.28	52.28	-	53.56	53.56	-
Primary Energy						
Industry						
Coal	0	0	0	0	0	0
Oil	1.37	1.37	0	1.17	1.12	0.27
Natural gas	13.90	13.90	0	14.93	14.93	0
Biomass	13.96	13.96	0	13.63	13.63	0
Power plants						
Coal	37.66	36.78	-2.27	31.22	31.49	0.88
Natural gas	25.22	25.32	0.42	19.26	19.63	1.91

The primary energy values referring to the productions of coal and natural gas power plants differ from the real values because the efficiencies that were introduced in the model are average efficiencies of these technologies and not the real efficiencies for those years, but this deviation between the values is considered too low to argue that the efficiencies used are not appropriate.

Table 3.3 shows all the powers introduced in the model, including those associated with storage and regulation of the power system. The difference between the installed capacities that were introduced in the model and those of the technical data is evident, namely concerning the capacity of coal-fired power plants and VRES. The values of the coal-fired and natural gas power plants entered were not the capacities found in the technical data for each technology, but the maximum of their respective hourly distribution in the load diagrams, provided by the TSO. Considering the maximum production observed for the year in question is more realistic in terms of modelling the energy systems than considering the nominal power and thus adding an apparent oversizing to the model. Regardless of this, it was still necessary to reduce the power of coal plants a little to achieve production values closer to reality.

[xviii] A negative value of import balance means that in that year the system exported (export balance). This means that a positive value of import balance means that the system is an importer.

Table 3.3 – EnergyPLAN input for 2017 and 2018 Portuguese calibration models: Installed capacities, transmission line capacity and minimum power plant operation. [38,39,51,52,53]

[MW]	2017 real values	2017 input	2018 real values	2018 input
Power Plants				
Coal fired[xix]	1761	1710	1761	1570
Natural gas	3445	3445	3417	3417
Dam hydro	4400	4400	4400	4400
Variable Renewable Energies				
Wind	5313	4445	5379	4435
Solar PV	585	405	673	435
Run-of-river hydro	2590	2170	2590	2590
Hydro pumping storage	2737	2737	2737	2737
Transmission line capacity[xx]	3050	3050	3050	3050
Minimum Power Plant	-	-	-	-

What EnergyPLAN does is normalize the annual distributions of each technology, creating new distributions where the annual maximum will be equal to unity and multiplies by the nominal power that is introduced by the user. [37] As RES power plants rarely operate at rated power, there is an excess of production if this power is considered. Hence the solution is to use the value of the maximum annual power or another value lower than the nominal power.

As for the VRES, there is a clear decrease in the installed power introduced for these technologies when compared with the data for those years. The reason for this is due to an oversizing caused by the rapid evolution of renewable systems in recent years. The installed capacities provided by the technical data refer to the capacities accounted for at the end of each year, but this capacity did not necessarily exist at the beginning of the same year. The production of newly installed capacities, for example, in the second half of the year, has a very low impact on that year's annual production.

This effect was easily detected when introducing the power of technical data and observing higher productions when compared to those that were observed. It was found more realistic for the modelling of the system, to reduce these powers until obtaining the corresponding final energy and to consider that these new powers would be responsible for the significant annual production of each technology.

Table 3.4 shows the final energy values obtained with the installed capacities, system regulation factors and other considerations, as well as the percentages of deviation between the known productions and those obtained by the model.

[xix] The power value here is the average maximum power and not the rated power.

[xx] Value for 2017 transmission line capacity values was assumed for 2018.

Table 3.4 – Production of power plants and variable renewable energy sources for the Portuguese reference years 2017 and 2018 obtained from the output given by EnergyPLAN compared to the known parameters for those years.[9,10,48,49.54]

Final Energy [TWh/year]	2017 real values	2017 EnergyPLAN output	Deviation [%]	2018 real values	2018 EnergyPLAN output	Deviation [%]
Power Plant Production						
Coal-fired power plant	13.61	13.94	2.44	11.12	11.97	7.67
Natural gas power plant	13.48	13.33	-1.10	10.13	11.08	9.35
Dam hydro	4.14	4.12	-0.51	6.21	6.06	-2.45
Industrial CHP						
Electricity produced	7.15	7.15	0.03	7.08	7.08	0.03
Variable Renewable Energy						
Wind	11.97	11.97	-0.03	12.35	12.35	-0.01
Solar PV	0.85	0.85	-0.35	0.82	0.82	0
Run-of-river hydro	3.49	3.49	-0.03	7.42	6.61	-10.73
Consumption of pumps	2.22	0	-	1.58	0	-
Pumped storage generation	1.80	0	-	1.28	0	-

In EnergyPLAN the storage is only used to avoid CEEP, so any storage simulation done in this study will not match reality as resorting to more or less storage depends on several other factors which are not necessarily linked to an excess of electricity or better efficiency of the power system in general. [37]

In this case, the type of storage is only hydro pumping, and for this reason, the model only starts pumping when CEEP is greater than zero, and when there is no critical excess, it does not pump. The turbine is used when the system has imports or has power plant production when the CEEP is greater than zero. [37] It is known that this is quite different from real operation because pumping storage depends heavily on economic factors (e.g. stored energy can be saved for later times when the value of electricity is higher) that are not taken into account in this study.

Pumping technology stores energy at times where there is more generation than energy consumption, especially with pumping technologies capable of handling fast ramps in both directions (up or down) and frequency regulated in both pump and generator mode, and thus act quickly on the variability of renewable resources. But storage can also take place to avoid periods of transmission line congestion, manage the transmission line more efficiently, and avoid interruptions in electricity supply. [55]

The output that is represented in Table 3.5 is the balance of imports and exports, determined by the hourly distribution of the external need to import and export, and the entire balance between production and consumption. The values obtained of external exchanges of the system show deviations of less than 5% compared to real values, giving us confidence in the choice of parameters chosen for the model.

Table 3.5 – Import and export values for the reference years 2017 and 2018 obtained from the output given by EnergyPLAN and compared to the known parameters for those years, critical excess electricity production (CEEP) and exportable excess electricity production (EEEP) given by the model. [38,39,53]

	2017 real values	2017 EnergyPLAN output	Deviation [%]	2018 real values	2018 EnergyPLAN output	Deviation [%]
Import [TWh/year]	2.98	2.93	-1.68	2.95	2.86	-3.05
Export [TWh/year]	5.62	5.50	-2.14	5.58	5.49	-1.61
CEEP [MW]	-	0	-	-	0	-
EEEP [MW]	3050	3050	0	3050	3050	0

The fact that there is no CEEP in both years for the capacity of the transmission line introduced, indicates that this capacity for the years 2017 and 2018 was the appropriate size for the flow of imports and exports with Spain.

Table 3.6 shows the known values and the values obtained by the model of the percentages of renewables in primary energy and electricity, as well as the total renewable generation.

Table 3.6 – Share and total generation of renewable energy sources in the Portuguese system for the years of 2017 and 2018. [9,10,38,39]

	2017 real values	2017 EnergyPLAN output	Deviation [%]	2018 real values	2018 EnergyPLAN output	Deviation [%]
RES share [%]						
On primary energy[xxi]	31.00	30.80	-0.64	38.50	37.60	-2.34
On electricity	40.00	39.10	-2.25	52.80	49.90	-5.49
RES generation [TWh/year]	21.14	20.5	-3.03	28.02	26.7	-4.71

The modelling of complex power systems, such as modelling at a country scale, involves several production technologies, and various forms of consumption, including storage and strategies for regulating systems to ensure a balance between consumption and production. The technical analysis carried out in this study has limitations because it does not consider some important economic factors in the management of the electrical grids. For these reasons, with the percentages of deviations we obtained, we can say that this EnergyPLAN model is a sufficiently reliable tool to simulate the Portuguese electricity system in the future.

3.2.2 Spain

The Spanish power system in 2017 and 2018 was also replicated using known data for those years provided by the Spanish national energy authority (Ministério para la Transición Ecológica and Secretaría de Estado de Energía), and its TSO (Red Eléctrica de España). The same type of data was used, including load diagrams to obtain hourly consumption and production profiles for the various technologies considered.

As mentioned in Section 3.2.1 on the Portuguese system, the model approach for the present in Spain is the same as outlined in Figure 3.2. However, Spain is a much larger and more complex system, as it deals with much higher generation and installed capacities, higher consumption, and

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[xxi] This information is not directly found in the technical data but can be calculated from the proportion of renewable production with the primary energy value in Table 3.2.

the introduction of nuclear power plants, which add one additional factor to be taken into account in the system's regulation strategy, as they are base load power plants.

Unlike Portugal, in both 2017 and 2018, Spain had an energy importing character, so in this case, we do not include the import balance in the total consumption of the system. The balance of imports and exports will be accounted for in the system in the distribution of the external need for imports and exports, in a more complex way that will be explained in page 27.

Primary energy was defined in the same way as it was in the Portuguese system, as was the distinction between electricity from cogeneration through industrial CHP since, according to Spanish balance sheets, the industry is also the main sector responsible for cogeneration. [56]

Upon running the Spanish models, the outputs were much lower than those values used as inputs. In this sense, the efficiencies of coal and natural gas power stations were reduced to force the model to increase the primary energy needed for the production of power plants in those years.

Table 3.7 – New efficiencies introduced in the Spanish calibration systems in 2017 and 2018 to match the known primary energy requirement, compared to the efficiencies considered as a reference in the remaining modelling and simulations in this study found in Table 3.1. [42,43]

	Reference efficiency [%]	**2017 new efficiency [%]**	**2018 new efficiency [%]**
Coal-fired power plant	38	35	33
Natural gas power plant	52	45	42

The fact that we had to lower these two efficiencies until reaching reliable primary energy values for coal and natural gas suggests that the literature-efficiencies were probably very optimistic when compared to the real efficiencies that these plants had in the Spanish system in 2017 and 2018.

The methods of introducing installed power in conventional plants, as for the VRES, were the same as for the Portuguese system. This means that the input capacities were the annual maximum of the load diagrams of each power plant, lower than the nominal installed capacity of the coal plant to reach an annual production value more similar to real values. The installed capacities of variable renewables were then reduced until they reached the productions that were effectively observed.

One of the main differences between this system and the Portuguese system is the definition of installed power and efficiency associated with nuclear power plants in the central power production tab. This technology presents a nuclear part-loading system regulation option in the balancing and storage tab and gives it some flexibility in case of the existence of critical excess (CEEP). The capacity for this flexibility (nuclear part-load) is introduced in the central power production tab, where the characteristics of nuclear power plants were defined.[37] For all the modelling of the Spanish system, including models of the future that will be discussed further ahead, the flexibility of up to 50% was considered in this part. By design, nuclear production is very inflexible, operating in an essentially constant profile, so this regulatory strategy will only decrease nuclear production to avoid critical excess electricity.

Another difference is in the definition of the minimum operation for coal and natural gas power stations. By analyzing the load diagrams in Spain for the years in question, adding the two production curves and looking for their minimum, a minimum value greater than zero for simultaneous production of the two types of plants was obtained. Unlike Portugal, the coal and natural gas plants never shut down simultaneously and that is why it is necessary to impose this on the system in the model for reliable modelling. [57]

Creating an hourly distribution that realistically represents the exchange of electricity between Spain and the systems to which it is interconnected is more complex than the Portuguese system. This is because Portugal is only interconnected with Spain and therefore only has a flow of imports and exports with one system. This is why it was possible to use the distribution of imports and exports provided by the Portuguese TSO. On the other hand, Spain has interconnections not only with Portugal but also with France, Morocco and Andorra that have to be accounted for in just one hourly distribution that represents an external need for import and export.

By detailed inspection of the data, one can observe that exports from Portugal from the perspective of Portugal are different from imports from Portugal from the perspective of Spain, while, logically, these two distributions should be identical. The only explanation for this is that Spain works as electricity transit and electricity from Portugal does not necessarily have Spain as its destination, but France. Thus, by subtraction and summation operations of distributions composed of imports and exports with four external systems, we are overlapping imports and exports that occurred simultaneously in different interconnections, and therefore, some electricity flowing through the interconnections is not being accounted for. With the data we have, it is not possible to build a single representative distribution of all energy flows between the four external systems and Spain in which we can account for all the imports and exports that occurred.

The best way to create this distribution was by analyzing the difference between the known exports and imports and the ones that the model calculates in the external need tab. Their ratio gives us a proportion factor of the difference between the imports and the exports. The new distribution is created by designing a function that multiplies the proportion factor related to exports when the value at that right time is positive and multiplies the factor of proportion relative to imports when the value is negative. In this way, when we introduce this hourly export and import balance in the model, we are introducing a distribution that allows us to obtain annual values for exports and imports similar to those known for the years in question.

The capacity of the transmission line introduced limits the values of this external need, so not to have any limitation, we have considered here an infinite transmission capacity to allow all the defined export and import to occur, since the capacity of the transmission line in Spain must be the sum of the interconnection capacities with each of the four systems to which it is interconnected. In these calibration models, considering this total transmission capacity or considering an infinite capacity is the same because the flow of imports and exports is totally defined and only depends on the distribution that was introduced.

3.2.2.1 Spanish Calibration Models Results

Table 3.8 present the calibration results for the Spanish model. Unlike Portugal, Spain was a net importer of electricity both in 2017 and 2018. However, the energy consumption value that we considered in Spain was the total consumption without subtracting the import balance since what interests us for the modelling is to consider the total consumption of the system without distinction between consumed electricity that is produced by the system, and the electricity imported into the system. The differentiation of imports and exports is made further in the definition of the external need distribution.

Table 3.8 – EnergyPLAN input for 2017 and 2018 Spanish calibration models: Electricity demand, import balance and primary energy. [57,58,59,60,61]

[TWh/year]	2017 real values	2017 EnergyPLAN output	Deviation [%]	2018 real values	2018 EnergyPLAN output	Deviation [%]
Electricity Demand	240.88	-	-	239.81	-	-
Import Balance[xxii]	-9.18	-	-	-11.10	-	-
Total Electricity Demand	250.06	250.06	-	250.91	250.91	-
Primary Energy						
Industry						
Coal	0	0	0	0	0	0
Oil	0	0	0	0	0	0
Natural gas	48.76	48.76	0	49.80	49.80	0
Biomass	0	0	0	0	0	0
Power plants						
Coal	123.45	122.8	-0.53	108.66	106.13	-2.33
Natural gas	76	74.89	-1.46	62	62.07	0.11

As discussed in page 26, it was possible to match the primary energy of the coal and natural gas power plants, changing their efficiencies until the values were as identical as possible. This change created a variation in the percentage of renewables in primary energy, as will be seen in one of the tables below.

Table 3.9 shows all the installed capacities that have been introduced, together with the capacities that are in the documentation for the years of study. The same methodology was used as in the modelling of the Portuguese system to do the definition of the installed capacities of the power plants as well as the installed capacities of the VRES technologies. The only novelty here is in the definition of the installed capacity (in this case, nominal power) of nuclear power plants, and in the definition of concentrated solar power (CSP) in the *Variable Renewables' Tab*. Note that for both years, it was also necessary to reduce the installed power of the CSP to the known values, as done above.

It is important to point out that here, the transmission line capacity introduced is 999999 MW, in order to simulate an infinite capacity that allows the program to give as output, the necessary electricity flows so that there is no critical excess of energy (curtailment).

[xxii] A negative value of import balance means that in that year the system imported. This means that a positive value of import balance means that the system is an exporter.

Table 3.9 – EnergyPLAN input for 2017 and 2018 Spanish calibration models: Installed capacities, transmission line capacity and minimum power plant operation. [57,62,63,64]

[MW]	2017 real values	2017 input	2018 real values	2018 input
Power Plants				
Coal fired[xxiii]	8657	6000	7659	4800
Natural gas	16948	16948	10314	10314
Nuclear	7117	7117	7117	7117
Dam hydro	15308	15308	15307	15307
Variable Renewable Energies				
Wind	22922	15517	23091	16018
Solar PV	4439	3680	4466	3710
CSP	2304	2200	2304	2185
Run-of-river hydro	1722	1090	1740	1302
Hydro pumping storage	3329	3329	3329	3329
Transmission line capacity[xxiv]	-	999999	-	999999
Minimum Power Plant	-	1560	-	1142

As opposed to the Portuguese case, when adding the hourly distributions of the production of coal and natural gas power plants and looking for a minimum it is found a value greater than zero, this indicates that in Spain these two types of power plants were not switched off at the same time. If we look for the minimum in both distributions for the two years, we always find values greater than zero, which means that none of them was turned off during these years. For this reason, the minimum value of the hourly distribution resulting from the sum of the production profiles of coal plants and natural gas plants was introduced in the model to impose this minimum production value of the plants, not letting them reach a null value to produce results as similar as possible to the reality.

In Table 3.10 are the values of final energy for the power plant production, industrial CHP, generation of VRES and for hydro pumping storage. Table 3.11 is the balance of imports and exports, determined by the hourly distribution of the external need to import and export, the CEEP and EEEP.

[xxiii] The power value here is the maximum power in the hourly production profile and not the rated power.
[xxiv] Value for 2017 transmission line capacity values was assumed for 2018.

Table 3.10 – Production of power plants and variable renewable energy sources for the Spanish reference years 2017 and 2018 obtained from the output given by EnergyPLAN and compared to the known parameters for those years. [62,63,57]

Final Energy [TWh/year]	2017 real values	2017 EnergyPLAN output	Deviation [%]	2018 real values	2018 EnergyPLAN output	Deviation [%]
Power Plant Production						
Coal-fired power plant	42.59	42.98	0.91	34.88	35.00	0.34
Natural gas power plant	33.86	33.7	-0.46	26.40	26.16	-0.92
Nuclear power plant	55.61	55.54	-0.12	53.20	53.16	-0.07
Dam hydro	14.58	13.89	-4.73	27.55	26.73	-2.98
Industrial CHP						
Electricity produced	28.13	28.13	-0.01	28.98	26.98	0.00
Variable Renewable Energy						
Wind	47.50	47.49	-0.02	48.95	48.95	0.01
Solar PV	7.99	7.99	0.03	7.37	7.37	-0.05
CSP	5.35	5.35	0.04	4.42	4.42	-0.09
Run-of-river hydro	3.91	3.91	0.05	6.62	6.62	0.08
Consumption of pumps	3.675	0.00	-	3.20	0.00	-
Pumped storage generation	2.249	0.00	-	2.01	0.00	-

Table 3.11 – Import and export values for the reference years 2017 and 2018 obtained from the output given by EnergyPLAN compared to the real values for those years, critical excess electricity production (CEEP) and exportable excess electricity production (EEEP) given by the model. [65,66]

	2017 real values	2017 EnergyPLAN output	Deviation [%]	2018 real values	2018 EnergyPLAN output	Deviation [%]
Import [TWh/year]	23.76	23.56	-0.84	24.02	24.12	0.42
Export [TWh/year]	14.59	12.69	-13.01	12.92	10.62	-17.78
CEEP [MW]	-	0	-	-	0	-
EEEP [MW]	-	22807	-	-	20634	-

In EnergyPLAN the storage modelling is completely dependent on the existence of CEEP while in reality, storage depends on economic factors. Here we have a null value of CEEP, so the system does not even assume hydro pumping. The fact of not being able to make correct modelling of the system's storage will introduce a series of differences from reality because it ends up influencing production, imports and exports. However, even with this limitation, when looking at the final energy values found in Table 3.10, we conclude that the deviations are low for the modelling of a system as complex as Spain and that the results are reliable enough to validate a future simulation based on this system.

The values we have in Table 3.12 and Table 3.13 show the flow imports and exports with all systems interconnected to Spain, facilitating the perception of exchanges carried out in the years 2017 and 2018. Negative values are imports by Spain, while positive values indicate Spain as an exporter.

By introducing an infinite transmission line power, we ensured that the model did not have a critical excess of electricity (CEEP). In this way, the EEEP value gives us a direct estimate of the total interconnection value required for all electricity flows to occur in that year. This value is useful for us to understand what the need for an increase in interconnection in Spain is due to the estimated increase in variable renewables. Table 3.14 shows that the real and calculated percentages of renewables in electricity are very similar, the same as for the total values of renewable generation

Table 3.12 – Known flow of imports and exports from Spanish interconnections in 2017. [65]

	2017 Imports [TWh/year]	2017 Exports [TWh/year]	2017 Import balance [TWh/year]
Andorra	0	0.22	0.22
France	15.56	3.09	-12.47
Portugal	8.19	5.51	-2.69
Morocco	0.01	5.76	5.75
Total	23.76	14.59	-9.17

Table 3.13 – Known flow of imports and exports from Spanish interconnections in 2017. [66]

	2018 Imports [TWh/year]	2018 Exports [TWh/year]	2018 Import balance [TWh/year]
Andorra	0	0.21	0.21
France	15.51	3.47	-12.05
Portugal	8.32	5.67	-2.66
Morocco	0.18	3.57	3.39
Total	24.02	12.92	-11.10

Table 3.14 – Share and total generation of renewable energy sources in the Spanish system for 2017 and 2018. [57,60,61,62,63]

	2017 real values	2017 EnergyPLAN output	Deviation [%]	2018 real values	2018 EnergyPLAN output	Deviation [%]
RES share [%]						
On primary energy[xxv]	24.23	16.3	-32.69	31.30	20.30	-35.15
On electricity	31.10	31.40	0.96	36.59	37.50	2.49
Renewable generation [TWh/year]	82.42	78.60	-4.63	100.45	94.10	-6.32

The percentage of RES in primary energy shows considerable variation compared to the value calculated from the data provided for those years, but it is due to some imbalance in the model caused by the variation in power plant efficiencies. As we are not evaluating CO_2 emissions, this variation is not relevant for the validation of the model since the final energy values obtained show a quite low percentage of deviation compared to the production observed in 2017 and 2018.

3.2.3 Influence of the dry year and wet year on the modelling of power systems

The years chosen as a reference for the creation of reference models were 2017 and 2018 because they correspond to a typical dry year and a typical wet year, respectively. We chose to model the systems for these two years, not only to understand the influence that climate (such as a change

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[xxv] This information is not directly found in the technical data but can be calculated from the proportion of renewable production with the primary energy value.

in precipitation) has on electricity generation but also to have a significant sample to say that the model used can be generalized to other simulations of these systems.

The precipitation determines whether a year is characterized as dry or wet, which translates into intra-annual variation in the water resource and consequently changes in energy production by both reservoir and run-of-river hydropower technologies. The character of these years was confirmed by the technical data documents that are issued annually by the TSO. In the document on the Portuguese system in 2017, it is stated that hydro production was unfavourable, recording a hydroelectric productivity index[xxvi] of 0.47, while in the document on the system in 2018 there was an above-average regime in hydro production, with a productivity index of 1.05. [48,49,67]

The hydroelectric productivity index for the same reference years of 2017 and 2018 in Spain were respectively 0.5 and 1.3. For both countries, the 2017 productivity indexes indicate the occurrence of a dry year, while the 2018 productivity indexes area both indicators of a wet year. [68] Consequently, the years considered for the calibration models are the same for the systems of the two countries under study.

The amount of precipitation that is captured by a watershed determines the amount of water available for hydropower production and seasonal variations in precipitation and long-term changes in precipitation patterns, such as droughts, can have large effects on the availability of hydropower production. [69]

The Portuguese Institute of Sea and Atmosphere (IPMA) provides the average monthly precipitation values for each year, which allowed us to create the hourly distributions to introduce a hydropower production (from reservoir) based on the water supply that was observed in the years we are modelling. [70] It was assumed that the average precipitation value for each month is equal for each day of the respective month, and successively for each hour of that month, thus creating the hourly distributions for a leap year.

Figure 3.3 represents the hourly distributions of water supply calculated for Portugal and allows us to visually confirm that 2017 was a dry year and 2018 a wet year, as 2018 shows a clear increase in precipitation compared to 2017 in March, April, and again in October and November. This differentiation confers a distinction in the water supply that justifies an increase in hydropower production from 2017 to 2018.

[xxvi] Hydroelectric Productivity Index (HPI): Indicator that allows to quantify the deviation of the total value of energy produced by water in a given period, in relation to what would be produced if an average hydrological regime occurred. [67]

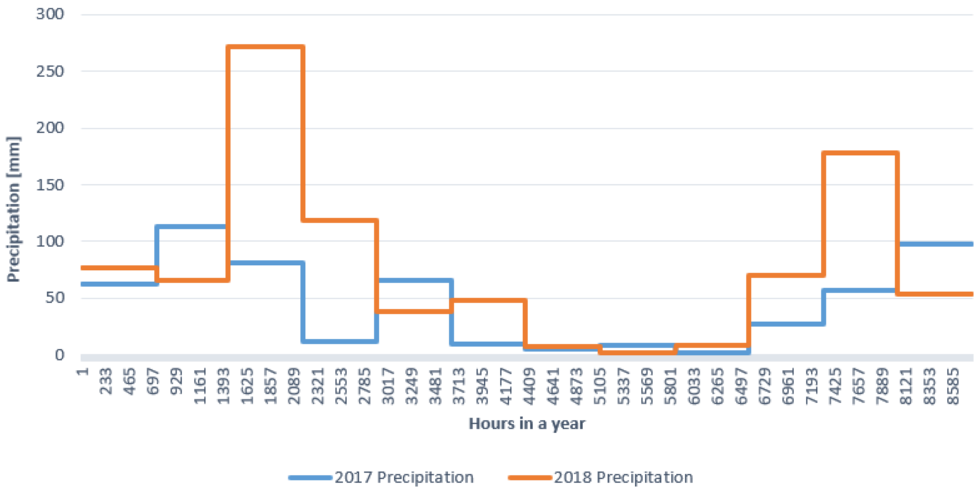


Figure 3.3 – Graphic representation of the hourly water supply distribution calculated using the average monthly precipitation values for 2017 and 2018 in Portugal.

Concerning this intra-annual variability of the water resource, a distribution of water supply similar to the Portuguese case was conceived for Spain, but here using rainfall data for Spain, provided in the hydrological bulletin made by the Spanish entity responsible for this study. [71] Figure 3.4 allows us to visualize the inter and intra-annual variability of rainfall in Spain during the dry year and the wet year.

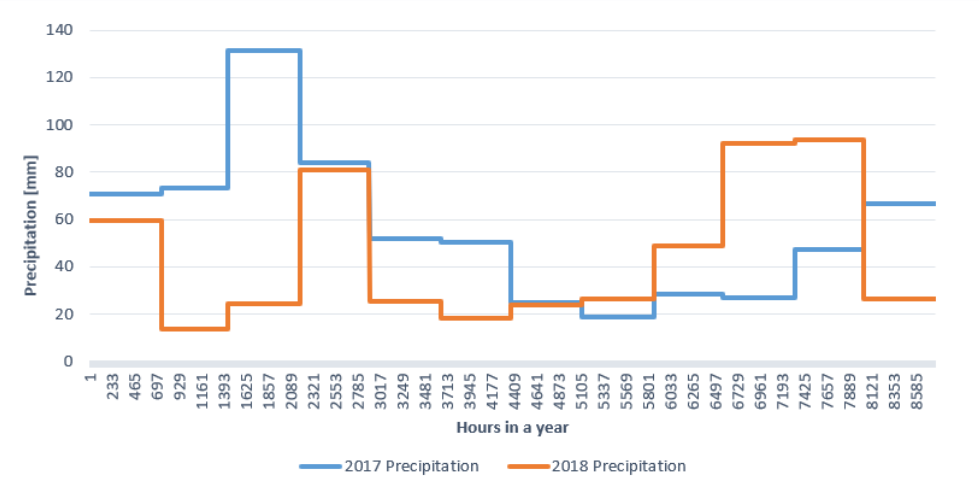


Figure 3.4 – Graphic representation of the hourly water supply distribution calculated using the average monthly precipitation values for 2017 and 2018 in Spain.

In the case of Spain we have higher rainfall in the dry year at the beginning of the year but higher rainfall in the wet year in the months towards the end of the year. The most reliable way to evaluate a dry year and a wet year, to make a correlation as correct as possible, would be to consider an average of rainfall from years considered typically dry and rainfall from years that were considered to be wet.

By analyzing Table 3.4, it is possible to compare the production values between the dry and wet years in Portugal. There is an evident increase in hydropower production (both from reservoirs and run-of-river). This increase caused a decrease in the production of natural gas and coal-fired power plants, and in electricity produced by cogeneration, as would be expected given that the consumption that would have to be suppressed by the production of power plants is lower in a year with greater renewable production, namely greater conventional hydropower plant production.

If we look at the values of technical data provided, we see that the increase in hydro production causes a decrease in pumped storage (pumping and turbine), which makes sense when we think that there is less need for pumped storage when we have more dispatchable dam hydro production.

Another interesting effect is related to the fact that from the dry to the wet year an increase in wind production and a decrease in solar PV production can be observed. This is relevant because it suggests a correlation between the availability of the water resource and the increase in wind production.

The daily correlation between wind and solar resources is well known, with solar production being concentrated at mid-day and wind being higher at night. Torres et al.[72] show that these two resources also show seasonal complementarity, with solar production being higher in the summer and wind power higher in the winter. This behaviour of wind production indicates that there is then another positive correlation with hydropower production, with precipitation occurring essentially in years with a predominancy of wind, so that solar production has a complementary factor to these other two renewable production technologies.

Since wind and hydro energy are expected to be the most relevant renewable energy sources in the next decade it is important to know that the availability of these resources essentially coexists in Portugal. The PV solar production in the models related to the system at present is still quite low, so it will be interesting to see if in the future solar energy will contribute to less inter-annual variability in renewable production. [72]

However, this only explains what happens at the intra-annual level, and what motivated us to model 2017 and 2018 was the interest to understand the inter-annual variations in renewable production. When realizing that hydro and wind productions have similar profiles, it is then logical to say that in this case, wind production does exactly what we saw in Tables 3.4 and 3.10 and produces more when there is greater hydro production in wet years. To be able to say this we had to do a simplified analysis in which we evaluated more than one dry year and one wet year to assess this correlation.

For this reason, we divided the productions by the installed capacities from 2012 to 2018 [73], which represent a pair of successive dry and wet years, of hydropower, wind and solar PV production to calculate their equivalent full-load hours for the years that were considered wet and for the years that were considered dry.

Based on the documented hydropower production values for Portugal and Spain, the years 2012, 2015 and 2017 were chosen because they were considered representative of a dry year. In comparison with these, we have the years 2013, 2016 and 2018 that show higher values of hydropower production, characteristic of wet years. Figure 3.5 shows the calculated equivalent hours, referring to each of these years, for hydropower, solar PV and wind production of the Portuguese power system.

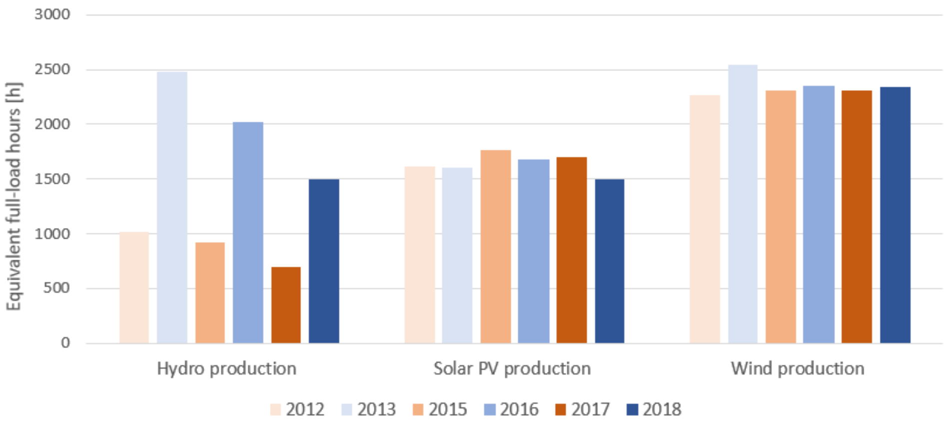


Figure 3.5 – Equivalent full-load hours for hydro, solar PV, and wind production in Portugal for the pairs of dry and wet years identified between 2012-2018. The columns in shades of orange represent the values for the dry years from 2012 to 2018, the columns in shades of blue represent the values for the wet years.

The columns in shades of orange represent the dry years and in shades of blue are the ones that represent the data related to wet years. After having the annual equivalent full-load hours per renewable technology, the average full-load hours for dry years and wet years were calculated for each of them (Table 3.15).

Table 3.15 – Average full-load hours for dry years and wet years, related to hydropower, wind and solar PV production in Portugal based on the pairs of years considered between 2012-2018.

	Dry years	Wet years
Hydro average full-load hours [h]	877	1997
Solar PV average full-load hours [h]	1689	1591
Wind average full-load hours [h]	2292	2411

The calculation of the equivalent full-load hours allows knowledge of a measure of operational performance of a certain technology. It represents how many hours the unit needs to operate at the nominal capacity to produce a certain amount of energy.[74]

From Table 3.15, it is then confirmed that hydro production is higher in wet years and that wind production also tends to be higher in those years, thus following hydro. However, this increase in wind energy is not as relevant as in hydro.

Another conclusion is the fact that the complementarity of solar PV already discussed is also possibly observed on an annual scale since, unlike hydro and wind, it presents a decrease in productivity in the year 2018. However, this decrease is not very marked when looking at the values of full-load hours calculated for the two types of years. We can conclude that for the years analyzed, solar PV production tends to decrease slightly.

For the Spanish system, the same years of solar, hydroelectric and wind production were studied and it was reached the same conclusions as for the Portuguese system. The values of average full-load hours and graphic representation for the Spanish power system are in Annex I. [62,63,75,76,77,78]

To understand whether considering a dry year or a wet year is something that can significantly influence our modelling of the Portuguese and Spanish systems, one may compare the final energy provided by the plans for 2030 in each country [2,4] (which do not make the differentiation between dry and wet years) for dam hydro, solar PV and wind technologies, with new production values with the effect of intra-annual seasonality. Figure 3.6 illustrate this comparison, for Portugal and Spain.

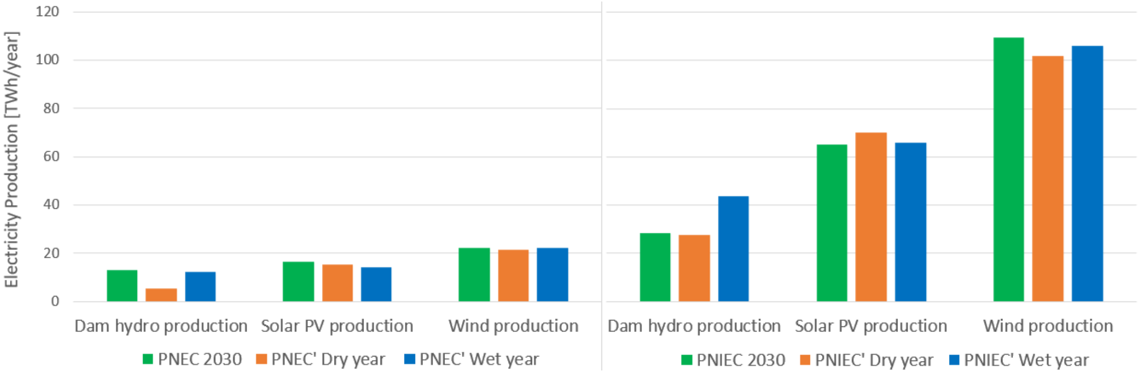


Figure 3.6 – Graphic representation of dam hydro, solar PV and wind production estimated in the PNEC 2030, in comparison with the productions for the dry year and the wet year calculated with the average values equivalent to full-load and taking into account the installed capacities of these technologies in 2030: Portugal (left) and Spain (right).

As expected, the production of dam hydro is higher in the wet years, and the production of wind power is also higher, but this difference is less pronounced, and solar PV production is slightly higher in the dry year. In comparison with PNEC, the estimated productions are a little more ambitious (e.g. dam hydro production) and wind production is in the middle of the values calculated for the dry year and the wet year. This tells us that not considering this difference does not produce data very different from the one considered if we want to make an approximation.

The same is true for Spain, however with the value associated with dam hydro in the PNIEC closer to what a dry year will be. The calculated and estimated values are similar enough to say that the numbers in PNIEC are a good enough approximation to not differentiate a dry year and a wet year for a future simulation.

It would be interesting in the future to create long-term simulations of the power systems of these countries considering in more detail this seasonal and intra-annual analysis with the appropriate tools to describe the dependence of the behaviour of renewable generation with these variations. However, an analysis of seasonal or intra-annual climate variability with that complexity is beyond the scope of this thesis.

So far, we have concluded that the EnergyPLAN tool allows the modelling of Portuguese and Spanish power systems with a very good approximation considering that we are studying a complex system with only technical optimization. Thus we can move towards modelling these systems in 2030, according to the respective plans defined by their governments according to targets defined by the European Union.

These plans did not contemplate the differentiation between a wet and a dry year, so the simulations that follow were carried out based on 2017 for two reasons: firstly, a dry year is more challenging for renewable energy generation and, secondly, due to climate change, the likelihood of dry years is expected to increase.

3.3 Methodology for the simulation of 2030 power systems

After confirming that the model used to replicate the power systems of Portugal and Spain using EnergyPLAN is reliable, we proceeded to the simulation of these systems in the future. EnergyPLAN is a model that essentially aims to model energy systems with a high penetration of renewables, so it was considered the most suitable for performing system simulations in the future, with the characteristics expected for 2030.

This section explains in detail the two types of simulations that were carried out for the two countries, as well as their interconnection. In the case of Portugal, the simulation of the system for 2030 is first explained based on the values found in the National Energy and Climate Plan (PNEC), and then a second simulation is carried out in which the main measures of the National Hydrogen Strategy (EN-H2) are added to the first PNEC model. The same is done for the Spanish system in which this system is simulated based on the Integrated National Energy and Climate Plan (PNIEC), and then is performed a model in which the Spanish strategy for hydrogen (*Hoja de Ruta del Hidrogéno*) is added.

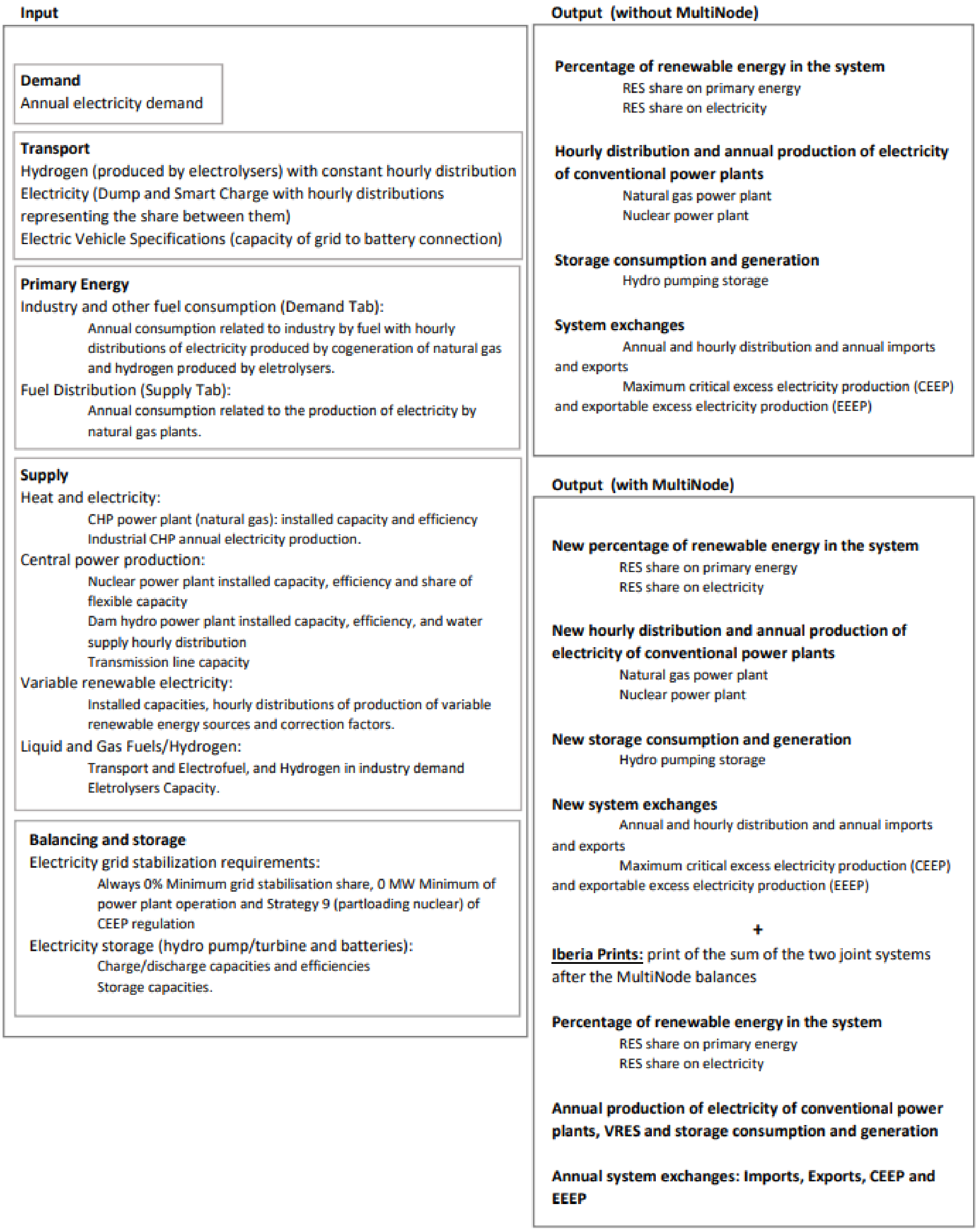
The objective of this section is to initially define the characteristics of the systems and explain how every component of the power systems were simulated in EnergyPLAN.

3.3.1 Portugal 2030

Two simulations of the Portuguese system were carried out in 2030. The first is a simulation based on PNEC values, from estimated consumption, import/export balance, and primary energy to final energy. There are also values for estimated transmission line capacity and water pump storage. It is important to mention that there is an update of the PNEC with additional measures [79] and that this update is essentially a scenario for 2030 similar to that of the PNEC with some corrections that make it more ambitious. As the objective here is to simulate the Portuguese system based on the PNEC using EnergyPLAN, values were used with additional measures scenario when it lacked the necessary information for the model.

In modelling the reference power systems, it was not necessary to consider that Spain is one hour ahead of Portugal because the exchanges were imposed in the model since they were known values for those years. For simulations of the future, however, these exchanges are unknown and thus it is important to take into account the time difference between the two countries.

Future simulations have to consider also the incorporation of new technologies. Figure 3.7 is a scheme like the one used to explain the model for the reference years, but outlining the approach defined for the 2030 simulations.



Input

Demand
Annual electricity demand

Transport
Hydrogen (produced by electrolysers) with constant hourly distribution
Electricity (Dump and Smart Charge with hourly distributions representing the share between them)
Electric Vehicle Specifications (capacity of grid to battery connection)

Primary Energy
Industry and other fuel consumption (Demand Tab):
Annual consumption related to industry by fuel with hourly distributions of electricity produced by cogeneration of natural gas and hydrogen produced by eletrolysers.
Fuel Distribution (Supply Tab):
Annual consumption related to the production of electricity by natural gas plants.

Supply
Heat and electricity:
CHP power plant (natural gas): installed capacity and efficiency
Industrial CHP annual electricity production.
Central power production:
Nuclear power plant installed capacity, efficiency and share of flexible capacity
Dam hydro power plant installed capacity, efficiency, and water supply hourly distribution
Transmission line capacity
Variable renewable electricity:
Installed capacities, hourly distributions of production of variable renewable energy sources and correction factors.
Liquid and Gas Fuels/Hydrogen:
Transport and Electrofuel, and Hydrogen in industry demand
Eletrolysers Capacity.

Balancing and storage
Electricity grid stabilization requirements:
Always 0% Minimum grid stabilisation share, 0 MW Minimum of power plant operation and Strategy 9 (partloading nuclear) of CEEP regulation
Electricity storage (hydro pump/turbine and batteries):
Charge/discharge capacities and efficiencies
Storage capacities.

Output (without MultiNode)

Percentage of renewable energy in the system
RES share on primary energy
RES share on electricity

Hourly distribution and annual production of electricity of conventional power plants
Natural gas power plant
Nuclear power plant

Storage consumption and generation
Hydro pumping storage

System exchanges
Annual and hourly distribution and annual imports and exports
Maximum critical excess electricity production (CEEP) and exportable excess electricity production (EEEP)

Output (with MultiNode)

New percentage of renewable energy in the system
RES share on primary energy
RES share on electricity

New hourly distribution and annual production of electricity of conventional power plants
Natural gas power plant
Nuclear power plant

New storage consumption and generation
Hydro pumping storage

New system exchanges
Annual and hourly distribution and annual imports and exports
Maximum critical excess electricity production (CEEP) and exportable excess electricity production (EEEP)

+

Iberia Prints: print of the sum of the two joint systems after the MultiNode balances

Percentage of renewable energy in the system
RES share on primary energy
RES share on electricity

Annual production of electricity of conventional power plants, VRES and storage consumption and generation

Annual system exchanges: Imports, Exports, CEEP and EEEP

Figure 3.7 – Future EnergyPLAN model approach.

In this new approach the transport sector is also considered because according to the plans for 2030, electric mobility becomes relevant and therefore has a direct influence on the power system. For this reason, an hourly distribution representative of the consumption profile of electric transportation had to be created. According to the RMSA-E 2019 (Report for Monitoring the Security of Supply of the National Electricity System 2020-2040) [53] it is expected that in the future the charging of electric vehicles (EV) will be based on the combination of two strategies: direct recharging, in which an EV is charged whenever it is necessary, and valley recharging, which privileges charging during off-peak hours. This document defines a possible combination: 10% of passenger and freight EVs use direct recharging and the remaining 90% use slow recharging, and within these, 20% are in the direct recharging strategy and 80% in the valley recharging strategy. Having independent hourly distributions for direct recharging and valley recharging [80], the distribution was created based on an equation that translates this combination. The same distribution is used for the Spanish systems.

When modelling systems including the hydrogen strategies, FCEV vehicles are also considered in the *Transport Tab* because this sector is one of those where there is an expected consumption of hydrogen that will be produced, but since this consumption is still very low in 2030, having little impact, it was simulated in a very simple way using the amount of energy consumed by hydrogen in this sector associated with a constant distribution.

Cogeneration power plants may be defined in the *Supply Tab* differently. In the models that described the 2017 and 2018 systems, coal and natural gas power plants generation were known. However, in the future, coal power plants are discontinued (in Portugal, coal power plants stopped operating in 2021). For this reason, natural gas power plants were defined where coal power plants were used to be defined, in the *Heat and Electricity Tab*, leaving in the *Central Power Production Tab* the definition of nuclear power plants (in the Spanish case), of the dam hydro power plants and transmission line capacity. In these simulations, a distribution for the external need for import/export is not considered because here the exchanges with the external systems are unknown, and this is something that we intend to study.

The VRES capacities and production profiles are defined in the same way, however, still in the *Supply Tab*, it is considered a new section tab in the models in which we simulate the systems with the respective strategies for hydrogen. In these models, the only difference is the addition of hydrogen which is produced through electrolysis. In the *Liquid and Gas Fuels Tab*, we have a *Hydrogen Section* where it is possible to define an installed capacity of electrolysers, the efficiency of the electrolysers and the hydrogen storage capacity.

EN-H2 considers a large installation of electrolyser capacity, making it the most relevant form of hydrogen production compared to reforming, gasification and others that are not important for this energy system modelling. The electrolysers use electricity from variable renewable energy from solar PV and dedicated wind, so this modelling becomes more interesting from the point of view of the power system. [11]

In this work we will not consider hydrogen storage because, according to the defined strategies, the most relevant use of hydrogen in 2030 energy systems will be its use in industry, only a small part will be in the transport sector, and there are no estimations for storage. Hydrogen in 2030 mobility will indeed be a very small fraction, but greater hydrogen consumption in this sector is expected beyond that date, so it could be pertinent to already add it to a 2030 simulation. [81]

Hydrogen is included in the industry in cogeneration as natural gas because it would be considered an alternative to the electrification of the industry. Many industrial processes are heat generation processes, and therefore hydrogen can be used as an alternative to natural gas (or injected into the natural gas network, mixing the two of them), and thus maintain some processes, but using a renewable source. [11]

Following the definition of the electrolyser capacity in the model, it is necessary to explain how the primary energy is defined in these simulations. In the *Industry and Other Fuel Consumption*

Tab (industry's primary energy), the hydrogen is defined here not only with a value that describes its consumption by the industry but also with an hourly distribution.

As mentioned before, the documents of the national plans for 2030 from both Portugal and Spain present the estimated values of the installed capacities and production of the technologies that will be part of the energy system of these countries, and the documents of the respective strategies for hydrogen give us the information to simulate these systems with new technologies of production and consumption of hydrogen. This hydrogen strategy document on the part of the Portuguese case also presents new installed capacities and productions of all the technologies in this new system with the integration of hydrogen as an update of PNEC 2030 with the addition of hydrogen.

In this work, it has also been said that we considered the PNEC 2030 for the Portuguese main future model and the PNIEC 2030 for the Spanish and added only the information related to hydrogen taken from the respective strategies. The reason why we considered this methodology is because the document of the Spanish hydrogen strategy does not mention new values of installed power and estimated production and because making two different models would not allow a direct comparison of the simulations with and without hydrogen to understand how hydrogen can influence future power systems.

Nevertheless, the data in the PNEC 2030 and the EN-H2 do not show great differences, albeit providing useful information for the dedicated solar PV and wind power to produce green hydrogen through electrolysers. These dedicated powers – 2640 MW of solar PV and 2200 MW of wind power – are just a part of the capacities of these technologies already considered when the installed capacities of the VRES are defined, so we can consider that in the simulation of the PNEC 2030 and of the PNEC 2030 integrated with the EN-H2, we have the same installed capacities of the VRES, but in the second model, part of it is reallocated to hydrogen production. [11] As the EnergyPLAN cannot differentiate these capacities and since their destination here is mostly for consumption in industry, in the *Industry and Other Fuel Consumption* tab, we have associated an hourly distribution to the hydrogen consumption to be able to manipulate its origin and time of production.

Hydrogen consumption occurs in the hours of excess production of solar PV and wind energy inducing the electrolysers to produce precisely using this excess electricity. For this reason, a hydrogen production distribution was created for each of the countries based on the 2017 solar PV and wind production distributions, and the dedicated powers of these technologies to produce electricity to supply electrolysers. These distributions are calculated according to Equation 3.1.

$$Eletrolysers\ production_i = \frac{P_{dedicated\ PV} \times norm\ PV_i + P_{dedicated\ Wind} \times norm\ Wind_i}{P_{dedicated\ PV} + P_{dedicated\ Wind}} \tag{3.1}$$

where $P_{dedicated\ PV}$ and $P_{dedicated\ Wind}$ represent the solar PV and wind dedicated capacities, and $norm\ PV_i$ and $norm\ Wind_i$ represent the successive values of the normalized distributions of solar PV and wind respectively.

In the EN-H2 hydrogen production/consumption balance, we can see that a large part of the hydrogen produced is destined for export, but EnergyPLAN by default does not produce hydrogen for export from the electrolysers, so it is important to consider that the hydrogen produced in the model is consumed by the system itself, and this can be considered as a limitation of this model. [11]

Contrary to what was done for the models in the present, the consumption values of the estimated systems documents are not those we introduced in the model because we now have two values of electricity consumption: the total electricity consumption of the system and the electricity consumption in the transport sector (in Table 3.16 in Section 3.4.1). The documents provide the total electricity consumption and to introduce this into the model we need to subtract the electricity consumption by the transport sector from this value. By introducing this new consumption, EnergyPLAN will automatically add it to the electricity consumption for transport resulting in the total electricity value given in the documents.

The charging strategy considered according to the RMSA 2019 was a combination of direct and smart charging, which in EnergyPLAN are defined respectively as *Electricity (Dump Charge)* and *Electricity (Smart Charge)* in the *Transport Tab*. When we run the model, the model assumes *Smart Charging* as *V2G Charge* and *Direct Charging* as *Flexible Electricity*. This makes sense and is part of the reason for separating this electricity consumption from the total electricity because this demand works as flexible consumption for the system.

When the estimated values for hydropower production were defined in the future simulations, it was assumed that the run-of-river production was as for the calibration models (present) for each country. This is because the plans for 2030 do not distinguish between run-of-river production from hydropower production in dams. The value of installed capacity and current run-of-river production was then subtracted from the expected total hydropower production, to define the installed capacity and production by dams.

EnergyPLAN sees the power system as if it had one dam, but with a very large capacity and supply, since it only defines the total installed capacity, the total value of water supply and the value for storage in a reservoir. For this reason, 1 TWh of pumped storage capacity was introduced in the model. This value is not a real value, but a value high enough to indicate to the model for this technology to operate, not creating any error, because it is not a fixed value, but an adjustable value depending on the balances that are made in the modelling and not user-controllable.

The definition of exchanges between Portugal and Spain in the models that portrayed the systems in 2017 and 2018 were easy to define since these values were known and therefore were imposed on the model. This part is open in the models where we simulate the future, and we only introduce the expected transmission line capacity according to the plans for the two countries. So, it is necessary to understand the exchanges of electricity obtained by EnergyPLAN, because the model here calculates the energy that the system needs to import and export at the end of the balances made considering all the production and consumption technologies previously introduced. Imports are easy to interpret on their own, but exports are given in two ways: the critical excess electricity production (CEEP) and the excess exportable electricity production (EEEP).

The same happens with the capacity of the transmission line, being the one that we introduce in the model the transmission line that allows passing a certain amount of electricity that will be considered exportable, and if there is an excess of energy that is not exportable is considered a critical excess. EEEP is the transmission line capacity introduced in the model as it is forecast from Portugal to Spain, and CEEP is the necessary increase in the transmission line so that all excess electricity is exportable.

Due to the way energy balances are made in EnergyPLAN, defining the transmission line capacity in future models is required to correctly simulate these energy systems. Limiting transmission line capacity causes the model to reduce its need for import and export by changing the way it does storage (although in this analysis we had already concluded that storage modelling should not be considered) and have an impact on the productions obtained by some technologies. For this reason, after imposing the expected transmission line value, and obtaining the value by which the line must increase for all excess electricity to be exportable, we then introduce the new capacity required by the interconnection.

Since Portugal only has its interconnection with Spain, understanding this for the Portuguese system is simple, however, it must be said that because Spain has more than one interconnection, this part of the study is much more complex and will be explained in the next section on the Spanish system.

3.3.2 Spain 2030

The modelling of the Spanish future system was done essentially in the same way as the Portuguese, to maintain the consistency of the methodology carried out in this work. In the same way, here we have the estimated data for the Spanish energy system for the future according to the PNIEC 2030, and for cases in which we intend to model the future Spanish system with the introduction of hydrogen technologies, we add the measures that are defined in the hydrogen strategy document for Spain analogous to the EN-H2, the *Hoja de Ruta del Hidrogeno*.

The assumptions for hydrogen production in Spain are largely the same as those for Portugal but applied to the scale of the Spanish energy system. The *Hoja de Ruta del Hidrogeno* also considers the production of hydrogen mostly from renewable sources, although it also considers production from fossil fuels and biomass. For this work, as it is a simulation of energy systems with a high penetration of renewables for 2030, aiming at the sustainability and decarbonization of the systems, we will only consider the production of hydrogen from the electrolysis of water using electricity from renewable sources, because that is how we simulate the Portuguese systems and it is also expected that electrolysis will be the most relevant method for hydrogen production.

The usefulness of hydrogen as a storage technology is mentioned for the hours of excess renewable production, but no concrete value of estimated storage capacity is given and therefore it was not considered here either. Storage in EnergyPLAN works based on assumptions quite different from real energy systems and therefore we cannot consider the storage values given in the model output as reliable for future modelling. As the model considers that the hydrogen produced cannot be exported but only used for the system's consumption, and as it is in the plans of both Spain and Portugal that exportation is one of the estimated destinations of hydrogen, we will always have this limitation that will also affect the storage capacity. This hydrogen strategy also refers to the introduction of green hydrogen in industrial processes that involve heat due to its high calorific value, as is the case with processes such as gasification and fusion and where hydrogen was already used but produced from non-renewable sources. The strategy states that hydrogen will represent 25% of the industry load. [12]

For mobility, the use of hydrogen is in the form of fuel cell vehicles (FCEV) and battery fuel cells (FCHV), to be used in road, rail, maritime and aviation transport. Although these uses of hydrogen in the transport sector are defined in the strategy, no concrete estimated value of consumption for hydrogen is given and therefore had to be estimated.

The strategy gives us some objectives to meet in hydrogen mobility, namely, the creation of 100 to 150 hydrogen filling stations, 150 to 200 FCEV buses, 5000 to 7500 light and heavy FCEV vehicles to transport goods and the creation of 2 hydrogen-powered train lines. With this information, we were only able to model road transport, but that was also the goal because the Portuguese model was only considered road transport too. For this reason, we only estimate the hydrogen consumption in transport based on the buses and light and heavy vehicles that are expected to exist. [12]

The estimate made was quite simplistic, presenting some limitations. In the PNIEC 2030 there is an estimated value for the total energy consumption in the transport sector of about 337.9 TWh/year [4] since the number of FCEV vehicles foreseen is given in the hydrogen strategy and knowing the total number of vehicles circulating in 2030, we can discover what percentage of these use hydrogen as fuel, and thus know what their percentage of consumption is in total transport consumption.

It was assumed that the total number of vehicles circulating in Spain in 2030 will be the same as in 2020 because the average lifetime of use of a vehicle is longer than the time left to reach 2030, and therefore we can consider that the car park will be similar to what it is today. In 2020, around 24.6 million passenger vehicles were registered in Spain, making it one of the European countries with the largest car fleet. [82] This value does not include buses and heavy vehicles, and if it did, it would be much higher than this and would cause the proportion of hydrogen in the final consumption of transport to be lower than that calculated using this value. Considering 200 FCEV buses and 7500 FCEV vehicles, their consumption is only 0.03% of transport consumption, which means, 0.101 TWh/year.

In terms of installed capacities, the main differences between the Portuguese and Spanish systems are the existence of nuclear energy in Spain (as in the present models), PNIEC 2030 considering battery storage in addition to hydro pumping and the fact that Spain has interconnections with more than one system.

It is known from the calibration models that the modelling of the Spanish systems is more complex in terms of import and export balances, and transmission line capacity required, as it is interconnected not only to Portugal, but also to France, Morocco and Andorra. Initially were considered as an input in model, only the transmission line capacity that Spain has with the Portuguese system, but then, to study the full potential to exports, the sum of EEEP and CEEP (the interconnection needed to let all the export energy to pass) is introduced in the simulation. In the Spanish system, when its considered the maximum potencial of interconnection, there is no destinction of the increase of capacity of each country.

In the next section, it is intended to analyze these results and compare them to the national Spanish plans. After the main models that represent the measures estimated in the PNIEC 2030 and the hydrogen strategy are well defined, it is important to understand what differs from the estimated, the reason behind inconsistencies and assess what is solid enough to say that what is obtained makes total sense with the plans and is likely to happen in the future operation of this power systems.

3.4 Results and Discussion of the 2030 power systems simulated models

In this section are presented the results obtained from the simulation explained in detail in Section 3.3. In this part is also discussed the differences between the data from the output models, and the numbers estimated by the Portuguese and Spanish plans for 2030.

From the data obtained it will be also discussed the impact of the introduction of hydrogen in the systems and the influence of interconnections and vary some other factors in these models to understand if there will eventually be any solution that contributes for greater efficiency and flexibility of systems or the achievement of more ambitious targets than anticipated. Therefore, in this section, we will divide the discussion of the results into the three parts that we intend to analyze, for earch system.

3.4.1 Portugal 2030 Results

The values for energy consumption, primary energy estimated according to PNEC 2030 and PNEC 2030 with EN-H2, in comparison to the values obtained as and output of the model, are shown in Table 3.16. Table 3.17 shows the installed capacities of the planned production units, such as storage by water pumping, the transmission line capacity and the minimum operating power of the plants imposed by the model.

Table 3.16 – EnergyPLAN input and output for PNEC 2030 and PNEC with EN-H2 models: Electricity demand, transport demand, import balance and primary energy. [2,80,53,83,79]

[TWh/year]	PNEC 2030 estimated values	PNEC 2030 model output	PNEC 2030 with EN-H2 estimated values	PNEC 2030 with EN-H2 model output
Electricity Demand	N.A. [xxvii]	57.85	N.A.	57.85
Transport Demand (EV)	7.3	5.91	7.3	5.91
Total Electricity Demand	65.15	65.15	65.15	65.15
Direct Charging	0.73	0.73	0.73	0.73
Smart Charging	6.57	6.57[xxviii]	6.57	6.57
Hydrogen in Transport	N.A.	N.A.	0.444	1.91
Primary Energy				
Industry				
Coal	0	0	0	0
Oil	0.3	0.3	0.3	0.3
Natural gas	14.2	14.2	14.2	14.2
Biomass	1.4	1.4	1.4	1.4
Hydrogen	N.A.	N.A.	0.989	0.99
Power plants				
Coal	0	0	0	0
Natural gas	25.4	18.64	25.434	20.07

[xxvii] Not Applicable.

[xxviii] The model does not distinguish direct from smart charging, only from charge, discharge and flexible electricity. This value indicates V2G charge.

Table 3.17 – EnergyPLAN input for PNEC 2030 and PNEC with EN-H2 models: Installed capacities, transmission line capacity. [2,79,51,54]

[MW]	PNEC 2030 estimated values	PNEC 2030 with EN-H2 estimated values
Power Plants		
Natural gas	3300	3300
Dam hydro	6142	6142
Eletrolysers	N.A.	2200
Variable Renewable Energies		
Wind	9300	9300
Solar PV	9000	9000
Run-of-river hydro	2590[xxix]	2590
CSP	300[xxx]	300
Hydro pumping storage	3850	3850
Transmission line capacity	3500	3500

In Table 3.18 are the output final energy values in comparison to the PNEC and EN-H2 estimated values.

Table 3.18 – Production of power plants and variable renewable energy sources for PNEC 2030 and PNEC with EN-H2 models obtained from the output given by EnergyPLAN compared to the known estimated values. [2,79,54]

Final Energy [TWh/year]	PNEC 2030 estimated values	PNEC 2030 model output	PNEC 2030 with EN-H2 estimated values	PNEC 2030 with EN-H2 model output
Power Plant Production				
Natural gas power plant	15.38	9.69	15.38	10.43
Dam hydro	13.209	13.21	13.209	13.21
Industrial CHP				
Electricity produced	6	6	6	6
Variable Renewable Energy				
Wind	22.1	22.1	22.1	22.1
Solar PV	16.5	16.5	16.5	16.5
Run-of-river hydro	3.491	3.5	3.491	3.5
CSP	1.5	1.5	1.5	1.5
Consumption of pumps	1	1.45	1	1.11

Table 3.19 shows the estimated values for exchanges between Portugal and Spain in the perspective of Portugal for 2030 according to the PNEC, and the same values, but obtained from the balances made by the model. The export values shown in Table 3.19 are the values limited by the capacity of the transmission line introduced.

[xxix] The value placed in the model for the estimated installed power of run-of-river in 2030 was adjusted to, without using the distributions correction factor, introduce the correct production in the model. The optimized value was 635 MW.

[xxx] The same was done for the CSP, considering in the model the installed power of 212 MW.

Table 3.19 – Import and export for PNEC 2030 and PNEC with EN-H2 models obtained from the output given by EnergyPLAN and compared to the estimated values, critical excess electricity production (CEEP) and exportable excess electricity production (EEEP) given by the model. [4]

	PNEC 2030 estimated values	PNEC 2030 model output	PNEC 2030 with EN-H2 model output
Import [TWh/year]	13.376	1.42	1.57
Export[xxxi] [TWh/year]	1.184	8.15	7.29
CEEP [MW]	N.A.	6596	5986
EEEP [MW]	3500	3500	3500
Required Interconnection [MW]	3500	10096	9486

Table 3.20 shows the new output values of the models after switching to the interconnection required by the model (i.e., the sum of the CEEP transmission line with the EEEP transmission line) and realizing specifically what varies when allowing all the exports to be effectively exportable. The values shown in the table are those that have changed with the new interconnection value, side by side with the previous values for a better comparison. All other variables in the power system that are not represented in the table remained unchanged.

Table 3.20 – New model values when the required interconnection is introduced in the PNEC 2030 and PNEC 2030 with EN-H2 models.

	PNEC 2030 model ouput	New PNEC 2030 model output	PNEC 2030 with EN-H2 model output	New PNEC 2030 with EN-H2 model output
Primary Energy [TWh/year] Natural gas power plant	18.64	20.37	20.07	21.39
Final Energy [TWh/year] Natural gas power plant	9.69	10.59	10.43	11.12
Consumption of pumps [TWh/year]	1.45	0.02	1.11	0.02
Exchanges				
Import [TWh/year]	1.42	1.43	1.57	1.58
Export [TWh/year]	8.15	9.66	7.29	8.45
CEEP [MW]	6596	12	5986	0
EEEP [MW]	3500	10096	3500	9486

After running the PNEC 2030 model with the new transmission line capacity, a non-zero CEEP value was still created, but it is very low and can be considered close to zero. This value does not influence the effect we want by giving to the model all the capacity of interconnection it needs to export all the excess electricity.

Table 3.21 shows the percentages of renewables in primary energy and in electricity, as well as total renewable generation, given as an EnergyPLAN output in the modelling of PNEC 2030 systems with and without EN-H2, and considering the different capacities of the transmission line.

[xxxi] The exports in this table refer to those that are effectively exported through the imposed transmission line capacity (EEEP).

Table 3.21 – Share and total generation of renewable energy sources in the Portuguese system for the PNEC 2030 and PNEC with EN-H2 models.

	PNEC 2030 model output	New PNEC 2030 model output	PNEC 2030 with EN-H2 model output	New PNEC 2030 with EN-H2 model output
RES share [%]				
On primary energy	63.7	62.5	61.9	62.7
On electricity	85.3	87.2	84.7	83.3
Renewable generation [TWh/year]	56.8	56.8	56.8	56.8

3.4.1.1 PNEC 2030 estimated values *versus* EnergyPLAN output

The discrepancies between the PNEC 2030 data and the EnergyPLAN output show that with the imposed values, the balances made by the model essentially produce differences regarding the consumption of electric transport, the electricity production from natural gas power plants, storage, in exchanges with the outside world and the capacity of the transmission line.

It is important to remember that the production of renewable energy is imposed in the model by the user as it is introduced, in addition to the planned installed capacities, and the hourly production profiles. Therefore, renewable technologies generation is fixed and non-renewable production, storage and exchanges with external systems will vary according to the balances made by the model to be able to meet the consumption of the systems.

The main difference between the estimated values and those obtained refers to the production of electricity through natural gas power plants and the consumption of natural gas in primary energy. PNEC 2030 estimate 15,39 TWh/year of natural gas electricity generation by cogeneration, 25.4 TWh/year of natural gas in primary energy.

Everything indicates that the value obtained by the EnergyPLAN (9.69 TWh/year), is an acceptable production considering the natural gas estimated in the primary energy and taking into account the role that natural gas power plants will have in the future in the mid-term of 2030 towards achieving system decarbonisation by 2050.

Due to the difficulty in modelling the storage, we will only consider its tendency to increase or decrease, and not its magnitude. In the way EnergyPLAN considers storage operation, here we can say storage increases in simulation output compared to the estimated model because a greater need for non-renewable production means that the system will have a greater need to store electricity as well.

Regarding system exchanges, the differences between the PNEC 2030 data and the data obtained by the output are relevant (Table 3.19). The behaviour of exports and imports is practically symmetric, indicating that in the PNEC 2030 the system is seen as an importer while EnergyPLAN modelling suggests an exporting character. This result makes sense because the introduction of large solar power planned for 2030 due to Portugal's great potential for solar production could lead to excess production at solar noon that will be exported. Figure 3.8 is the graphical representation of two weeks in the 2030 model output by EnergyPLAN. On the left, we have a typical winter week (the first week of the year), and on the right, we have a typical summer week (the first week of July).

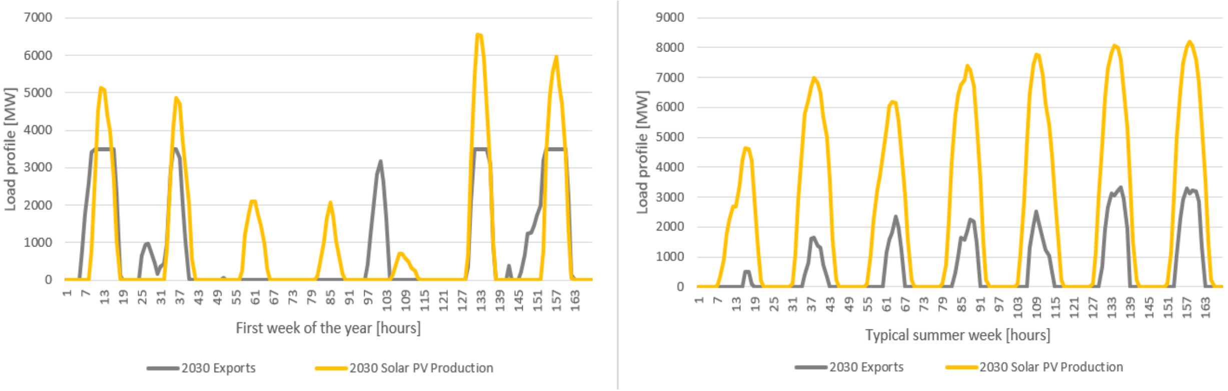


Figure 3.8 – Load diagram of exports (in grey) and solar PV production (in yellow) in a typical winter week (left) and a typical summer week (right), obtained from the model output.

The load diagrams confirm that the exports take place at the peak of solar PV production, which means that this type of production will be the most responsible for the country's exports, especially in the summer months when there will be less wind production, but essentially less hydropower production.

Finally, the data estimated by the PNEC 2030 aim to reach 80% of renewables in electricity and 47% renewables in final energy consumption by the end of 2030. The simulation in the EnergyPLAN according to the data from the PNEC 2030 results in a system with 85.3% of renewables in electricity and 77.4% of renewables in final energy.

3.4.1.2 Integration of EN-H2 in the PNEC 2030 power system simulation

The integration of the hydrogen strategy (EN-H2) in the simulation of the PNEC 2030 model causes changes in the production of electricity in natural gas power plants and the consequent consumption of this resource in primary energy, storage, in the exchanges of the system with the outside and the transmission line capacity.

As the hydrogen introduced in EnergyPLAN is only destined for production and consumption within the system itself, and it is not possible to produce hydrogen for export, this model ends up considering a hydrogen strategy a bit different from that provided in EN-H2. For this reason, the introduction of hydrogen works as an extra consumption in the system, and, although it is produced by renewable sources, part of this renewable production introduced by the user and fixed, is only reallocated to the production of hydrogen, and compensated in the power systems increasing the production of natural gas power plants. Although the increase in fossil production is undesirable, this increase translates to only 0.74 TWh in a year, so it is necessary to assess the dimension of the benefits in the whole energy system.

One of these advantages is the reduction in storage, which indicates that the introduction of hydrogen reduces consumption by hydro pumping and that this may be an indication of its contribution to the flexibility of the system. However, from Table 3.19 we conclude that imports increase slightly, and exports decrease. This is due to the decrease in renewable production since part of it is now dedicated to hydrogen production, but it also tells us, like the increase in non-renewable production, that the hourly distribution created to manipulate the production of electrolysers in the hours of excess renewable production, uses that excess, and renewable production that is not system excess, but electricity needed to meet the system consumption. The decrease in exports decreases the value of the required transmission line capacity, but we cannot conclude that this will be true in the real energy system due to hydrogen not being produced in this model for exports, and because of that it is likely that in reality, the production of hydrogen involves an increase in the transmission line.

In the simulations where the integration of the hydrogen strategy is considered, the percentages of renewables in the system decrease compared to simulations without hydrogen, but even so, they are higher than those estimated in the PNEC 2030.

3.4.1.3 Influence of the total required interconnection

The increase in the transmission line capacity for the interconnection necessary for all exports to be exportable through the line produces differences in terms of electricity production in natural gas power plants, storage and system exchanges.

The increase in electricity production in natural gas power plants indicates that the model produces electricity from fossil sources for export, which is considered undesirable in a system with high renewable penetration, in which the objective is renewable export, complementing systems with other characteristics and consequent renewable generation with different hourly profiles. It is possible to associate the production of natural gas power plants with the increase in exports because both parameters increase on a similar scale.

Storage tends to decrease with the increase of interconnection because the model assumes that the system decreases its need to store, not because of imports since the increase in imports is very low and can be considered irrelevant, but because of the increase in production of natural gas power plants.

The most relevant result of this part is the estimated transmission line capacity being possibly undersized in relation to the output of the simulations made here.

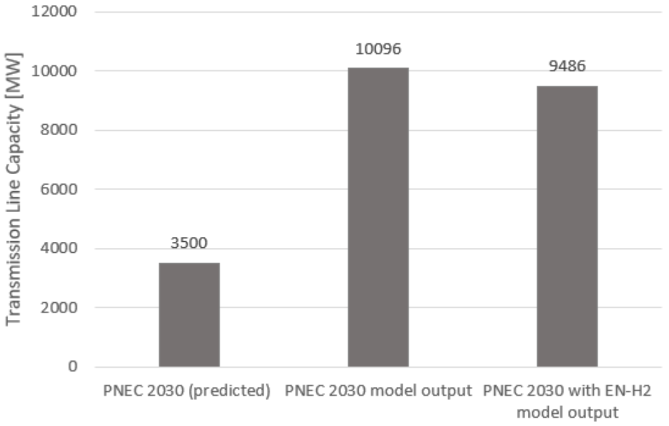


Figure 3.9 – Transmission line capacities required by the model to pass all exportable electricity in the PNEC 2030 simulation models with and without EN-H2, compared to estimated interconnection capacity.

The results of the simulations carried out indicate that it is necessary to increase the transmission line capacity compared to the expected in the order of 288% and 271% for the models without and with the hydrogen strategy, respectively. As already stated above, the transmission line needed is lower when is considered hydrogen integration in the system simulation.

However, these values of the transmission line capacity may not be enough to suggest an increase of this capacity compared with the estimate for 2030. These values obtained are based on the total capacity that the transmission line needs to allow all the excess energy to be exported, taking into account the export peaks that may occur sporadically.

As it is not feasible to build the transmission line to deal with sporadic peaks, that not represent the majority of exports flows, the hourly distributions of 2030 exports provided by the programa were analyzed to remove this export peaks. For the Portuguese energy system according to PNEC 2030 with the EN-H2, the transmission line capacity estimated of 3500 MW is enough deal with 97% of the export energy. This allow us to conclude that the estimated transmission line it's well sized considering the modeling done in EnergyPLAN.

3.4.2 Spain 2030 Results

Table 3.22 shows the data on the values of electricity consumption, consumption in the transport sector and primary energy in the system provided for by PNIEC 2030 and PNIEC 2030 with the hydrogen strategy for Spain, as well as the output obtained by the simulations made in EnergyPLAN.

Table 3.22 – EnergyPLAN input and output for PNIEC 2030 and PNIEC with Spanish hydrogen strategy models: Electricity demand, transport demand, import balance and primary energy. [4,53,12]

[TWh/year]	PNIEC 2030 estimated values	PNIEC 2030 model output	PNIEC 2030 with H_2 strategy values	PNIEC 2030 with H_2 strategy model output
Electricity Demand	N.A.	244.619	N.A.	244.619
Transport Demand (EV)	18.081	14.65	18.081	14.65
Total Electricity Demand	262.70	262.70	262.70	262.70
Direct Charging	1.808	1.81	1.808	1.81
Smart Charging	16.273	16.27	16.273	16.27
Hydrogen in Transport	N.A.	N.A.	0.101	8.73
Primary Energy				
Industry				
Coal	16.372	16.37	16.372	16.37
Oil	0	0	0	0
Natural gas	83.744	83.74	83.744	83.74
Biomass	0	0	0	0
Hydrogen	N.A.	N.A.	6.28	6.28
Power plants				
Coal	0	0	0	0
Natural gas	48.59	49.99	48.59	59.35

Table 3.23 shows all the planned installed capacities that were introduced in the model from the PNIEC 2030 model with and without the addition of hydrogen technologies.

Table 3.23 – EnergyPLAN input for PNIEC 2030 and PNIEC with the Spanish hydrogen strategy models: Installed capacities and transmission line capacity. [4,12,64]

[MW]	PNIEC 2030 estimated values	PNIEC 2030 with H_2 strategy estimated values
Power Plants		
Natural gas	24560	24560
Dam hydro	22400	22400
Nuclear	3050	3050
Eletrolysers	N.A.	4000
Variable Renewable Energies		
Wind	48550	48550
Solar PV	38404	38404
Run-of-river hydro	1740[xxxii]	1740
CSP	7300	7300
Hydro pumping storage	7890	7890
Batteries storage	2500	2500
Transmission line capacity	4200	4200

As in Section 3.4.1 referring to the Portuguese system, Table 3.24 shows the estimated production values side by side with the EnergyPLAN output from the PNIEC 2030 model without the hydrogen strategy and with the hydrogen strategy, for comparison. Here we also have, in addition to the Portuguese system, the nuclear power plants' production and the consumption of battery storage. As mentioned before, the values related to this consumption are not reliable because we are not able to manipulate the model regarding the storage operation strategy.

Table 3.24 – Production of power plants and variable renewable energy sources for PNIEC 2030 and PNIEC with the Spanish hydrogen strategy models obtained from the output given by EnergyPLAN compared to the known estimated values. [4,57]

Final Energy [TWh/year]	PNIEC 2030 estimated values	PNIEC 2030 model output	PNIEC 2030 with H_2 strategy estimated values	PNIEC 2030 with H_2 strategy model output
Power Plant Production				
Natural gas power plant	27.617	26.00	27.617	30.87
Dam hydro	28.468	28.47	28.468	28.47
Nuclear	22.034	22.17	22.034	22.39
Industrial CHP				
Electricity produced	18.399	18.40	18.399	18.40
Variable Renewable Energy				
Wind	109.464	109.46	109.464	109.46
Solar PV	65.18	65.18	65.18	65.18
Run-of-river hydro	3.908	3.91	3.908	3.91
CSP	19.785	19.79	19.785	19.79
Consumption of pumps	1	18.5	1	16.7
Batteries	13.782	3.8	13.782	3.32

Table 3.25 presents the expected values of imports, exports and capacities of the transmission line between Spain and the systems to which it is interconnected, with no exchanges with Andorra and Morocco in 2030 (no longer having a transmission line with Andorra but maintaining 900 MW with Morocco).

[xxxii] The value placed in the model for the estimated installed power of run-of-river in 2030 was adjusted to, without using the distributions correction factor, introduce the correct production in the model. The optimized value was 1090 MW.

Table 3.25 – Imports, exports, and transmission line capacities estimated according to PNIEC 2030, between Spain and the external systems to which it is interconnected. [4]

	Import [TWh]	Export [TWh]	Estimated Interconnection Capacity [MW]
Portugal	1.184	13.376	4200
France	7.339	34.464	8000
Marroco	0	0	900
Total	8.523	47.84	13100

Considering the various interconnections and exchanges estimated, and knowing that in this model we introduce as transmission line capacity only the one between Spain towards Portugal, the values from Table 3.26 present the estimated values of exchanges between these two systems and the ones taken as the model output.

Table 3.26 – Import and export for PNIEC 2030 and PNIEC with the Spanish hydrogen strategy models obtained from the output given by EnergyPLAN compared to the estimated values, critical excess electricity production (CEEP) and exportable excess electricity production (EEEP) given by the model.

	PNIEC 2030 estimated values	PNIEC 2030 model output	PNIEC 2030 with H_2 strategy model output
Import [TWh/year]	1.184	0.01	0.02
Export [TWh/year]	13.376	14.89	13.87
CEEP [MW]	8900	39337	36742
EEEP [MW]	4200	4200	4200
Required Interconnection [MW]	13100	43537	40942

The exports here are those considered exportable (EEEP), as they pass through the transmission line to Portugal, but we have a very high value of CEEP in the transmission line. This CEEP is the transmission line capacity necessary for all the electricity that can be exported to be exportable. When we have this large value, we know from the outset that the exports possible through the Spanish system are much higher than those that are exportable in this model. This is because we are only considering the interconnection with Portugal, leaving all exports destined for France as curtailment, as the capacity of the line between Spain and France is not considered.

To model the Spanish system and understand the implications of considering the total exchanges that this system has with the external systems to which it is interconnected, we created new models as was done in Section 3.4.1 for the Portuguese system which we introduced as the transmission line capacity, the required line capacity that is in Table 3.26 (the sum between the EEEP and the CEEP capacity) given by the output of the previous models.

Table 3.27 presents the values where the model output differed when introducing these new interconnection capacities. It should be noted that in both the Spanish and Portuguese systems, the change in the transmission line influenced the same system parameters.

Table 3.27 – New model values when the required interconnection is introduced in the PNIEC 2030 and PNIEC 2030 with the Spanish hydrogen strategy models.

	PNIEC 2030 model output	New PNIEC 2030 model output	PNIEC 2030 with H_2 strategy model output	New PNEC 2030 with H_2 strategy model output
Primary Energy [TWh/year] Natural gas power plant	50.07	80.87	59.35	86.99
Final Energy [TWh/year] Natural gas power plant	26.04	42.04	30.87	45.23
Consumption of pumps [TWh/year]	18.5	0.06	16.7	0.06
Batteries [TWh/year]	3.8	0.01	3.32	0.01
Exchanges				
Import [TWh/year]	0.01	0.02	0.02	0.02
Export [TWh/year]	14.89	48.29	13.87	42.75
CEEP [MW]	39337	0	36742	0
CEEP [MW]	4200	43537	4200	40942

In Table 3.28 are the percentages of renewables in primary energy and electricity, as well as total renewable generation, given as an EnergyPLAN output in the modelling of PNIEC 2030 systems with and without the Spanish hydrogen strategy, and considering the different capacities of the transmission line.

Table 3.28 – Share and total generation of renewable energy sources in the Spanish system for the PNIEC 2030 and PNIEC with the hydrogen strategy models.

	PNIEC 2030 model output	New PNIEC 2030 model output	PNIEC 2030 with H_2 strategy model output	New PNIEC 2030 with H_2 strategy model output
RES share [%]				
On primary energy	42.0	49.4	51.0	49.1
On electricity	74.0	87.9	79.2	85.4
Renewable generation [TWh/year]	227.0	231.0	228.2	231.8

3.4.2.1 PNIEC 2030 estimated values *versus* EnergyPLAN output

After analyzing the analogous simulations for the Portuguese system, we realized that many of the conclusions will be based on the same assumptions, but that there are also some differences between the Spanish system and the Portuguese system because they have different characteristics. This means that the differences that we observed in the Spanish system when comparing the estimated data with the model output are in the same parameters described in the section on the Portuguese system, however, the way these parameters vary differ between the two systems.

The electricity consumption in transport is lower than expected (Table 3.22), for the same reason stated in Section 3.3.2. Here too, the biggest difference is in the production of electricity in natural gas power plants. Table 3.22 shows that there is an increase in the consumption of natural gas in primary energy, as in the Portuguese system, but it produces slightly less electricity through these power plants when compared to the expected production. The increase in production while primary energy increases mean that we have some inconsistency between the efficiency of these power plants that we have introduced in the system and the efficiency considered in the plans (which we do not know). However, this difference can be considered not significant and the slightly lower production by this technology in the output of the model results from the balances made in EnergyPLAN, producing a lower need for non-renewable production compared to that obtained with the methodology used to create the PNIEC 2030.

In the Spanish system in 2030 we have batteries as a new energy storage technology. From Table 3.24, we can see that, as in the Portuguese system, hydro pumped storage tends to be higher in the simulations performed, however, battery consumption decreases compared to their consumption estimated in PNIEC 2030. This is because, in addition to all the limitations known so far in storage modelling for the systems we are studying, when introducing a new storage technology, EnergyPLAN assumes an order of merit in which the first technology introduced has priority of operation compared to the second, thus explaining such a high value for hydro pumping consumption and so low for the battery consumption.

Regarding the exchanges between Spain and the external systems, the analysis is a little more complex. By introducing a 4200 MW transmission line we are assuming only the exchanges between Spain and Portugal, so, through the data in Table 3.26 we can say that the expected imports were already quite low but the simulation gives us values close to zero with and without the hydrogen strategy. Exports to Portugal are a little higher but also considered very similar to those forecasted.

The big difference is in the required transmission line capacity obtained. In Section 3.3.2 we also saw that the capacity of the planned transmission line was quite undersized when compared to what we obtained, but in Spain, the increase is about 332% and 313% when we compare the estimated with the simulations of PNIEC 2030 and PNIEC 2030 model with the hydrogen strategy, respectively. The reasons however are different. While for the Portuguese system the increase in interconnection results from the increase in the exporting character of Portugal obtained by the model in contrast to what is expected, here the increase in interconnection is due to not taking into account the connections Spain has with other countries, namely the connections it has with France (Table 3.25). In any case, the percentages of increase are considering the interconnections with the various external systems, so one result that can be drawn from this study is that there is a significant undersizing that could limit Spain's export capacity.

Here it is not necessary to justify Spain as a system with an exporting character in 2030 because both in the plans and the model outputs obtained, this characteristic is reaffirmed.

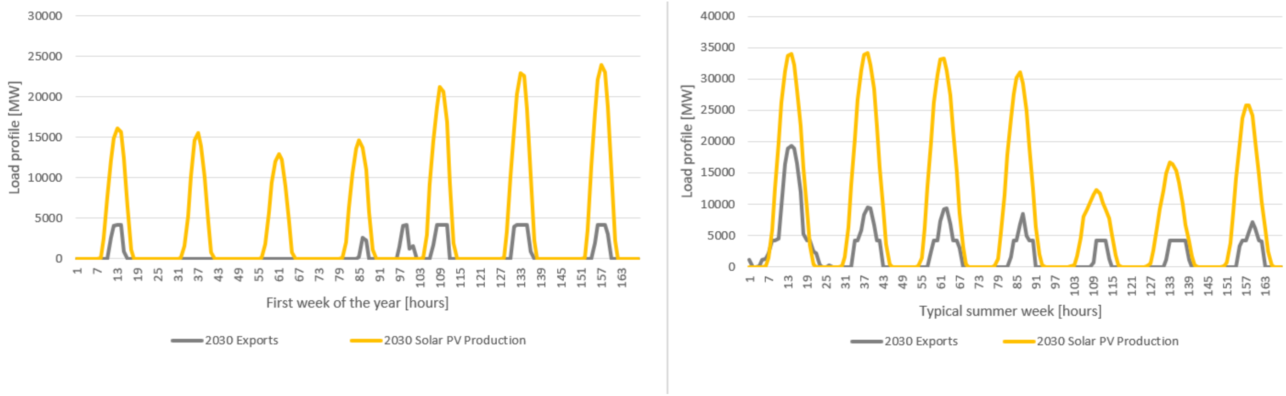


Figure 3.10 – Load diagram of exports (in grey) and solar PV production (in yellow) in a typical winter week (left) and a typical summer week (right), obtained from the model output.

Anyway, it is interesting to see in Figure 3.10 that the export peaks calculated by the model also occur in the peaks of solar PV production, indicating that this production is the main responsible for the excess for export.

Looking at the system in general and at the targets set out in PNIEC 2030 when applying the strategy described in the model to achieve 42% of renewables in final energy and 74% of renewable generation in electricity production, we conclude that outputs of 74% and 87.9% respectively, are above the expectations (Table 3.28).

3.4.2.2 Integration of the Spanish hydrogen strategy in the PNIEC 2030 power system simulation

The integration of the Spanish hydrogen strategy (*Hoje de Ruta del Hidrogeno)* in the simulation of the PNIEC 2030 causes the same variations observed in Section 3.3.2 for the Portuguese case, in the same parameters. Therefore, the conclusions drawn for the Spanish system are similar, concluding that the introduction of hydrogen in both systems influences both in the same way, regardless of the different characteristics of the power systems.

Figure 3.11 shows the data obtained for the consumption of electrolysers, hydrogen and natural gas in the industry primary energy, natural gas in the final energy of the plants and, for this system, we also have the production in nuclear power plants represented.

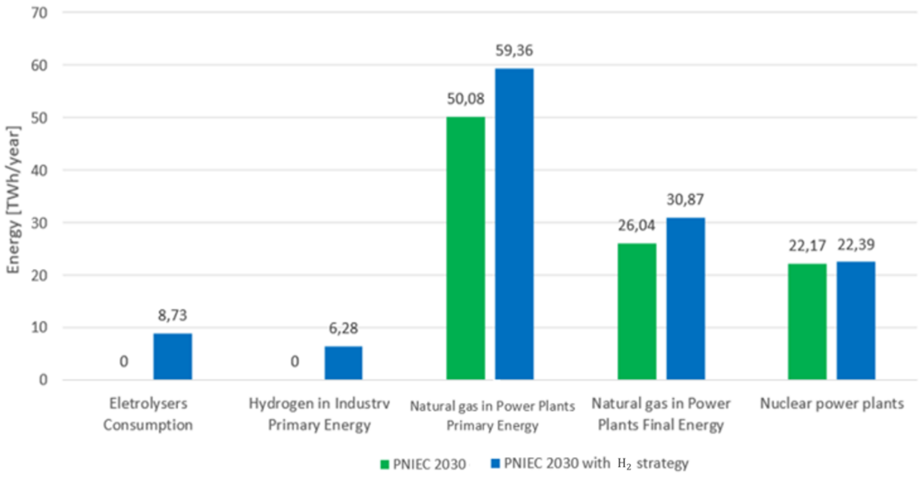


Figure 3.11 – Electrolysers consumption, hydrogen in industry primary energy, natural gas in power plants primary and final energy and nuclear power plant production for the 2030 Spanish models with and without hydrogen strategy.

From the graph, it can be concluded that the introduction of hydrogen in this system also increases the production of electricity through natural gas power plants. In Spain, we also have energy production through nuclear power plants, and as can be seen, their production increases in the system model with the hydrogen strategy. The increase in production from natural gas is more significant because, as already noted, the model uses natural gas to produce hydrogen, and because nuclear power plants are less flexible therefore the production fluctuates within a smaller amplitude.

Another characteristic that differs from the Portuguese system is that in the model of the Spanish power system according to PNIEC 2030, two storage technologies are considered: water pumping, and energy storage in batteries.

Figure 3.12 shows the values obtained for storage from the model after introducing the estimated capabilities of these technologies.

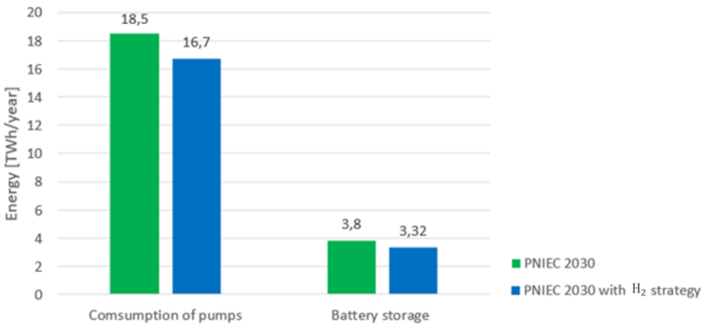


Figure 3.12 – Consumption of pumps and battery storage for the 2030 Spanish models with and without hydrogen strategy.

The previous figure shows that the introduction of hydrogen in the system reduces the need for storage (in both technologies) since hydrogen acts as a load and the system has less excess electricity from renewable sources that would be stored. In the chapter 3.5 it will be seen that the same happened in the Portuguese system but only after integration with the Spanish system.

3.4.2.3 Influence of total required interconnection

For the Spanish case, we have the same influence: the increase in the transmission line capacity for the interconnection necessary for all exports to be effectively exportable through the line, produces differences in terms of electricity production in natural gas power plants, storage and system exchanges.

The reasons for the simulations to present this behaviour are the same as those described in Section 3.3.2 about the Portuguese system in 2030. What differs here is the fact that Spain has connections with more than an external system and therefore it is necessary to analyze exchanges with the outside in a different way.

As for the Portuguese model, the interconnections are undersized. The values described above of exchanges were only related to exchanges between Spain and Portugal, but by taking a look at Table 3.25, the system is expected to import 8.52 TWh/year and export 47.84 TWh/year when considering the sum of exchanges expectations between Spain with Portugal, France and Morocco.

Analyzing Table 3.27 and comparing the simulation with the capacity of the line only with Portugal and with the capacity of the line required to pass all the potential for export, we see that exports become similar to the maximum expected from Spain with the outside as a whole, although the imports are close to zero.

Figure 3.13 allows us to look at the interconnections estimated individually for each system connected to Spain, for the total of these and to understand the dimension of the interconnection that the output taken from EnergyPLAN calculates as necessary for approximately the same exports.

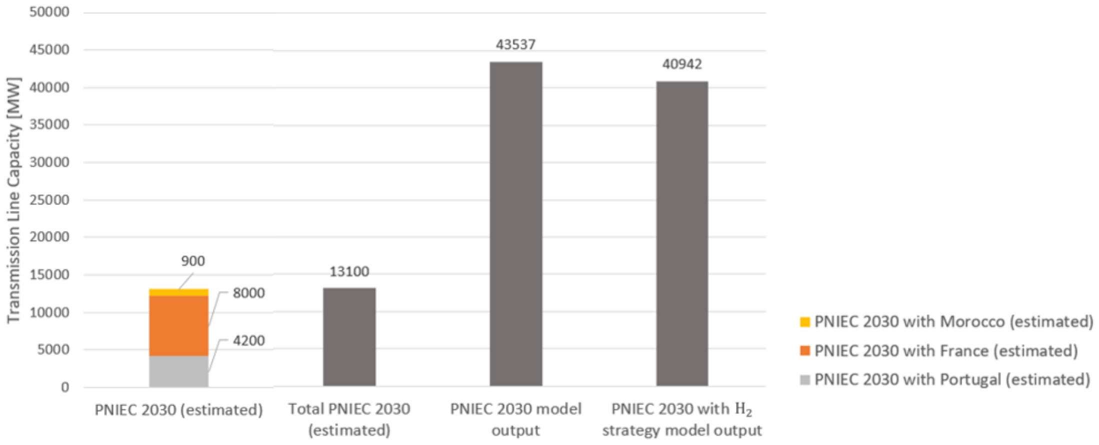


Figure 3.13 – Transmission line capacities required by the model to pass all exportable electricity in the PNIEC 2030 simulation models with and without the hydrogen strategy, compared to the total estimated interconnection capacity. The capacities of individual lines from Spain to Portugal, France and Morocco are also represented.

This result becomes even more relevant in the case of the Spanish system, where the planned interconnection may be very low, limiting the export capacity of this system to Europe.

As for the Portuguese system, were studied the export peaks in the hourly distributions obtained from the modeling of the Spanish system according to the PNIEC 2030 with the national strategy for hydrogen. In this case, the transmission line capacity estimated of 13100 MW appears to continue to be undersized, as a line capacity of 26858 MW allows 95% of the estimated exports to pass through the interconnection.

It is concluded that although the capacity of the necessary transmission line does not need to be 40942 MW, an increase of about twice that estimated is needed in the direction of Spain to external systems.

3.5 Integrated Models

The main objective of this work is to study the result of the integration of Portuguese and Spanish power systems. The PNEC 2030 and the PNIEC 2030 together with their respective strategies for hydrogen present estimates for production, consumption and exchanges between these two systems and between the Spanish system with the other systems to which it is interconnected in 2030. However, the interest in re-estimating these electricity exchanges, in addition to realizing the utility of the EnergyPLAN coupled to the Multinode tool, also involves varying some factors of these power systems and efficiently studying how they influence exchanges with the external systems.

This section also intends to study how changing some variables defined in the national plans of the countries we are studying, could bring benefits or disadvantages in terms of flexibility of systems and complementarity from the perspective of the Iberia.

3.5.1 Portuguese individual model after integration in Multinode

In Section 3.1.1, the main operating assumptions of Multinode were explained. In this section, the output of the model after the integration of Portugal and Spain will be analyzed, from the perspective of the Portuguese power system.

A new version of the Portuguese electricity system studied in the chapter 3.4 (with and without EN-H2) is taken from the model that creates changes in certain system variables due to the calculation of a new fixed balance of imports and exports between Portugal and Spain (that here we are going to name as system 1 and system 2 respectively). Through this balance, it is possible to assess the level of complementarity between the two systems and the potential for electricity exchanges.

Figures 3.14 – 3.18 show the variables of the Portuguese electricity system (with or without a hydrogen strategy) that changed when the fixed balance of imports and exports with Spain was created through Multinode. All other primary or final energy productions that are not represented here can be considered unchanged or negligibly changed.

Figure 3.14 shows changes in hydrogen and natural gas consumption for the Portugal system models before and after running them in Multinode (with and without the hydrogen strategy), thus allowing a direct comparison of the effect of the model interconnection between Portugal and Spain.

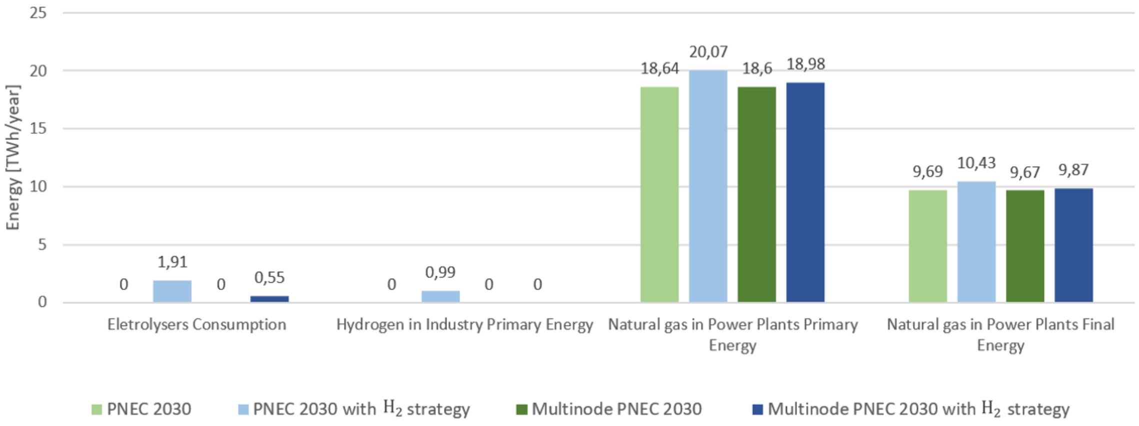


Figure 3.14 – Electrolysers consumption, hydrogen in industry primary energy, and natural gas in power plants primary and final energy for the 2030 Portuguese models with and without hydrogen strategy, before and after integration with Spain in Multinode.

One can observe that the new balance of imports and exports reduces the need for consumption of hydrogen and natural gas in both primary and final energy. After the integration of the model through the Multinode, there was no longer hydrogen in the primary energy of the industry because the model assumes that hydrogen is no longer requested to satisfy the industry's needs and all the hydrogen that was produced was also consumed by the system. The hydrogen produced by electrolysers is what is defined to be needed for the transport sector.

For natural gas, the results show that in models without EN-H2 there is no significant difference in industry primary energy and production by power plants. However, in the simulations of the system in which we consider the Portuguese hydrogen strategy, the integration with the Spanish system introduces a significant decrease in the need for natural gas in the primary energy of the industry and its production by power plants. This may mean that the hydrogen modelling could not be completely decoupled from the production in natural gas plants, although this work intended to create a distribution of hydrogen production in electrolysers that follow the production of solar PV and wind energy.

In chapters 3.2 we concluded that storage modelling in EnergyPLAN is not realistic, as it does not consider factors related to the energy market that ultimately determine whether, for example, there is energy export or storage. For this reason, analysis of storage is only performed qualitatively.

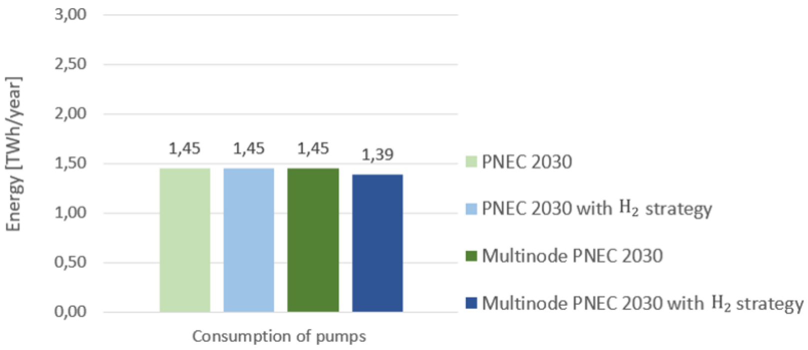


Figure 3.15 – Consumption of pumps for the 2030 Portuguese models with and without hydrogen strategy, before and after integration with Spain in Multinode.

From Figure 3.15, in Portugal's PNEC 2030 perspective, the interconnection with Spain in Multinode does not cause any difference in the need for the system to storage. This need is even the same when we introduce hydrogen into the Portuguese independent system. However, in this case, when the Portuguese model with the hydrogen strategy interconnects in Multinode to the respective Spanish system, the need for storage decreases. One would expect that interconnection with Spain should reduce storage due to the export of excess energy, regardless of the hydrogen strategies.

Figure 3.16 shows the need to import and export for the Portuguese system models, before and after integration in Multinode. The exports are divided into *Excess Exportable Electricity Production* (EEEP) and *Critical Excess Electricity Production* (CEEP). This terminology here means that the electricity considered EEEP is the one that is produced and that is exported to the external system with the transmission line that is considered (3500 MW), while the CEEP refers to the exportable electricity that cannot be exported due to the limited transmission line capacity.

Chapter 4.1 below is dedicated to the study of how changing this value alters the system's import and export capacity, and consequently can alter the systems production and consumption of resources.

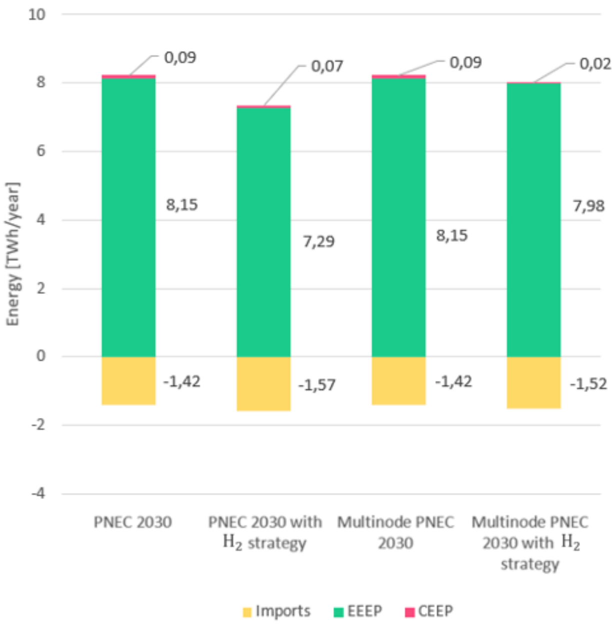


Figure 3.16 – Electricity exchanges [TWh/year] from the perspective of the Portuguese system and before and after the interconnection in Multinode with the Spanish system (systems with and without national hydrogen strategies). On the left are imports and on the right the exports with the distinction between EEEP (exportable excess) and CEEP critical excess).

From fig. 3.16, it is possible to see that the system without hydrogen does not present any differences in the exchanges with the outside when it is interconnected in Multinode, while in the system with the hydrogen strategy there is a small decrease in imports and an increase in exports.

This leads to the conclusion that there is a clear bond between the introduction of hydrogen and the increase of flexibility of the system. It is known that the model does not consider hydrogen for export, thus this increase in exports is not due to the export of hydrogen directly, but to its use to create an excess of (renewable) exportable.

It is important to note that in exports, the introduction of hydrogen causes the CEEP to decrease, but this decrease is lesser than the increase if the EEEP, increasing net exports.

Figure 3.17 represents the required interconnection capacities obtained in the Portuguese system perspective. In yellow is represented the line capacity for Portugal to import electricity (i.e. in the direction of Spain to Portugal). In blue we have the transmission line capacity necessary for Portugal to export all the electricity that it can export to Spain.

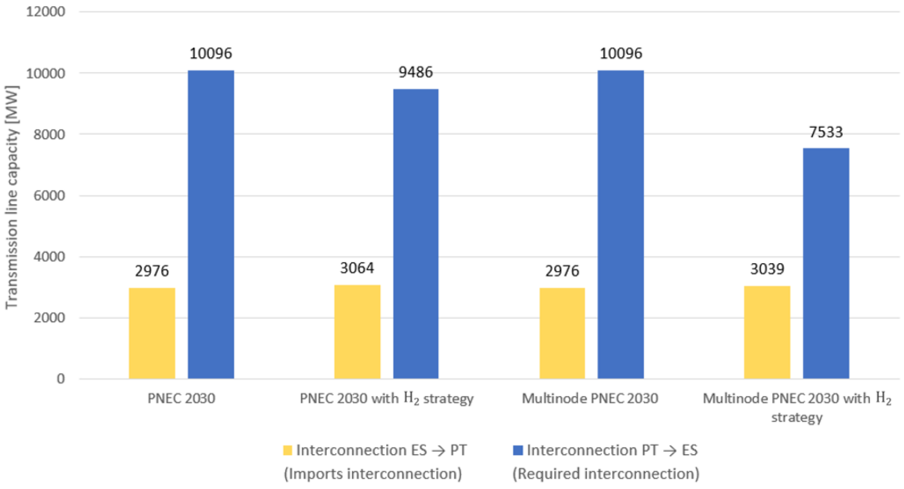


Figure 3.17 – Transmission line capacity [MW] obtained by EnergyPLAN modelling calculations, before and after the connecting the systems in Multinode, from the perspective of the Portuguese system.

Figure 3.18 shows the transmission line capacity required from Portugal to Spain divided by the fractions of what corresponds to the exportable in these models (EEEP) and to the critical excess (CEEP), that is, the one that needs to be increased for which the system model according to its production potential, would be able to export. In other words, the sum of the transmission line capacities related to EEEP and CEEP represented in Figure 3.18 results in the blue bars of required interconnection from Portugal to Spain in Figure 3.17.

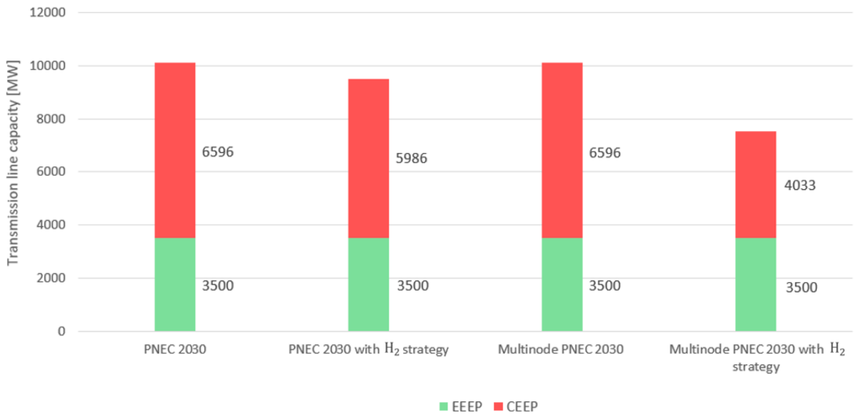


Figure 3.18 – Transmission line capacity that is required to pass all electricity, divided into exportable (EEEP) and critical (CEEP).

As has been observed with all system variables related to storage and exchange of electricity, the interconnection of the Portuguese system in the Multinode also does not cause changes in the capacity of the transmission line. It is observed that for both before and after the Multinode, this system reaches its maximum export potential with the increase of the interconnection to 10096 MW.

Looking only at the Portuguese models with the incorporation of the EN-H2 (before Multinode), it appears that the introduction of hydrogen in the power system leads to a decrease in the required transmission line capacity. Interconnecting the Portuguese model with hydrogen in the Multinode, intensifies this decrease. In any case, even these models with hydrogen before and after interconnection with the Spanish system is required an increase of more than double what is foreseen in the plans for 2030.

Since a transmission line capacity of 4200 MW is estimated from Spain to Portugal, the values obtained in Figure 3.17 indicate that an increase in the transmission line is not necessary in the sense of imports from the perspective of Portugal.

3.5.2 Spanish individual model after integration in Multinode

In this section, the same analysis is made, but from the perspective of Spain. It is important to mention that from Section 3.4 it was found that Portugal in 2030 has an exporter character as well as Spain, but it has more need for imports when comparing the two sysrems. For this reason, in the order of merit in which the models are introduced in Multinode, Portugal is first introduced, followed by Spain. This is because we want Spain to export to satisfy Portugal's imports.

The balance value of imports and exports obtained by the integration of the two systems in Multinode in the prespective of Spain, is symmetrical to the value that the model calculated for Portugal. It’s important to know that for the Portuguese system, the fixed balance is a negative value because it has an importer character, which makes de Spanish value positive since this is system is the exporter.

Interconnecting the Spanish model with the Portuguese one does not cause any change in electricity production because it is a much larger system. When compared with the Portuguese system, both its consumption and production dimensions are very different, and therefore, the little electricity that is imported and exported through the creation of the fixed balance of import and export value, resulting from the small complementarity between these two systems, is not significant in terms of the size of the Spanish system while in the Portuguese system it already introduces some differences. The transmission line capacity also does not change with the interconnection with the Portuguese system.

Figure 3.19 represents the energy involved in exchanges of this system with the outside when considering only the capacity of the planned transmission line from Spain to Portugal.

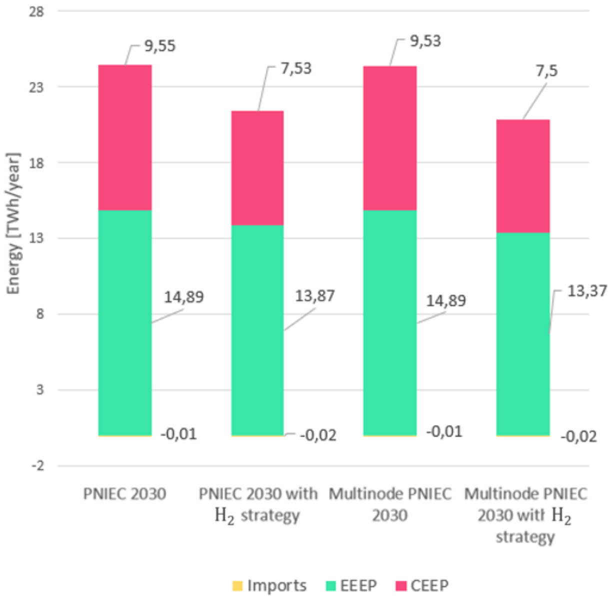


Figure 3.19 – Electricity exchanges [TWh/year] from the perspective of the Spanish system and before and after the interconnection in Multinode with the Portuguese system (systems with and without national hydrogen strategies). On the left are imports and on the right the exports with the distinction between EEEP (exportable excess) and CEEP critical excess).

As with the Spanish system variables that have been discussed so far, imports and the EEEP of exports vary only with the introduction of hydrogen in the power system models. However, the CEEP of exports varies both with the introduction of hydrogen and the interconnection with the Portuguese system in the model.

Imports increase with the introduction of hydrogen because the system creates a new consumption point due to the electrolysers. This is the also reason behind the decrease in the EEEP. The CEEP decreases with the introduction of hydrogen and with the interconnection with the Portuguese system (although this decrease after running the model in Multinode, is less relevant).

3.5.3 Iberia in 2030

Analyzing the future of the Iberia is one of the main objectives of this study. When the systems are integrated in the Multinode add-on tool, the model also outputs a PDF file with the merge of all the productions and consumptions of the connected models, taking into account the balance created. This output is an optimized new large system formed by the two systems studied.

Due to the lack of complementarity between these systems, due to their similar profiles of production and consumption, joining the two systems results practically in the sum between them. However, it is interesting to study the system variables that change with the optimization of the systems through the fixed import and export balance, from the perspective of the Iberia.

To illustrate the effect of the balances between the two systems, figures 20-25 represent the values that have changed side by side with what they would be if they were the sum and not an optimized data of the Iberia system.

As would be expected, the variables that were mentioned earlier that underwent changes in the individual systems before and after the Multinode, are essentially those that also introduce differences in the Iberia systems. In addition to these, the balances also influenced electricity consumption in transport, CHP production in industry and the amount of renewable generation.

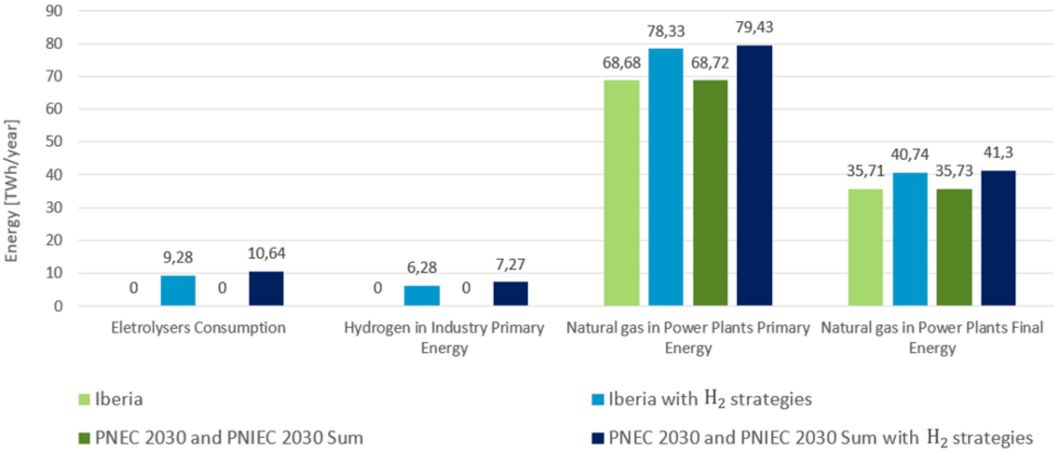


Figure 3.20 – Electrolysers consumption, hydrogen and natural gas in industry primary energy, and natural gas in power plants final energy for the 2030 Iberian models compared with the sum of the Portuguese and Spanish models, with and without the hydrogen strategies.

In a first analysis, it is possible to conclude that the productions of all the variables represented in the figure are lower in the optimized model of the Iberia when compared with the simple sum of the two systems. This is evidence that the interconnection between the two systems through the balances made by the model optimizes the production and consumption of energy resources.

In addition to the technologies that already showed variations in the individual systems with and without the fixed balance value, the Iberia system also optimizes electricity consumption in transport and the production of electricity by CHP in the industry (Figure 3.21).

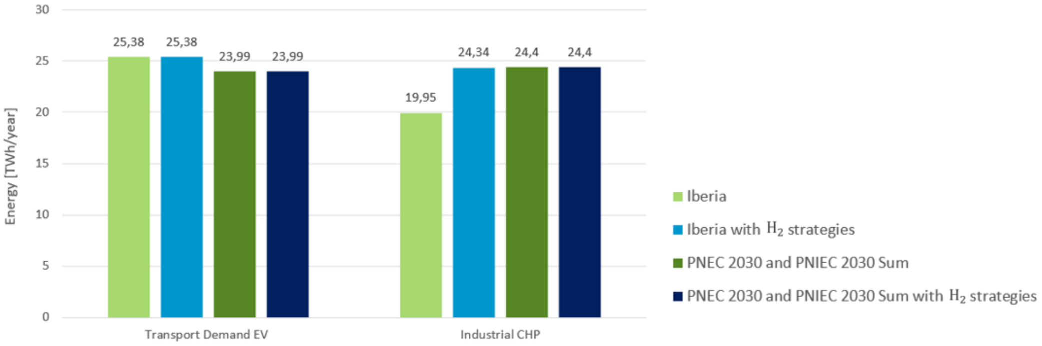


Figure 3.21 – EV transport demand and industrial CHP production for the 2030 Iberian models compared with the sum of the Portuguese and Spanish models, with and without the hydrogen strategies.

Figure 3.21 allows us to conclude that the optimized junction in the Iberia system causes the value for electricity consumption in transport to increase when comparing the sum of electricity consumption in this sector to the individual systems. This means that the connection of the two systems maximizes the use of renewable energy in the sense that there is a greater capacity for the consumption of electric mobility. This effect is a confirmation of the increased flexibility of the systems resulting from their interconnection.

For the production of electricity from industrial CHP, the Iberia system, in which the models do not include hydrogen technologies, has a lower production than the sum of the individual systems after Multinode. When we have the national hydrogen strategies in the equation, the Iberia system increases this production it is necessary to count hydrogen as primary energy in industry, however, as production from natural gas is a little lower, we do not have a value equal to the sum of the models.

In Figure 3.22 we have the exchanges of the Iberian system with the external system – Europe through the interconnection with France.

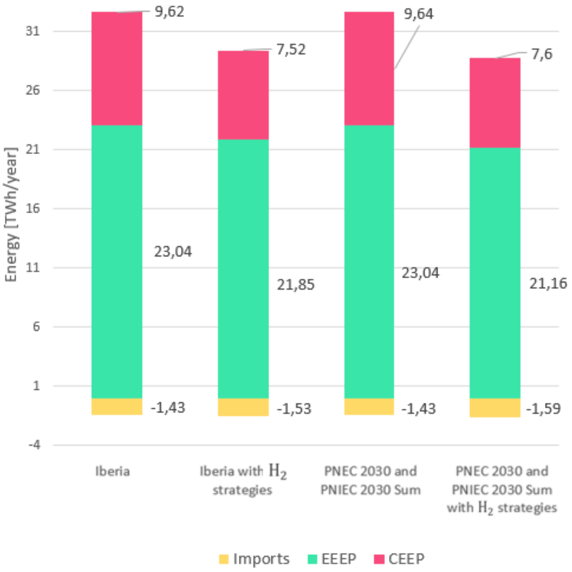


Figure 3..22 – Electricity exchanges [TWh/year] from the perspective of the Iberia system compared with the sum of the Portuguese and Spanish models (with and without national hydrogen strategies). On the left are imports and on the right the exports with the distinction between EEEP (exportable excess) and CEEP critical excess).

Imports are essentially the same as the simple sums of the systems, however, it should be noted that this value is slightly lower when we have Iberia optimized and with the hydrogen strategies. The introduction of hydrogen causes an increase in imports when we compare Iberia without these technologies, due to the increase in consumption because of hydrogen production. As a consequence of this, there is also a decrease in exports.

As for exports, the EEEP is lower than for the sums of the models. For the CEEP fraction, there is no difference when analyzing the Iberia system without hydrogen, but for the Iberia system with hydrogen, the balances made by the model introduce an increase in the critical excess of electricity. It is concluded that in the Iberia systems, balances improve exchanges in terms of imports, but worsen exports.

Figure 3.23 presents the capacities of the transmission lines taking into account the export potential of the Iberia system with and without hydrogen, compared with the sum of the capacities of the lines required from Portugal and Spain as individual systems after Multinode in their maximum export potential.

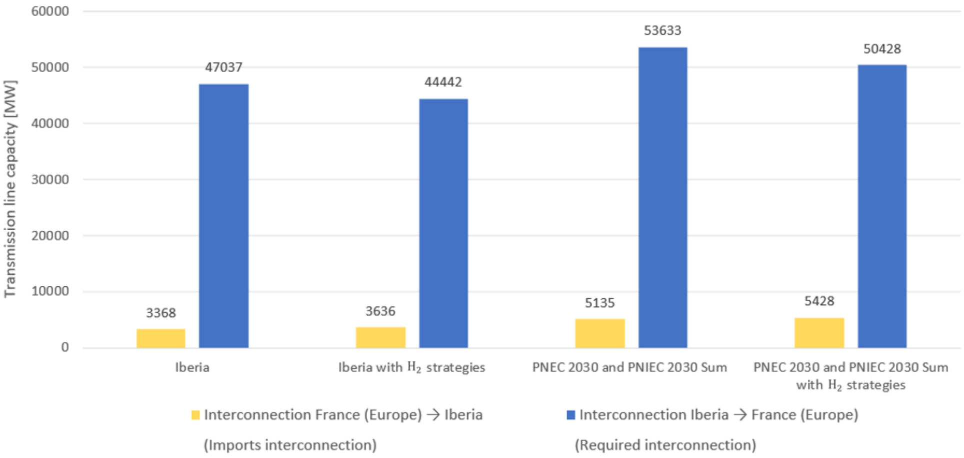


Figure 3.23 – Transmission line capacity [MW] obtained by EnergyPLAN modelling calculations, from the perspective of the Iberia system compared with the sum of the Portuguese and Spanish models (with and without national hydrogen strategies).

It can be concluded that the interconnection of systems in a single optimized Iberia system causes the interconnection to decrease in both directions in about 12%. This happens due to the compensation of imports and exports that happens to be internally in the system. However, this interconnection capacity is well below current plans [2,4] which may lead to large renewable energy curtailment.

The combination of the two systems in an Iberia system with and without hydrogen reduces the renewable generation when compared to the simple sum of the total renewable generation of each model (Figure 3.24).

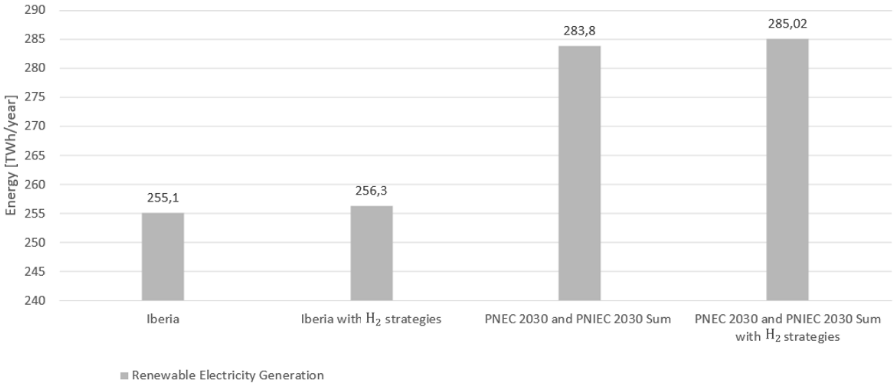


Figure 3.24 – Total renewable generation of the Iberia system and compared with the sum of the Portuguese and Spanish models (with and without national hydrogen strategies).

The figure above is one more confirmation of the conclusion drawn about the balances created internally with Multinode, which optimises consumption and production due to differences in production and consumption profiles between connected systems.

The interconnection between the systems creates a decrease in the production of natural gas, and this decrease is more accentuated in systems that include the hydrogen strategy (decrease in electricity production through natural gas plants decreases by 0.06% in systems without hydrogen, and 1.36% in systems with hydrogen). Other important results include the fact that the interconnection between the Portugal system and the Spain system contributed to reducing the need to increase the capacity of the transmission line by 12%, and the need for renewable generation by 11%.

It is important to note that the same analysis of the hourly distribution of exports that was performed on the individual models was also performed on the models after integration into MultiNode. It is only mentioned here in the section on the Spanish system because it is more relevant here, given that it was previously concluded that the transmission line capacity in Portugal is not underestimated.

The distribution obtained allows us to conclude that interconnection slightly reduces the need to increase interconnection, and in this simulation the capacity of the transmission line necessary to allow 95% of exports to pass is 26644 MW. This is in line with the expected effect, because part of the energy is exported to Portugal, reducing the amount of energy towards France.

4 | Effect of introducing variations in 2030 model data

In the previous chapter, the influence of hydrogen and the integration of the two systems on Multinode was studied. In this section, we intend to take the previous models, based on estimated capacities, consumptions and productions of the various systems technologies, and change some of these variables to understand how future systems change and, in a final phase, to understand if some of these changes, can increase system flexibility or even increase renewable production.

More precisely, the objectives are to know how the addition of hydrogen as a technology, and the increase in wind, solar PV and transmission line capacity, can influence the Iberian system. Finally, in chapter 4.4 a simple analysis is made to understand how the change in the orientation of the PV panels can influence the hours of solar production in Portugal and how this can contribute to the balance between the systems of Portugal and Spain, and consequently the system of the Iberian Peninsula as a whole.

The analysis is performed for the Multinode approach including the hydrogen strategies.

4.1 Effect of interconnection capacity

The effect of the interconnection between Portugal and Spain was assessed by sensitivity analysis. According to the national plans for 2030, the expected interconnection capacity is 3.5 GW (PT-SP) and 4.2 GW (SP-PT).

The graphical representation of the results of the study of this variation for each individual system are in Annexes II. Here we will only analyze the most relevant results from the perspective of the Iberian Peninsula system as a whole.

The following figures illustrate the effects of increasing the capacity of the lines of the two systems combined in the Iberia system. The transmission line capacity consider here is in the perspective of Iberia system connected to France (Europe).

Figure 4.1 shows how the consumption of eletrolysers and hydrogen as primary energy in the industry varies with the increase in transmission line capacity.

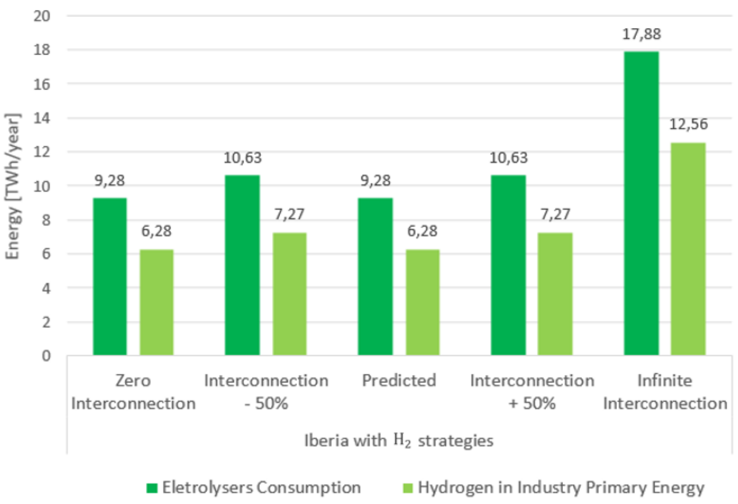


Figure 4.1 – Variation of eletrolysers consumption and hydrogen in industry primary energy, with the variation of the interconnections in Iberia combined system.

Unlike the individual systems studied in Annex II, when we combine the two systems into one, we have variations in the variables that affect hydrogen production and consumption.

As in some variables of the Portuguese system (Figure II.1 in Annexes), when we have the interconnection 50% lower and 50% higher than expected, the same values are obtained for the hydrogen technologies. This is also observed when comparing these values for systems with zero interconnections with those for systems with estimated interconnections.

The concrete conclusion that can be drawn from this is that when we do not limit the interconnection of the Iberia, we have a considerable increase in hydrogen production through eletrolysers and consumption of hydrogen as primary energy in the industry.

Figure 4.2 shows the primary and final energy in natural gas power plants, final energy in nuclear power plants, industrial CHP, and consumption of hydro pumps.

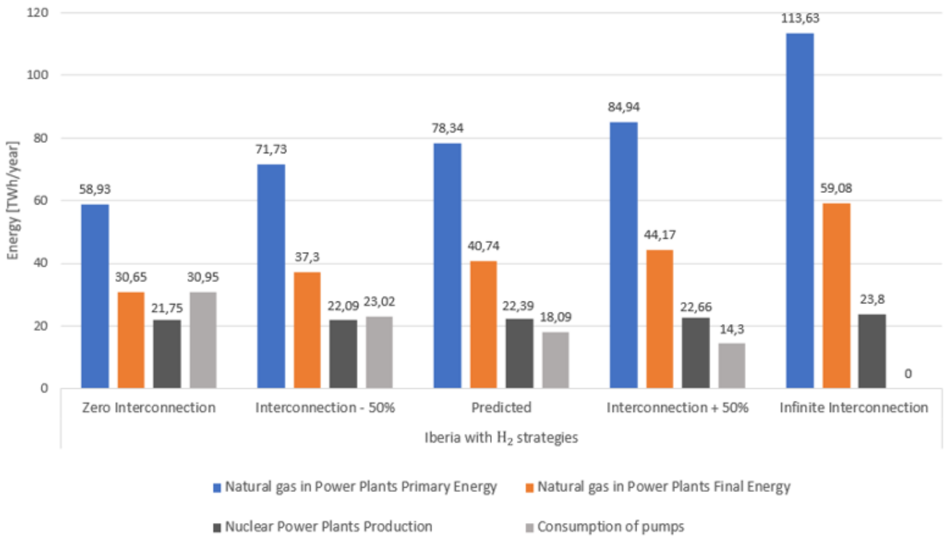


Figure 4.2 – Variation of primary energy and final energy of natural gas power plants, nuclear power production, industrial CHP and consumption of hydro pumps (storage) with the variation of the interconnection in the Iberia combined system.

As observed in the individual models, what is related to the production of electricity through natural and nuclear gas increases with increasing interconnection. In the same way, the consumption of the pumps, that is, the storage decreases.

In Figures 4.3 and 4.4 we have illustrated the effect of interconnection on imports and exports, and on transmission line capacity required in both directions, respectively.

These variables vary in the same way as in the individual systems (Figure II.2 and Figure II.3 in Annexes), but they are the result of small balances calculated by the model and represent the exchanges between the Iberia and France as a vector for Europe.

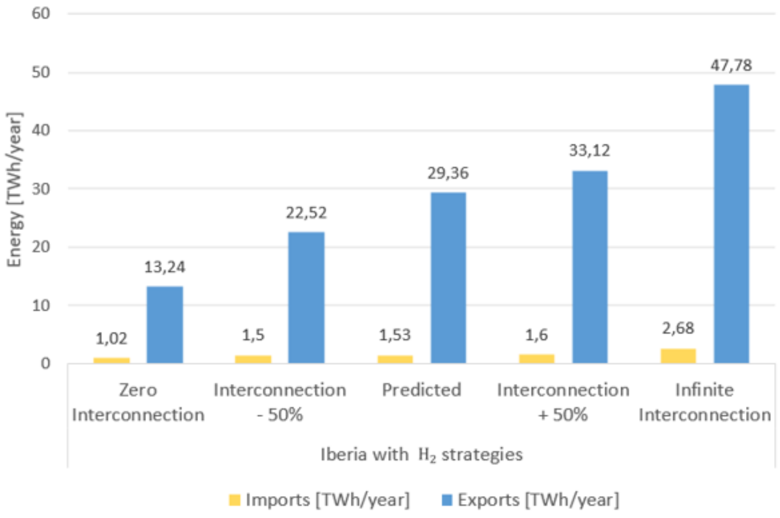


Figure 4.3 – Variation of imports and exports with the variation of the interconnection in Iberia combined system.

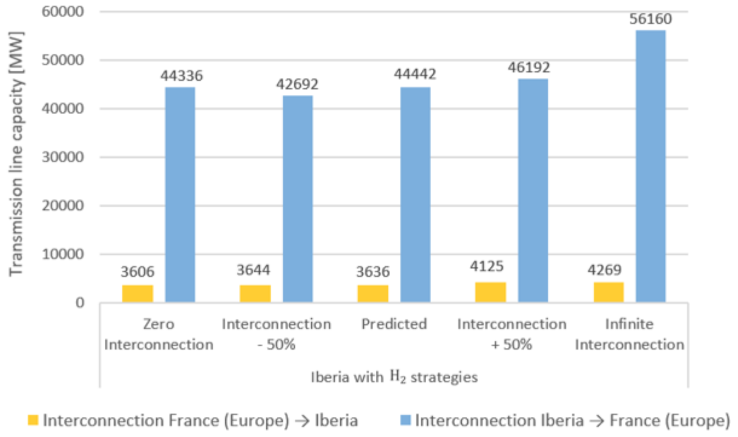


Figure 4.4 – Variation the required imports and exports interconnection with the variation of the interconnection in Iberia combined system.

The balances made by the model optimize the capacity of the line between the systems of Portugal and Spain, and what we obtain here is the capacity of the transmission line that is required from the perspective of the Iberia in relation to the rest of Europe.

From this it can be concluded that the capacity of the line required from Spain to France is 56 160 MW and in the opposite direction, 4 269 MW. This reinforces that the Iberia will be a major exporter with capacities sized for 2030 for both countries, and that the expected increase in transmission lines is far below what would be appropriate for estimated production and consumption.

4.2 Variation in the size of the installed capacity of solar PV in Portugal and Spain

To analyze whether there is any oversizing of capacities, and what effect this will have on these power systems in 2030, changes were made to the forecast, reducing the power to be installed of solar PV and wind by 50%, 30% and finally 10% (Table 4.1).

Table 4.1 – Installed solar PV capacities introduced in the Portuguese and Spanish models: -50%, -30% and -10% of planned capacities for 2030.

	-50% Solar PV capacity [MW]	**-30% Solar PV capacity [MW]**	**-10% Solar PV capacity [MW]**	**Estimated Solar PV capacity [MW]**
Portugal 2030	4500	6300	8100	9000
Spain 2030	19202	26883	34564	38404

The following figures illustrate the influence of the decrease in PV solar power in each system in relation to the Iberia system, after the integration in Multinode, and considering the national strategies for hydrogen.

Figure 4.5 shows how in the perspective of Iberia system, the final energy of natural gas power plants, nuclear power plants and consumption by water pumping varies with the decrease in installed solar PV power in Portugal and Spain.

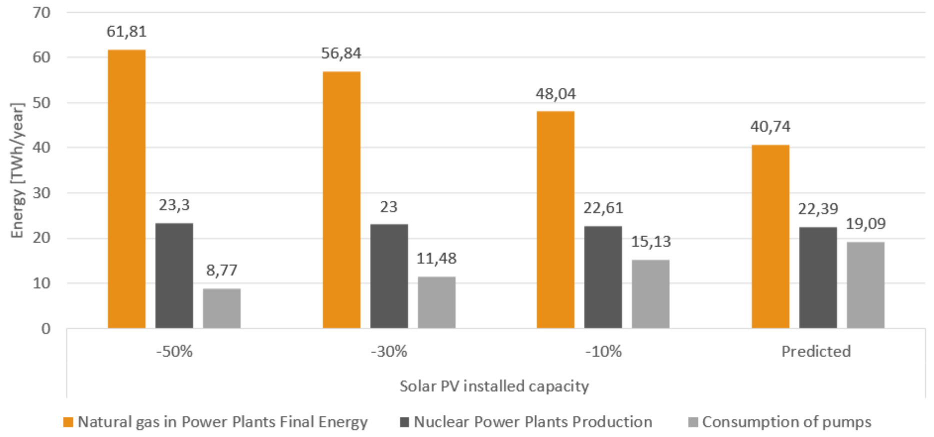


Figure 4.5 – Variation of final energy of natural gas power plants, and consumption of hydro pumps (storage) with the variation of solar PV capacity in the perspective of the Iberia system with hydrogen strategies.

As would be expected, the decrease in solar generation increases production from natural gas plants and nuclear power plants production. Storage tends to decrease with decreasing solar PV power because if there is less renewable production, there is less surplus production for storage.

Figures 4.6 and 4.7 represent exchanges between the Iberia system with Europe through France interconnection.

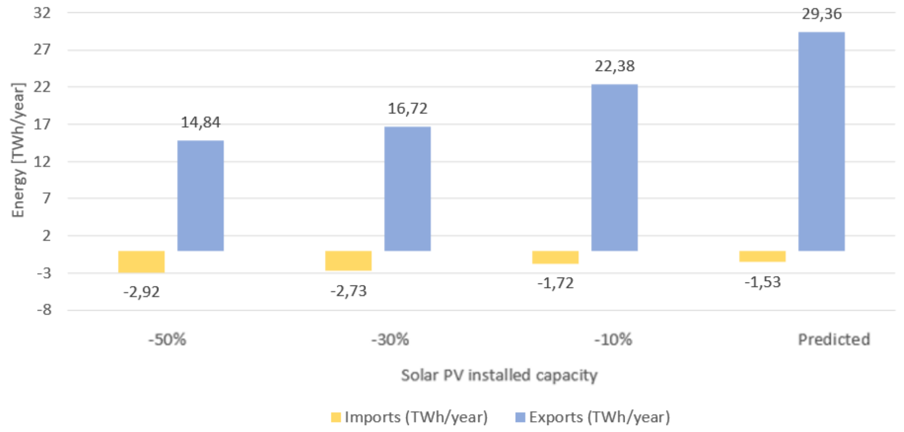


Figure 4.6 – Variation of imports and exports with the variation of solar PV capacity in the perspective of Iberia system with hydrogen strategies.

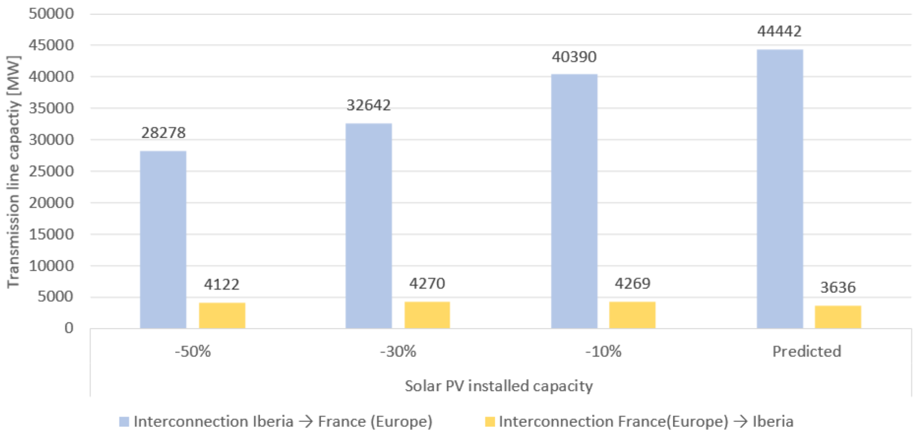


Figure 4.7 – Variation of the required imports and exports interconnection with the variation of solar PV capacity in the perspective of Iberia system with hydrogen strategies.

The decrease in solar power and consequent decrease in renewable generation decreases exports and increases imports. For this reason, the capacity of the line from the Iberia system to France decreases, and in the opposite direction increases as expected.

In Annexes III are the graphical representations of these results for the individual systems of Portugal and Spain, as well as some additional information useful to understand what leads to these results for the Iberian Peninsula.

4.3 Variation in the size of the installed capacity of wind energy in Portugal and Spain

In Table 4.2 are the wind power capacities that were introduced in the model.

Table 4.2 – Installed wind capacities introduced in the Portuguese and Spanish models: -50%, -30% and -10% of planned capacities for 2030.

	-50% Wind capacity [MW]	-30% Wind capacity [MW]	-10% Wind capacity [MW]	Estimated Wind capacity [MW]
Portugal 2030	4650	6510	8370	9300
Spain 2030	24275	33985	43695	48550

The following figures illustrate the influence of the decrease in wind power in the each system in the prespective of the Iberia system after the integration in Multinode, and considering the national strategies for hydrogen.

Figure 4.8 shows how energy of natural gas plants, nuclear power plants production, and the consumption by water pumping, varies with the decrease in installed wind power.

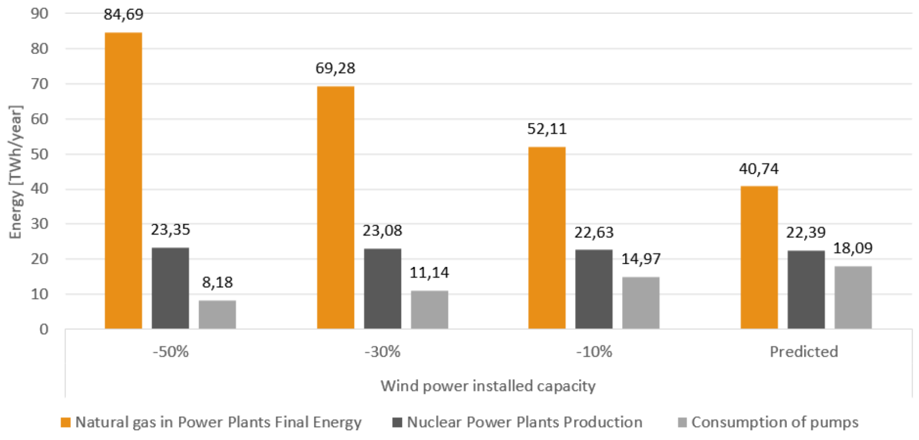


Figure 4.8 – Variation of final energy of natural gas power plants, and consumption of hydro pumps (storage) with the variation of wind power capacity in the persective of the Iberia system with hydrogen strategies.

The same behavior is observed when wind power is reduced, but the effects are more pronounced.

The same happens with the exchanges of electricity in the system, as can be seen in Figure 4.9 and Figure 4.10. The increase in imports and the decrease in exports are more accentuated, as well as the transmission line capacities.

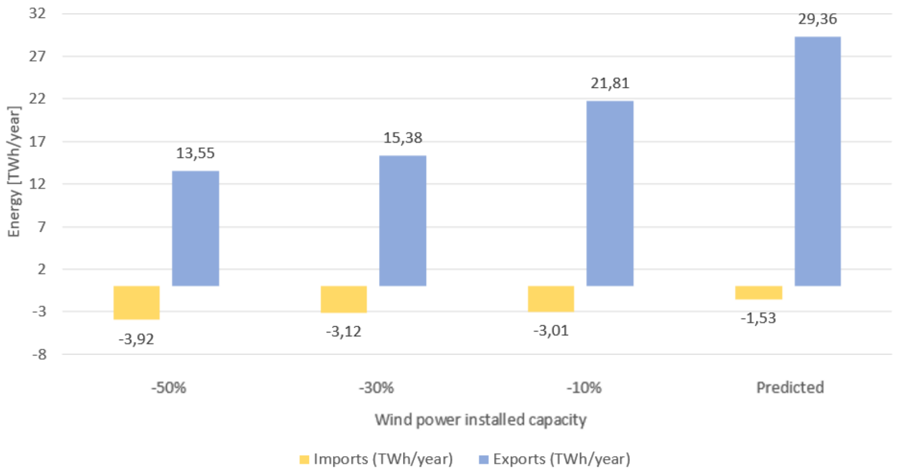


Figure 4.9 – Variation of imports and exports with the variation of wind power capacity in the perspective of Iberia system with hydrogen strategies.

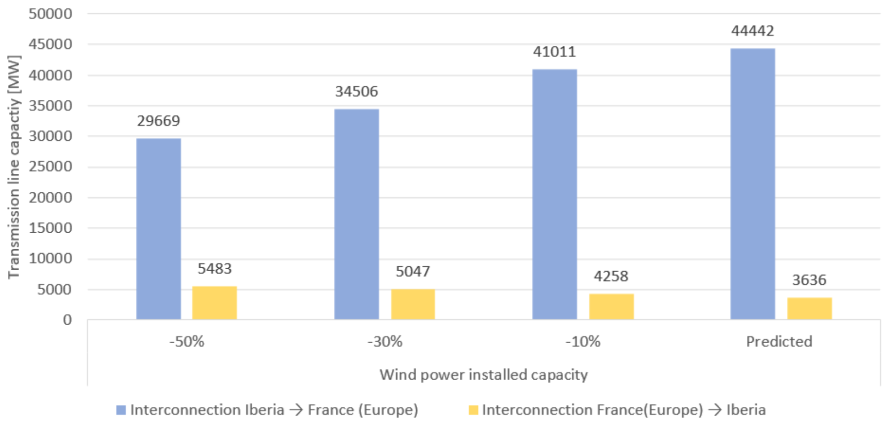


Figure 4.10 – Variation of the required imports and exports interconnection with the variation of wind power capacity in the perspective of Iberia system with hydrogen strategies.

In Annexes I.V are the graphical representations of these results for the individual systems of Portugal and Spain, as well as some additional information useful to understand what leads to these results for the Iberian Peninsula.

4.4 Effect that the variation in the orientation of the Portuguese PV panels have in 2030 exchanges

The orientation of the PV panels was varied to the southwest and southeast to understand how a shift in production hours could influence exports from the Portuguese system to the Spanish system, and thus increase the complementarity between the two systems.

To draw any conclusions, it is necessary to understand the PV production characteristics of these two systems. In Figure 4.11, the known PV productions of a 2017 typical summer day in the two countries, are represented with the respective time difference, together with the production profiles taken in PVGIS if the panels, instead of being oriented to the south, were oriented to the southwest (SO) and the southeast (SE).

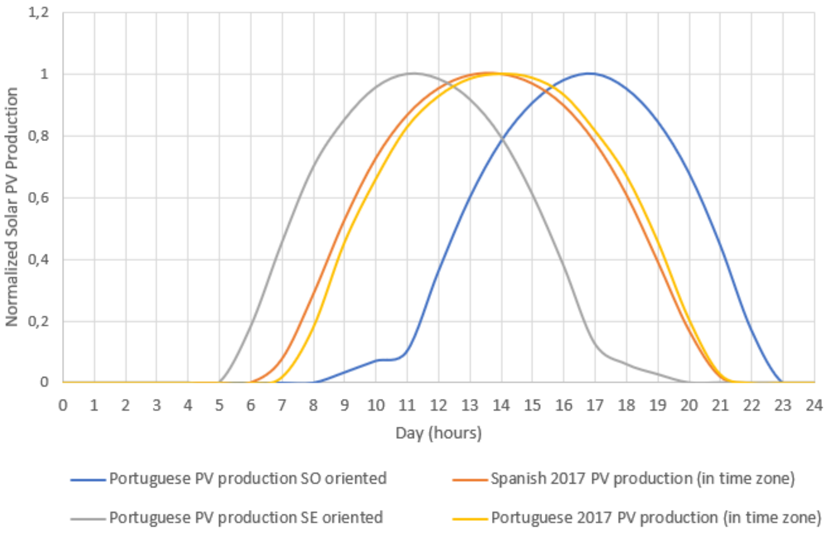


Figure 4.11 – PV production profiles from Portugal and Spain on a typical summer day of 2017 (July 1st), in the respective time zone, compared to the production profiles obtained for the two sites in PVGIS considering the panels orientation to the southwest (SO) and southeast (SE).

The real profiles of 2017 show that Spain, due to the time difference with Portugal, starts solar production an hour earlier, however, the difference is not very significant, and these systems show great simultaneity of solar production. When considering the southeast orientation, the PV production peaks significantly earlier (about 2 hours earlier), and in the case of the southwest orientation, a two-hour shift is observed, but after the PV production peak considering that the panels are installed facing south.

The optimal orientation of the panels in Portugal (and Spain) is towards the south, and therefore with this orientation, they reach their maximum production potential.

Considering the southeast and southwest orientations, as illustrated in Figure 4.11, makes the production peaks ahead or behind (respectively) the production peak of south-facing solar plants. Although the change in the variation of the panels can cover different consumption times of the day, it has the consequence of reducing the generation because it is not producing in the optimal orientation, not reaching its peak at solar noon.

The differences in solar PV production with the orientation of the panels are shown in Figure 4.12, together with the influence it has on the primary and final energy of natural gas power plants, and the consumption of hydro pumps.

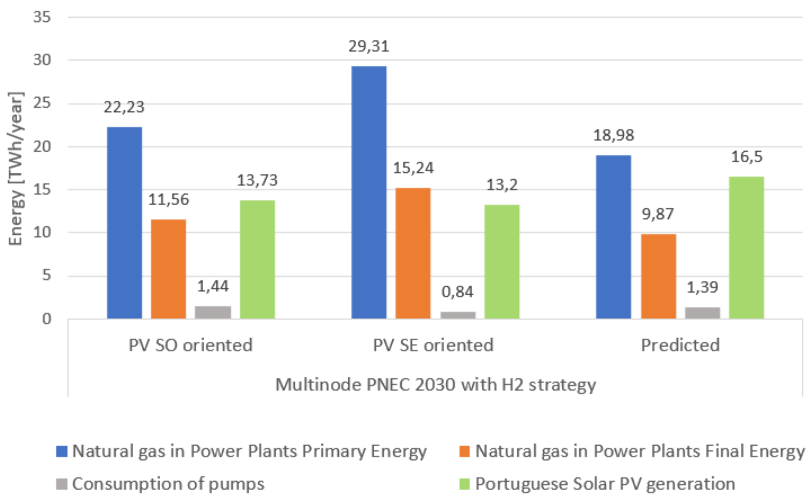


Figure 4.12 – Variation in gas primary and final energy in natural gas power plans, and consumption of hydro pumps (storage), considering the Portuguese panels orientation to the southwest (SO) and southeast (SE).

It is confirmed that for these new orientations, lower solar PV production values are achieved in Portugal and that consequently, the system has greater production from natural gas plants.

However, it is important to note that the orientation southwest results in greater solar PV production than in the southeast (and consequently, less production from natural gas power plants). On other hand, Pv towards southeast leads to lower consumption of hydro pumps. The system only stores electricity from renewable sources, so if renewable generation declines due to decreased solar PV production, the electricity that could be available for storage is consumed.

Figures 4.13 and 4.14 show how imports, exports and transmission line capacities in Portugal vary in the two directions of exchange, with the change in the orientation of the panels.

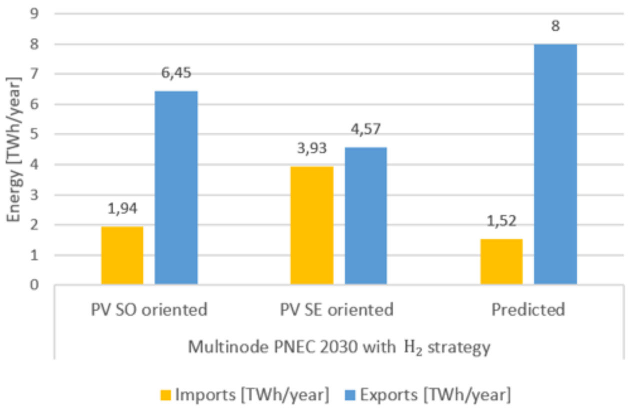


Figure 4.13 – Variation in imports and exports, considering the Portuguese panels orientation to the southwest (SO) and southeast (SE).

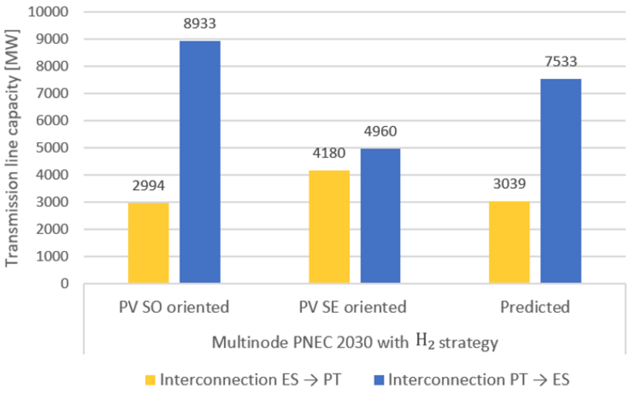


Figure 4.14 –Variation of the required imports and exports interconnection, considering the Portuguese PV orientation to the southwest (SO) and southeast (SE).

In comparison with the PV production oriented towards the south, both in the southeast and the southwest, we can observe increased imports and decreased exports as a consequence of the decrease in renewable generation.

However, analyzing the two new orientations considered, it is concluded that the southwest is more favourable to the Portuguese system because although imports rise and exports decrease, the difference is not as relevant.

5 | Conclusions

Energy systems are complex systems with several components, from the definition of consumption, the various technologies of energy production and storage, to the interconnection and exchanges between systems. The modelling done in this work through EnergyPLAN and the Multinode tool allows analyzing the energy systems as a whole in a way that can be considered quite immediate and simplified, but precisely for these reasons it has some limitations.

During the work, it was explained in several occasions that the way energy is defined for storage or for exports and imports depends on factors related to the energy market and not only on technical factors. Not taking market aspects into account when modelling an energy system means that we are not counting decisions about the operation of the system that are not directly related to the best technical efficiency of the system. Sometimes imports and exports occurred due to energy cost values being higher/lower than production costs. Thus, it is expected that modelled results will partially diverge from reality, and the objective here is to say that these variations may occur due to economic factors that are unrelated to this assessment. In this work we intend to have a macro view of the system's behavior.

One of the first and most important conclusions that we can draw from this work is that the installed capacity estimated for 2030 according to the respective plans for Portugal and Spain result in higher percentages of renewables in electricity and primary energy than those estimated in these same plans. The effect of introducing hydrogen into systems is essentially felt in the increase in production of natural gas plants by reallocation of solar and wind energy for the electrolysis. Also, introducing the hydrogen shows a reduction of the need for water pumping, which can be an indicator that hydrogen it’s a energy vector that provides flexibility to the system.

Throughout this study, there is a strong complementarity between Portugal and Spain, due to their very similar consumption and production profiles, being in similar geographic locations and being influenced by the same environmental conditions. The strong growth of renewables predicted for the Iberian Peninsula poses an overlapping problem since renewable peaks occur simultaneously.

The excess electricity from an internal perspective between Portugal and Spain has little value, but from a European perspective it is in line with the need to increase the interconnection capacity between Spain and France (from the Iberian Peninsula to the rest of Europe).

The main conclusion of this work is related to the obtained values of transmission line capacity in the studied systems. The increase in renewable production in both energy systems results in higher export potential, and as a consequence, is necessary to increase the transmission line capacity to carry all this excess energy from Iberia Peninsula.

The models created in this work for the two systems indicate that the capacity of the transmission line estimated in the direction from Portugal to Spain is well sized allowing the passage of most of the exported energy. However, it was concluded that in the direction of Spain for external systems it is undersized. According to the models and not considering sporadic export peaks, the Spanish system require a transmission line capacity of about 26858 MW, which translates into an increase of about twice that estimated in the national plans for 2030. The interconnection with Portugal with MultiNode, slightly reduces the line capacity to 26644 MW.

This results shows that the interconnection between Spain and France should have greater focus for reinforcement, and that the role of interconnections is decisive to achieve the objectives. The transmission line between Spain and France must be strengthened above expectations since it will be the passage of the export of the Iberian Peninsula mainly in hours of solar production.

This conclusion is in line with the current situation in which strengthening interconnections is considered crucial to maintain the resilience of energy systems by making them more independent of fossil fuels through renewable energy exchanges.

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ANNEXES

Annex I. Influence of the dry year and wet year on the modelling of the Spanish power system

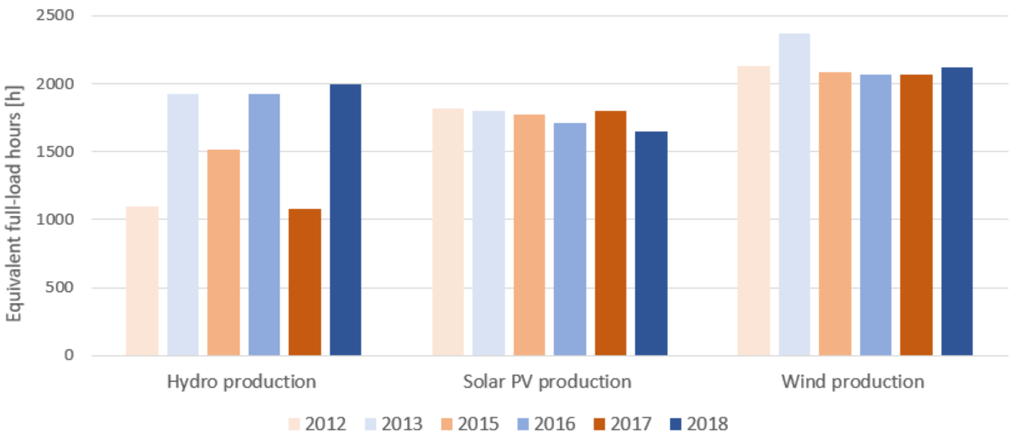

Figure I.1 – Equivalent full-load hours for hydro, solar PV, and wind production in Spain for the pairs of dry and wet years identified between 2012-2018. The columns in shades of orange represent the values for the dry years from 2012 to 2018, the columns in shades of blue represent the values for the wet years. [62,63,75,76,77,78]

Table I.1 – Average full-load hours for dry years and wet years, related to hydropower, wind and solar PV production in Spain based on the pairs of years considered between 2012-2018. [62,63,75,76,77,78]

	Dry years	**Wet years**
Hydro average full-load hours [h]	1229	1950
Solar PV average full-load hours [h]	1796	1719
Wind average full-load hours [h]	2097	2185

Annex II. Effect of interconnection capacity in the Portuguese and in the Spanish systems

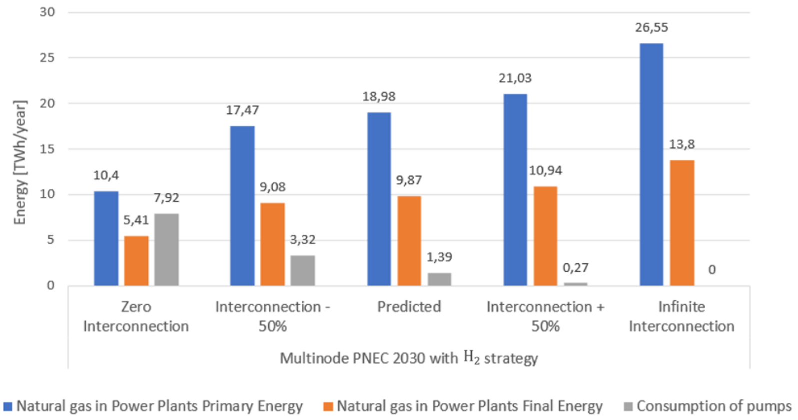

Figure II.1 – Variation of primary energy and final energy of natural gas power plants, and consumption of hydro pumps (storage) with the variation of the interconnection in the Portuguese models.

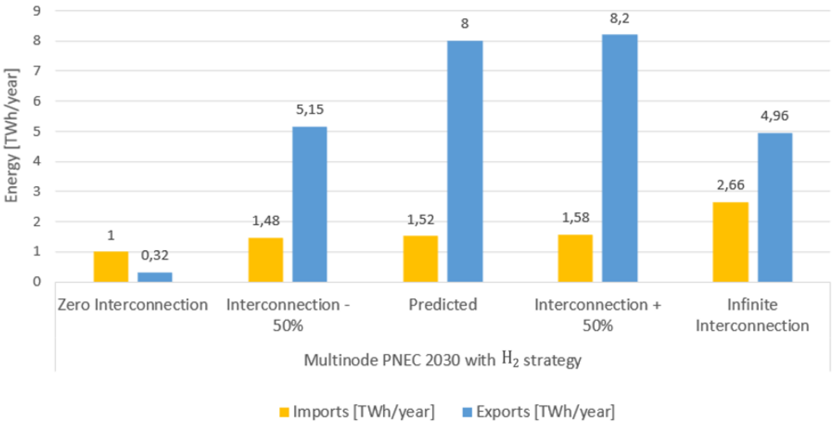

Figure II.2 – Variation of imports and exports with the variation of the interconnection in the Portuguese models.

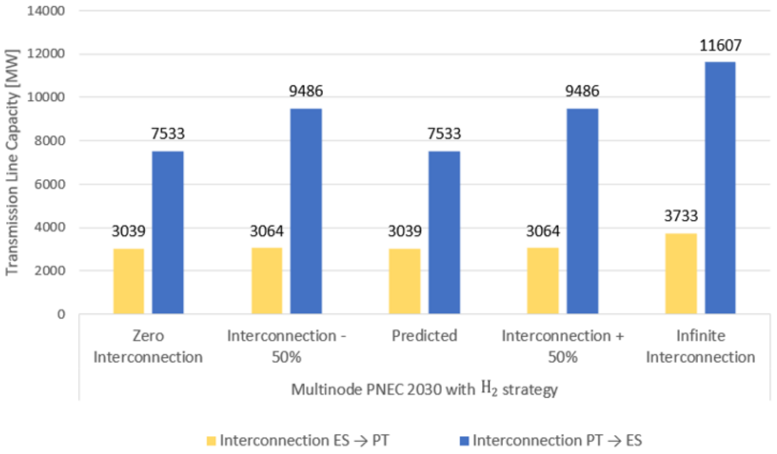

Figure II.3 – Variation the required imports and exports interconnection with the variation of the interconnection in the Portuguese models.

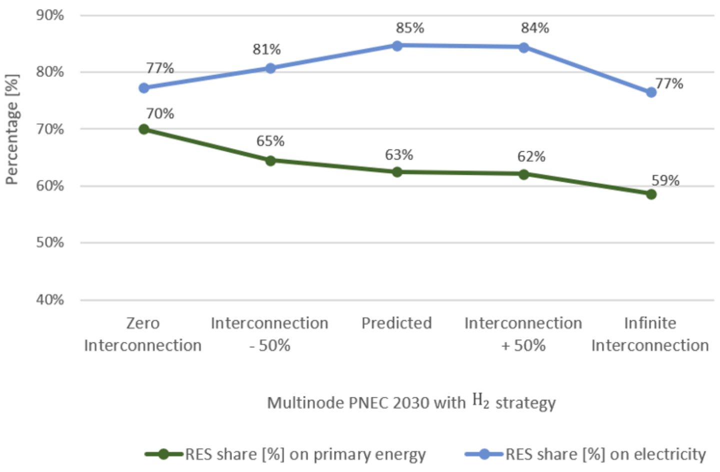

Figure II.4 – Variation of the share of renewable energy sources (RES) on primary energy and on electricity with the variation of the interconnection in the Portuguese models.

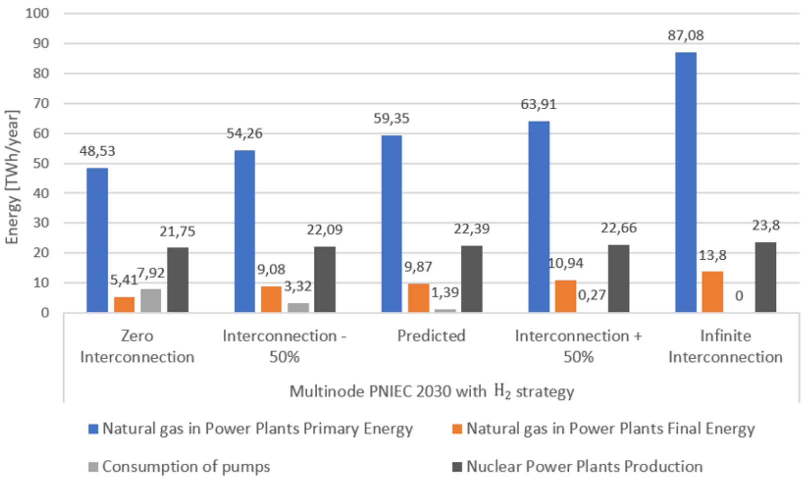

Figure II.5 – Variation of primary energy and final energy of natural gas power plants, nuclear power production, and consumption of hydro pumps (storage) with the variation of the interconnection in the Spanish models.

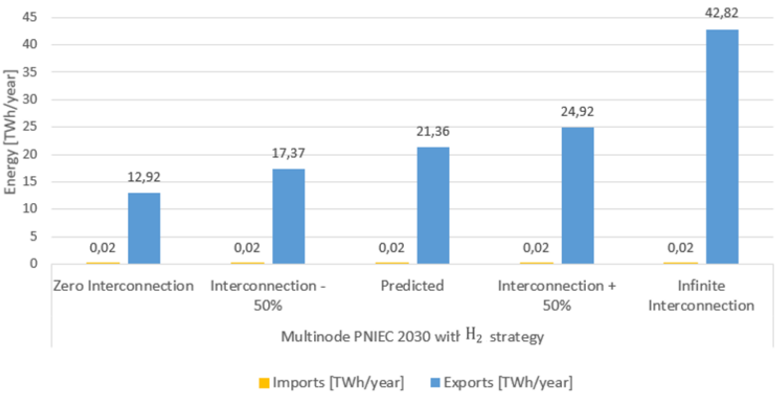

Figure II.6 – Variation of imports and exports with the variation of the interconnection in the Spanish models.

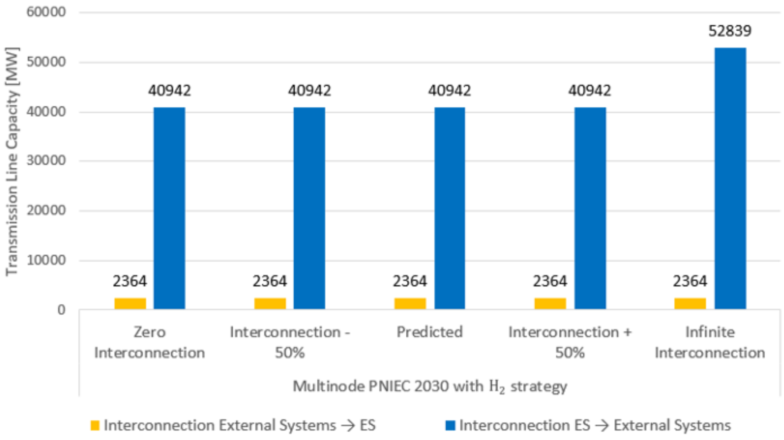

Figure II.7 – Variation the required imports and exports interconnection with the variation of the interconnection in the Spanish models.

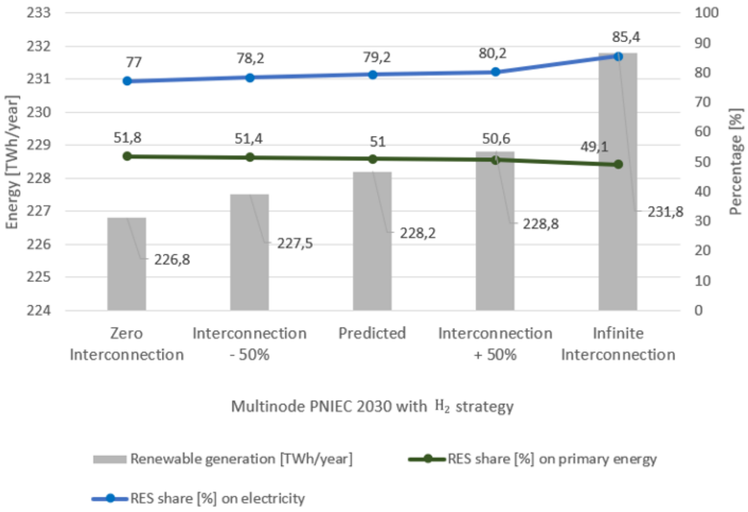

Figure II.8 – Variation of the share of renewable energy sources (RES) on primary energy and on electricity with the variation of the interconnection in the Spanish models.

Annex III. Variation in the size of the installed capacity of solar PV in Portugal and Spain individually

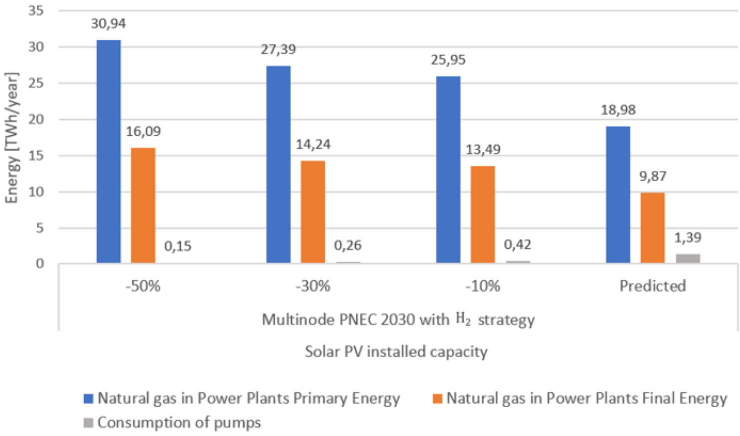

Figure III.1 – Variation of primary energy and final energy of natural gas power plants, and consumption of hydro pumps (storage) with the variation of solar PV capacity in both systems, in the perspective of the Portuguese model.

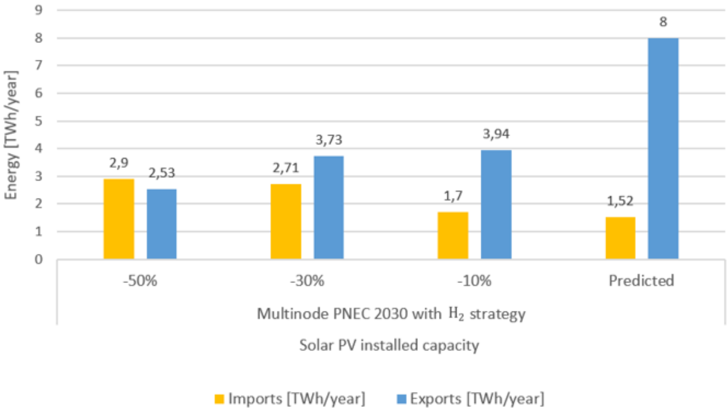

Figure III.2 – Variation of imports and exports with the variation of solar PV capacity in both models, in the perspective of the Portuguese system.

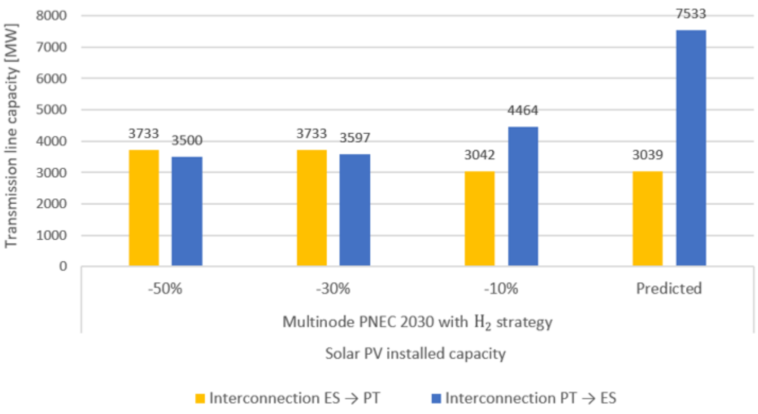

Figure III.3 – Variation of the required imports and exports interconnection with the variation of solar PV capacity in both models, in the perspective of the Portuguese system.

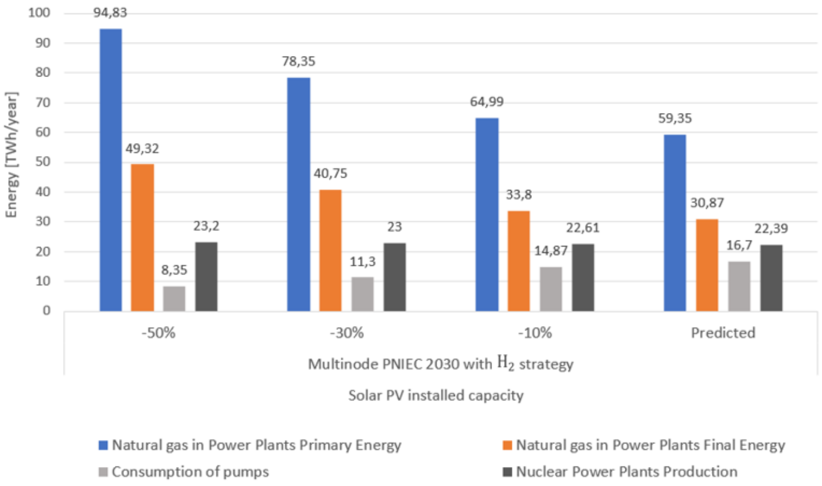

Figure III.4 – Variation of primary energy and final energy of natural gas power plants, nuclear power production, and consumption of hydro pumps (storage) with the variation of solar PV capacity in both systems, in the perspective of the Spanish model.

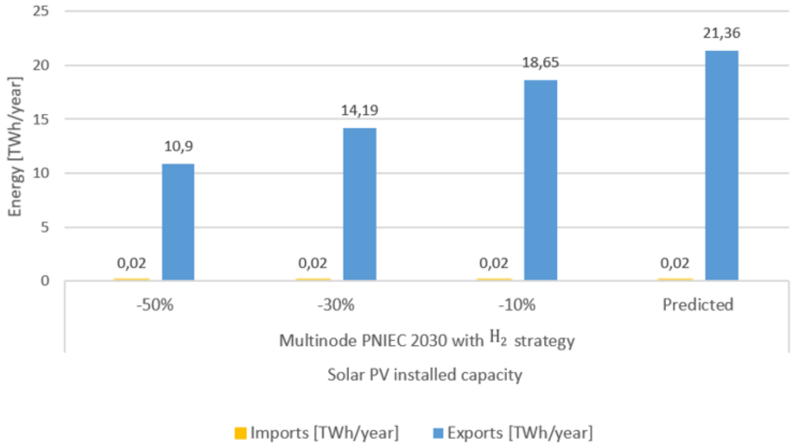

Figure III.5 – Variation of imports and exports with the variation of solar PV capacity in both models, in the perspective of the Spanish system.

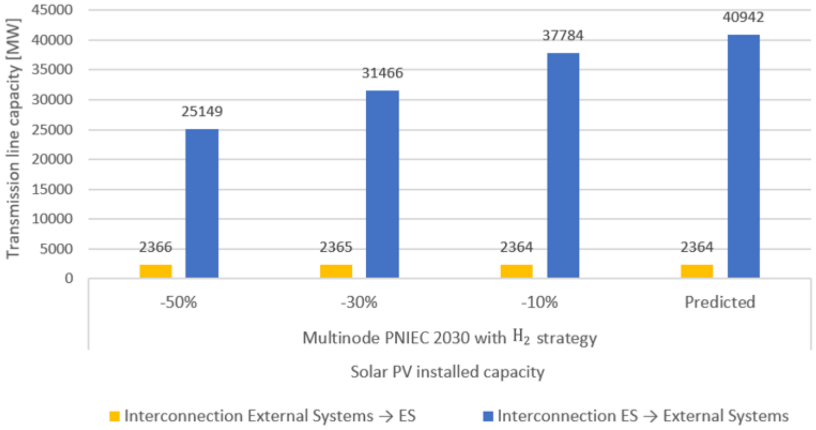

Figure III.6 – Variation of the required imports and exports interconnection with the variation of solar PV capacity in both models, in the perspective of the Spanish system.

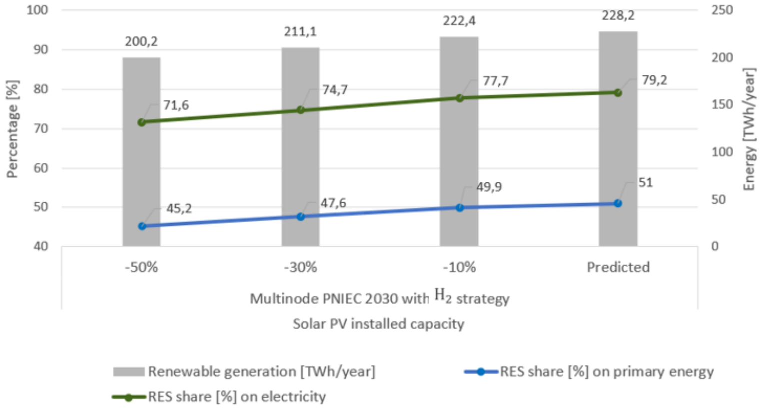

Figure III.7 – Variation of the share of renewable energy sources (RES) on primary energy and on electricity with the variation of solar PV capacity in both models, in the perspective of the Spanish system.

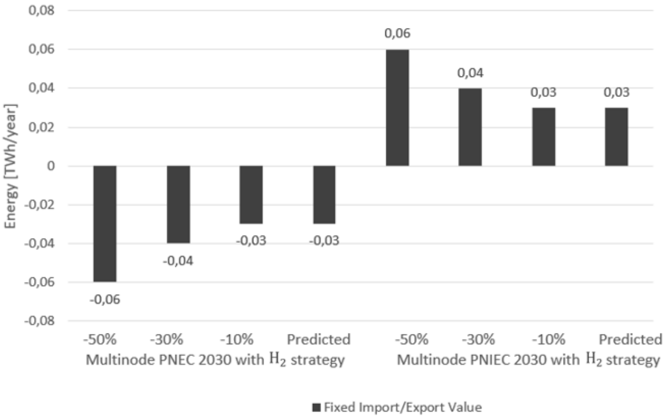

Figure III.8 – Fixed import and export balance values created in the interconnection of the two systems for the models where the variation of PV solar power.

Annex IV. Variation in the size of the installed capacity of wind energy in Portugal and Spain individually

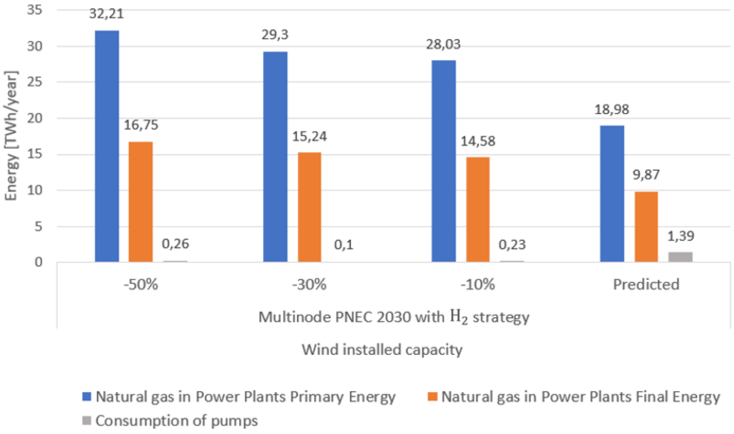

Figure IV.1 – Variation of primary energy and final energy of natural gas power plants, and consumption of hydro pumps (storage) with the variation of wind capacity in both systems, in the perspective of the Portuguese model.

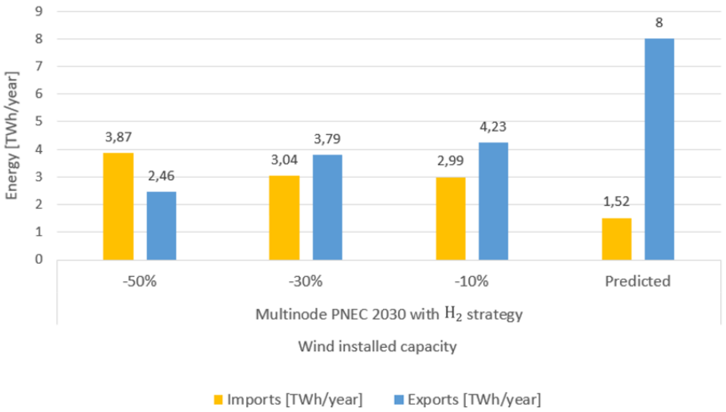

Figure IV.2 – Variation of imports and exports with the variation of wind capacity in both models, in the perspective of the Portuguese system.

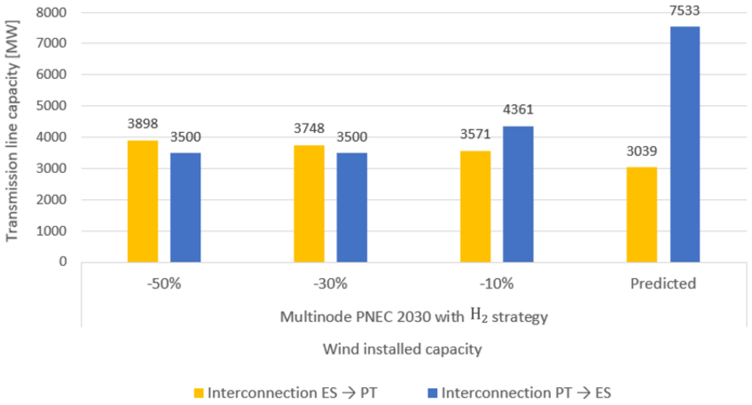

Figure IV.3 – Variation of the required imports and exports interconnection with the variation of wind capacity in both models, in the perspective of the Portuguese system.

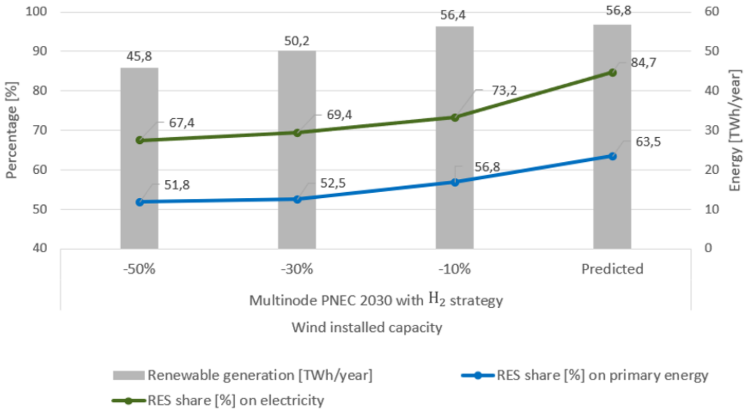

Figure IV.4 – Variation of the share of renewable energy sources (RES) on primary energy and on electricity with the variation of wind capacity in both models, in the perspective of the Portuguese system.

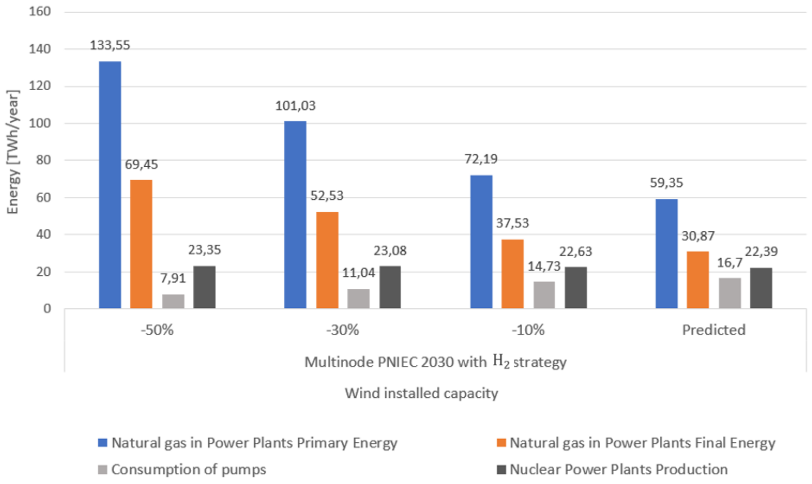

Figure IV.5 – Variation of primary energy and final energy of natural gas power plants, nuclear power plants production, and consumption of hydro pumps (storage) with the variation of wind capacity in both systems, in the perspective of the Spanish model.

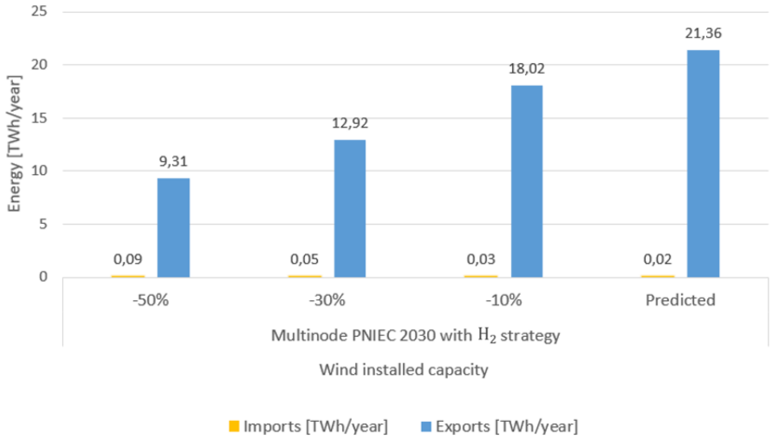

Figure IV.6 – Variation of imports and exports with the variation of wind capacity in both models, in the perspective of the Spanish system.

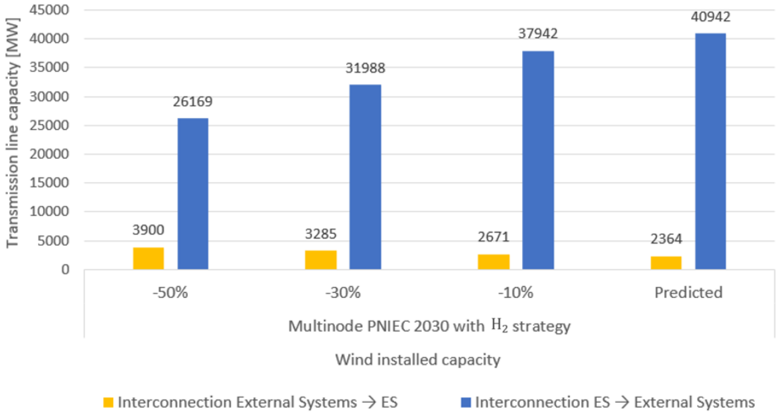

Figure IV.7 – Variation of the required imports and exports interconnection with the variation of wind capacity in both models, in the perspective of the Spanish system.

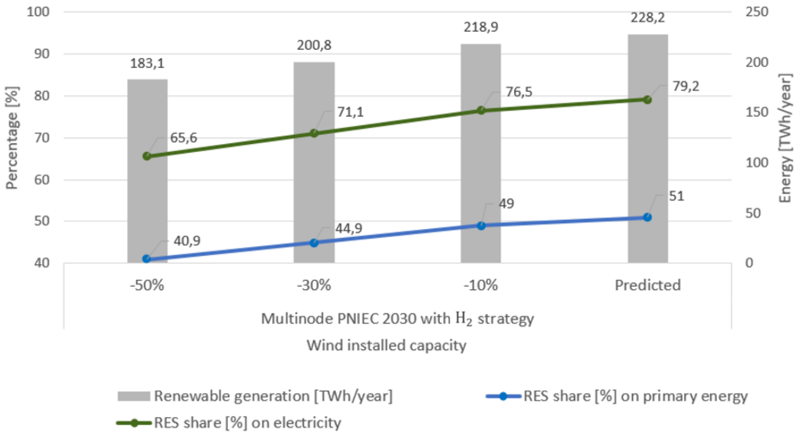

Figure IV.8 – Variation of the share of renewable energy sources (RES) on primary energy and on electricity with the variation of wind capacity in both models, in the perspective of the Spanish system.

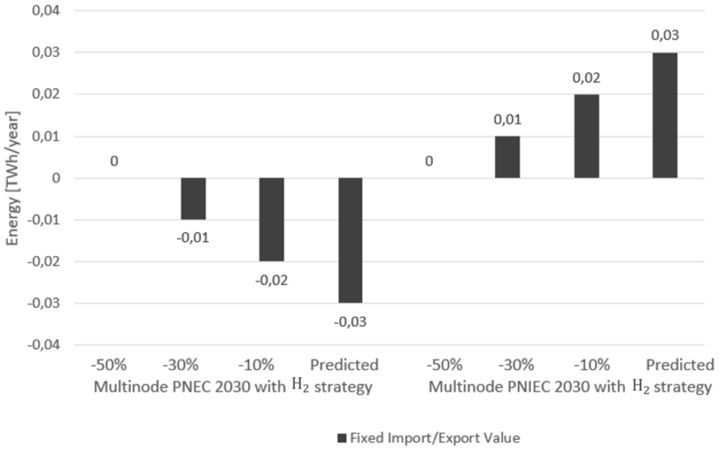

Figure IV.9 – Fixed import and export balance values created in the interconnection of the two systems for the models where the variation of wind power.