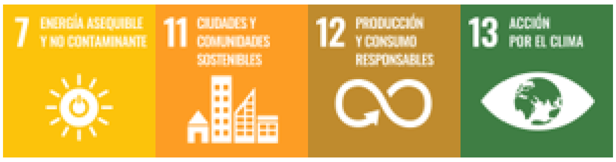
eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea
BILBOKO INGENIARITZA ESKOLA
ESCUELA DE INGENIERÍA DE BILBAO

MÁSTER UNIVERSITARIO EN INGENIERÍA INDUSTRIAL

# TRABAJO FIN DE MASTER

## *SPAIN'S FULLY RENEWABLE ENERGY SYSTEM'S ANALYSIS EXTRAPOLATING FROM DANISH SYSTEM DESIGNS*




**Estudiante**: del Hoyo Ortiz de Zarate, Jon

**Director/Directora:** Nami, Hossein

**Codirector/Codirectora:** Wenzel, Henrik

**Curso:** 2023-2024

**Fecha:** Odense, 17/06/2024

SDU University of Southern Denmark

# Abstract

This thesis investigates the potential for Spain to transition to a fully renewable energy system by extrapolating from Danish system designs. It examines Spain's current energy landscape, future plans, and the role of renewable energy sources and hydrogen storage technologies in achieving carbon neutrality by 2050. The study compares Spain's strategies with those of Denmark, highlighting the differences in their approaches due to distinct socio-economic contexts and existing energy infrastructures. The analysis concludes that while hydrogen storage is vital for Spain's renewable energy goals, other storage technologies like hydropower with reverse pumping and CSP solar parks also play significant roles. The study underscores the importance of tailored energy strategies for different countries to meet European environmental goals.

Key words: Energy transition, Hydrogen, Spain, Denmark, 2050

# Resumen

Esta tesis investiga el potencial de España para transitar a un sistema de energía completamente renovable extrapolando de los diseños del sistema danés. Examina el panorama energético actual de España, los planes futuros y el papel de las fuentes de energía renovable y las tecnologías de almacenamiento de hidrógeno en la consecución de la neutralidad de carbono para 2050. El estudio compara las estrategias de España con las de Dinamarca, destacando las diferencias en sus enfoques debido a distintos contextos socioeconómicos e infraestructuras energéticas existentes. El análisis concluye que, aunque el almacenamiento de hidrógeno es vital para los objetivos de energía renovable de España, otras tecnologías de almacenamiento como las plantas hidroeléctricas con bombeo reversible y los parques solares CSP también juegan roles significativos. El estudio subraya la importancia de estrategias energéticas adaptadas a diferentes países para cumplir con los objetivos ambientales europeos.

Palabras clave: Transición energética, Hidrógeno, España, Dinamarca, 2050

# Laburpena

Tesi honek Espainiak sistema energetiko guztiz berriztagarria lortzeko duen potentziala aztertzen du, Danimarkako sistemaren diseinuetatik extrapolatuz. Espainiako energia egoera, etorkizuneko planak eta 2050erako karbono neutraltasuna lortzeko energia berriztagarrien iturrien eta hidrogeno biltegiratze teknologiaren papera aztertzen ditu. Ikasketak Espainiaren estrategiak Danimarkakoekin alderatzen ditu, haien ikuspegi desberdinak nabarmentzen ditu, testuinguru sozio-ekonomiko eta energia azpiegitura desberdinak direla eta. Azterketak ondorioztatzen du hidrogeno biltegiratzea ezinbestekoa dela Espainiako energia berriztagarrien helburuetarako, baina beste biltegiratze teknologiek ere, hala nola, ponpaketa alderantzizkoa duten zentral hidroelektrikoek eta CSP eguzki parkeek, rol esanguratsuak dituzte. Ikasketak herrialde ezberdinetarako energia estrategien garrantzia azpimarratzen du Europako ingurumen helburuak betetzeko.

Hitz gakoak: Trantsizio energetikoa, Hidrogenoa, Espainia, Danimarka, 2050

SDU
University of Southern Denmark

SDU
Syddansk Universitet

Master's Thesis

# Spain's Fully Renewable Energy System's Analysis Extrapolating From Danish System Designs

Jon del Hoyo Ortiz de Zarate

Supervisors: Hossein Nami & Henrik Wenzel

*25th of May of 2024*

# Abstract

This thesis investigates the potential for Spain to transition to a fully renewable energy system by extrapolating from Danish system designs. It examines Spain's current energy landscape, future plans, and the role of renewable energy sources and hydrogen storage technologies in achieving carbon neutrality by 2050. The study compares Spain's strategies with those of Denmark, highlighting the differences in their approaches due to distinct socio-economic contexts and existing energy infrastructures. The analysis concludes that while hydrogen storage is vital for Spain's renewable energy goals, other storage technologies like hydropower with reverse pumping and CSP solar parks also play significant roles. The study underscores the importance of tailored energy strategies for different countries to meet European environmental goals.

## Table of Contents

SDU University of Southern Denmark

## Table of Figures

# 1. Introduction

## 1.1. Motivation behind the Report

The global energy landscape is undergoing a transformative shift as countries strive to reduce their carbon footprints and transition towards sustainable energy systems. This transition is driven by the urgent need to mitigate climate change, enhance energy security, and promote economic resilience. Spain and Denmark, both recognized for their proactive energy policies, serve as exemplary models in this global movement. However, their unique socio-economic contexts and energy resource endowments necessitate tailored approaches to achieving their energy goals. Understanding these approaches provides valuable insights into the broader dynamics of energy transition.

In Spain, the motivation for energy transition is strongly linked to its abundant renewable energy resources, particularly solar and wind. The country aims to leverage these resources to reduce its dependence on imported fossil fuels, thereby enhancing energy security and economic stability. Moreover, Spain's commitment to the European Union (EU)'s climate targets underscores its dedication to environmental sustainability and technological innovation in the energy sector.

Denmark, on the other hand, has established itself as a pioneer in wind energy technology, a status that is deeply rooted in the country's historical reliance on fossil fuels and its subsequent desire to achieve energy independence. One of the key pillars of Denmark's energy strategy has been its substantial investment in wind energy. The country leveraged its favorable geographic conditions and wind resources to develop extensive wind energy infrastructure. Today, wind energy constitutes more than half of Denmark's energy supply.

Moreover, Denmark's energy strategy also places significant emphasis on biomass. Biomass has been utilized extensively for heating and electricity generation, providing a renewable alternative to fossil fuels. However, recognizing the sustainability challenges associated with large-scale biomass use, Denmark is now focusing on reducing its reliance on biomass. One interesting way to reduce this dependency is taking into account the potential of hydrogen to serve as a key energy carrier, enhancing energy storage and facilitating the decarbonization of sectors that are difficult to electrify directly, such as heavy industry and long-haul transport.

Denmark's strategic investments in renewable energy infrastructure and innovation have positioned it as a leader in sustainable energy practices. This dual focus on reducing carbon emissions and fostering economic growth through green technology forms the cornerstone of Denmark's energy policy. The country's success in the renewable energy sector serves as a model for other countries aiming to transition to sustainable energy systems, such as Spain.

### 1.2. Problem Statement and Similar Studies

Despite the global momentum towards energy transition, the complexity of the situation requires of continuous monitoring of the prevention and control measures. The United Nations have projected that the global population will increase till values of 9.7 billion inhabitants in 2050 and 10.4 billion in 2100. This estimation, alongside the rise in per capita welfare and an apparent shift towards higher meat consumption, would result in a dramatic increase in demands for land for animal feed production. Thus, requiring of a higher energy demand that must be addressed in countries' plans. (United Nations, 2023)

Furthermore, there is a notable gap in comparative analyses that explore the specific strategies and outcomes of different countries regarding their energy transitions. This report addresses this gap by examining the current and future energy scenarios of Spain and Denmark, two countries with distinct yet equally ambitious plans for reducing carbon emissions and increasing their reliance on renewable energy sources. The focus on the report will be on the hydrogen generation and storage as it is appropriate for both countries' development.

Spain and Denmark, while both committed to achieving carbon neutrality by 2050, adopt different approaches tailored to their unique geographic, economic, and technological contexts. Spain leverages its abundant solar resources and significant wind potential, aiming for a diverse energy mix. The Spanish National Integrated Energy and Climate Plan (PNIEC) outlines ambitious targets for increasing renewable energy capacity and improving energy storage technologies, aiming for 22 GW of storage by 2030 and 30 GW by 2050. Spain also faces the challenge of balancing its regional energy needs, particularly in heating and cooling, with heating demand significantly higher than cooling. (Spanish Government, 2023)

In contrast, Denmark's energy strategy focuses heavily on wind energy and biomass. The country has pioneered innovations in wind technology and is a global leader in offshore wind farms. Denmark's approach also involves reducing its reliance on biomass and integrating new technologies to enhance energy sustainability.

Additionally, there are significant differences in the heating and cooling demands of the two countries. In Spain, heating demand is more than twice that of cooling, reflecting the diverse climate across its regions, from the Mediterranean coast to the Atlantic islands. This regional variability necessitates tailored energy solutions that can efficiently address the different climatic needs. Denmark, with its colder climate, has a higher overall demand for heating compared to cooling, which is less of a concern.

The study "The role of electrification and hydrogen in breaking the biomass bottleneck of the renewable energy system: a study on the Danish energy system" serves as a foundational reference for this analysis. This research highlights the critical role of electrification and hydrogen in enhancing the sustainability of renewable energy systems. It emphasizes the need for integrated approaches that combine various renewable technologies to overcome the limitations associated with biomass reliance. (Mortensen, et al., 2020)

However, while this study provides deep insights into Denmark's energy strategies, it does not extend its comparative lens to other countries, leaving a gap that this report aims to fill.

Specifically, this study will serve as the base for the calculation and visualization of both countries planned intersectional energy grids. The Danish Generic Design Strategies outlined in the study are the graphic way in which the analytical methodology will be applied for the evaluation of the plans set by both countries by 2050.

### 1.3. Aim of the Report

The primary aim of this report is to conduct a detailed comparative analysis of the energy sectors of Spain and Denmark, focusing on both the current state and future projections. This analysis will provide a "solution space" of how each country is navigating the complexities of energy transition. Specific objectives include:

- Quantitative Analysis: Assessing the current energy demand and supply in both countries, including a breakdown by energy sources and per capita consumption.
- Future Projections: Evaluating the projected energy scenarios for 2030 and 2050, with a focus on renewable energy targets and carbon neutrality goals.
- Technological Integration: Analyzing the role of key technologies such as wind, solar, and specially hydrogen in the energy transition strategies of each country.
- Policy Frameworks: Comparing the policy approaches and regulatory environments that support the energy transitions in Spain and Denmark.
- Hydrogen and electrolysis: Assessing the approximate values of the hydrogen demand and electrolysis capacity in the near future, as the main way to supply a solution to the actual gas and carbon dependency in Spain.

By achieving these objectives, this report aims to provide valuable insights into the comparative dynamics of energy transition in Spain and Denmark. It will serve as a resource for policymakers, researchers, and stakeholders involved in shaping the future of sustainable energy systems in both countries.

In line with the objectives set for the study, three main research questions are proposed, which in turn are extended to a series of sub-questions, guiding the analysis in a more targeted manner.

- Main research question 1: What are Spain's future plans and how aggressive must they be to follow Denmark's steps?
    - Which renewable sources are planned to be pushed in Spain?
    - How does the geography, dimensions and climate affect the development of existing sources?

    - How does the plans for Spain in 2030 and 2050 look like compared with Denmark's future possible cases?
- Main research question 2: How much hydrogen demand and electrolysis capacity for 2050 would be required in order to fulfill the objectives set by EU and Spain?
    - Is the predicted hydrogen storage capacity essential?
    - How are the ending-use sectors affected by the implementation of hydrogen?
    - In which ways is the use of hydrogen in Spain similar or different to Denmark's?

The hypothesis of this research is that, on one hand, the difference in climate and geography will strongly condition the main dissimilarities between both countries. On the other hand, it is thought that hydrogen is indispensable for the revolution of the industrial and transport sectors, as these two pollute in the processes of their operation and their functioning must change completely. In addition, it has also been thought that hydrogen demand levels will be similar in Spain and Denmark by 2050, as it is known that hydrogen is a priority for both countries and the future of hydrogen is dependent on the collaborative international effort of its research and development stages.

# 2. Present Framework

## 2.1. Energy Goals in the European Union

The EU has set ambitious targets for transitioning to a sustainable and decarbonized energy system. The EU aims to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels, as part of its broader climate objectives under the European Green Deal. This policy framework seeks to make the EU the world's first climate-neutral continent by 2050, achieving net-zero greenhouse gas emissions. (European Commission, 2019)

The EU, therefore, hopes to transform "an urgent challenge into a unique opportunity", by promoting the European Green Deal (proposed by the President of the European Commission in 2019); a new growth strategy with the aim of reshaping the European landscape into a society characterized by equity and prosperity, being the ultimate goal achieving climate neutrality and improving the quality of life of citizens.

To meet these ambitious targets, the EU has revised its Renewable Energy Directive, increasing the binding renewable energy target to at least 42.5% of total energy consumption by 2030. This revision reflects the EU's commitment to significantly scaling up renewable energy deployment across member states. Key strategies to achieve these goals include boosting energy efficiency, integrating energy systems and promoting innovative technologies. (European Commission, 2023)

Boosting energy efficiency is a cornerstone of the EU's approach, aimed at reducing overall energy consumption while enhancing the performance of the industry, and transportation systems. By improving energy efficiency, the EU not only cuts emissions but also lowers energy costs and reduces dependency on external energy supplies, something that several European countries suffer from.

Integrating energy systems is another critical strategy. Facilitating the seamless operation of electricity, heating, cooling, and gas networks across the continent is seem as vital. The EU's focus on innovative technologies includes investing in research and development to advance renewable energy solutions, energy storage systems and smart grid technologies. Such innovations are crucial for overcoming the intermittency of renewable energy sources like solar and wind and for ensuring a reliable energy supply.

These initiatives are designed to ensure a sustainable energy supply across the EU, while fostering economic growth and technological innovation. By leading the global transition to a low-carbon economy, the EU not only addresses environmental challenges but also positions itself as a leader in green technology and sustainable development. This comprehensive approach underscores the EU's dedication to building a resilient and future-proof energy system that benefits both its citizens and the global community.

## 2.2. The Current Energy State in Spain

### 2.2.1. Spain's Present Energy Demand

Spain has made significant strides in its energy transition, leveraging its abundant renewable energy resources, particularly solar and wind. According to Spain's Electrical Network (REE), as of 2023, Spain's energy mix is diversified with notable contributions from wind (23.5%), solar (15,80%), nuclear (20.3%) and natural gas (21.43%). Figure 1 shows the distribution of every energy source in Spain. The country has a total energy demand of approximately 250 TWh, with a per capita consumption of around 5150 kWh. (REE, 2024)

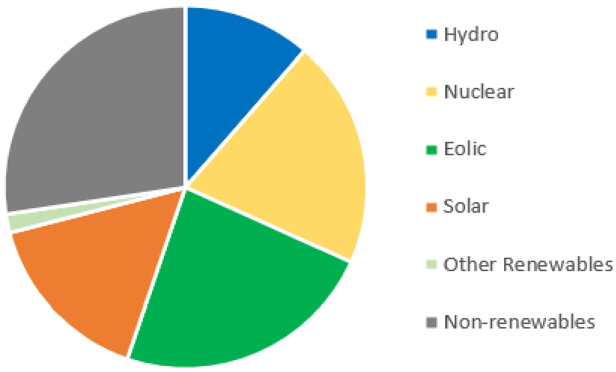



*Figure 1 Present energy supply mix in Spain*

Comparing with previous data, 2018 seems to be the year with a higher energy demand, however, the difference between years is minimal and the only two conclusions obtainable from them should not interfere with the future calculus' veracity in this document. The first conclusion is that the bigger change happens in 2020, where the total demand decreases almost 15,000 GWh. The reason behind this is Covid-19 and this phenomenon is not directly related to the current situation nor the future plans, as these were conceived after the pandemic. The second conclusion would be that the energy consumption is decreasing, as the last few years show a negative slope. The data could reflect the impact of the Spanish government's efforts to decrease the countries energy dependency, and thus, ease the way to fulfill the established goals. Since the annual change is not notable enough, this detail will not be considered when the future is analyzed later in the report. (REE, 2024)

Looking deeper into the monthly demand distribution, it is apparent that winter and summer are the seasons where more energy is utilized. This inclination is related to both heating and cooling necessities of the country and are discernible in other near countries. Figure 2 shows the exact distribution for the last two years. (REE, 2024) (EMBER, 2024)

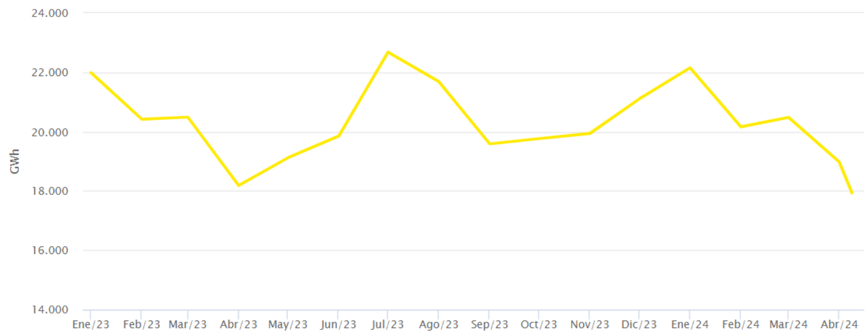



*Figure 2 Monthly demand of the last 2 years in Spain (REE, 2024)*

The self-consumption of energy, particularly through rooftop solar panels, has grown more rapidly than previously anticipated. This growth is partly due to favorable policies and incentives that encourage households and businesses to install solar photovoltaic (PV) systems. As a result, decentralized energy production is becoming an increasingly important component of Spain's energy landscape, contributing to reducing grid dependency. (Endesa, 2023)

Current developments in energy storage technologies are pivotal for Spain's energy transition. There are several pilot projects and operational facilities focusing on hydrogen battery storage, pumped hydro storage and thermal storage. These technologies are crucial for managing the intermittency of renewable energy sources, ensuring a reliable energy supply and enhancing grid stability. With respect to exact policies, Spain contemplates a variety of situations, that will depend on the immediate development of the mentioned technologies.

Spain's progress in energy transition is supported by robust regulatory and policy frameworks. The government provides various incentives and subsidies to facilitate the growth of renewable energy projects. Regulatory support is essential for attracting investments and fostering innovation in the energy sector.

### 2.2.2. Spain's Industrial Sector

This value sits just above the electricity use of industrial process, which at 25.6% of the total demand share, is consumed at around 1300 kWh pe capita. The percentual value aligns with the average of the European Union and it has been maintained stable since 2008. In volume, Spain's industry is the fourth biggest in Europe; just behind Germany, France and Italy. Additionally, the energy intensity index is also in compass with the rest of the European industry. (Opina360, 2023)

Energy is what makes the industry possible and, in Spain's case, natural gas is the main source with a big margin. While the second largest source is electricity with a 32.4%, natural gas is used as the industry source in the 43.5% of the cases. This dependency has undergone a gradual increase in the last 15 years and still shows a growing slope. This reliance is not only way higher that the European average, but also the more substantial than in the bigger industries, where they account for a maximum of 35.6% share. (Opina360, 2023)

On the positive side, the renewable energy consumption within the sector escalates uniformly. Both the electricity generated renewably and the heat attained from environmentally safe origin are being used more each year. In 2021, 25.1% of all the energy used in Spanish industries of all kinds was renewable energy. This is larger than in the bigger industries and a few points above the European average of 22.3%. This figure varies significantly between the different industry areas. Spain is a country with diverse industrial practices and while the wood industry uses around 75% of renewable energy to operate, the chemical plants are estimated to consume only 11.2% of renewable sources. Figure 3 shows the progression of the green electricity and green heat use, while Figure 4 depicts the estimated consume of renewable sources in each Spanish industry. (Opina360, 2023)

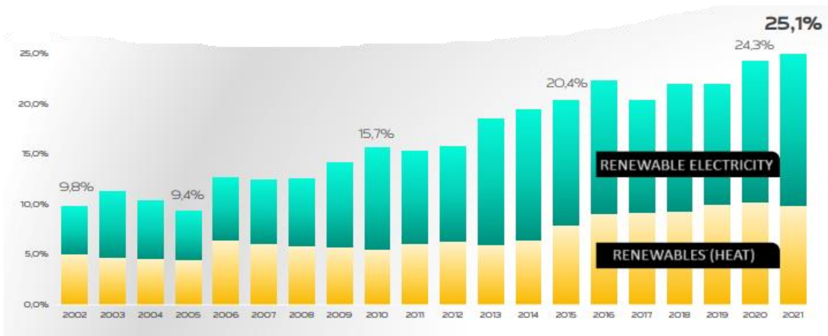



*Figure 3 Use of renewable sources in Spain since 2002 (Opina360, 2023)*

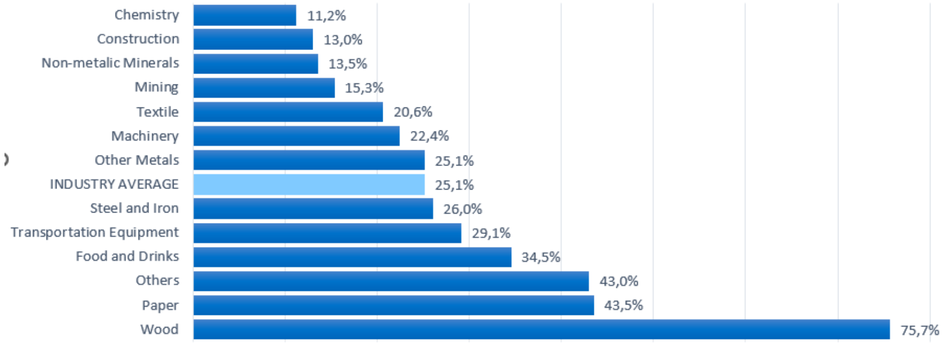



*Figure 4 Use of renewable sources in each Spanish industry (Opina360, 2023)*

### 2.2.3. Spain's Transportation Sector

The sector with the highest demand is the transportation, where the per capita demand averages at around 7500 kWh, way above the other cases. The weight of transportation in the energy share is larger than what it can be seen in most European countries with similar conditions. Transportation in Spain counts up to 38.6% of the total energy demand nowadays, around 8% more than the EU average. In this particular case, the diversity in the connections between different lands and the complex orography of the country ask for a mixture of different means of transportation, which hinders the calculation of the total demand. (Spanish Ministry of Transport, 2020)

Analyzing further into the different transportation methods, the aviation and marine means have endured a distinguishable increase in their consumption. While air transport consumed around 33% more energy in 2018 than in 2013, the sea transport almost doubled the demand. The other areas, the road and railway transportations, seem to show a stable state, where the gradient between the mentioned years does not reach the 10%. (Spanish Ministry of Transport, 2020)

It must be mentioned that the road transportation is by a great amount the main mean of transport for Spaniards, as more than the 90% of the energy consumption is utilized this way. This supposes a big difference. According to Spanish Ministry of Transport and Sustainable Movility, the energy consumption per kilometer and traveler is around 3 times bigger in the road than by railway transport, as shown in Figure 5. (Spanish Ministry of Transport, 2020)

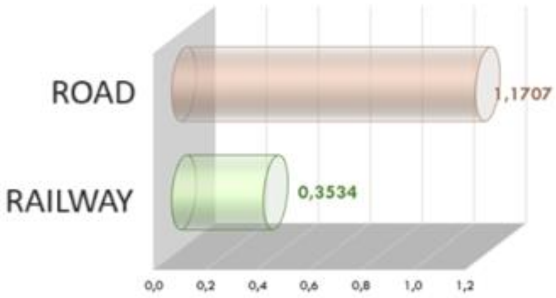



*Figure 5 Energy consumption in transports per traveler [TJ/pers./km] (Spanish Ministry of Transport, 2020)*

Currently, while the adoption of electric vehicles (EVs) is increasing, the pace is slower than anticipated. Barriers include the higher upfront cost of EVs, limited charging infrastructure and consumer concerns about range and battery life. The development of infrastructure supposes significant investment, planned to expand the EV charging network across the country. This includes installing fast chargers on highways and in urban areas to alleviate range anxiety and promote EV adoption.

#### 2.2.4. Spain's Heating and Cooling Demand

As previously mentioned, the heating and cooling demand is complex and variable. According to ADHAC's 2023 census, there are almost none exclusively cold networks and while 490 networks are only intended to supply heat, 40 networks can act as both heater and coolers. However, these do not have the same dimensions or capabilities. While heating exclusive networks sum a total of 812MW of installed power, mixed networks count with a similar 818MW of installed power. (ADHAC, 2023)

When splitting the system exclusively by the final use, the 79% of the installed power is utilized for heating and the rest for cooling. Nonetheless, in 2023, the considerably high temperatures asked for more cooling than usual. This is one of the reasons behind the final energy demand, as cooling supposes the 29% of the energy demand, with around 450 GWh. On the other hand, heating's demand sums a total of around 1100 GWh. (ADHAC, 2023)

Spain's consumption is characterized by regional variations. Overall, heating demand is notably higher than cooling, reflecting the diverse climatic conditions across the country. In regions with colder winters, such as the northern parts, heating is a critical energy need, whereas cooling demand is more prominent in the southern and coastal areas during the summer months. Figure 6 shows the detailed distribution of how much heating and cooling power is installed in each region. (ADHAC, 2023)

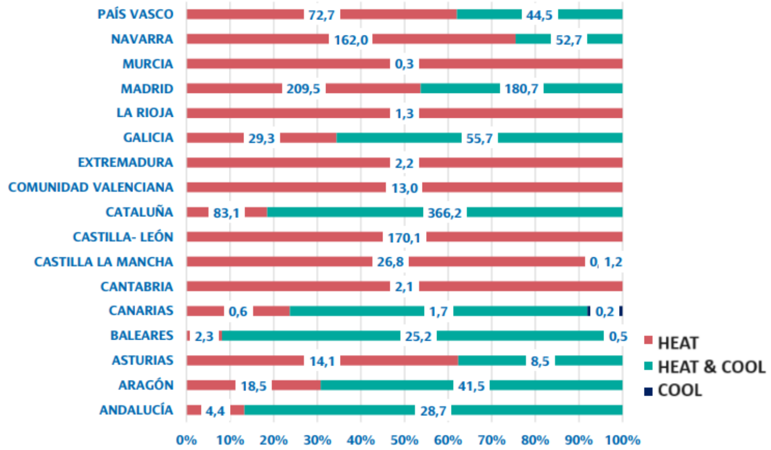



*Figure 6 Installed power of different networks classified by Spanish regions (ADHAC, 2023)*

The distribution trough the different regions is not only set by the climate but also the different heating policies between provinces. These policies re closely related to the development level of each regions industry and overall economy. Figure 7 shows how the places with stronger industrial economies require of more heating and cooling power; being these regions Catalonia, Madrid, Basque Country and Navarra. (IDAE, 2020) (ADHAC, 2023)

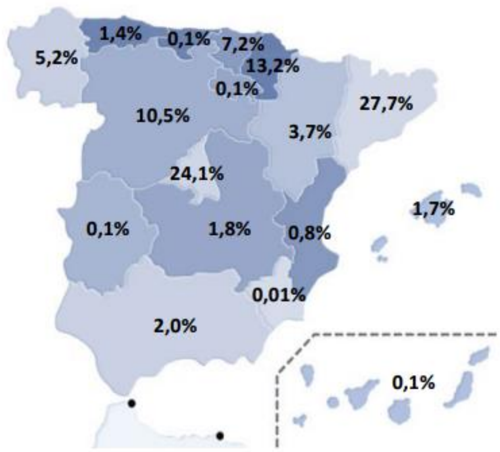



*Figure 7 Total heating plus cooling power installed in each Spanish region, represented in a map (ADHAC, 2023)*

### 2.2.5. Spain's Energy Supply Mix

Looking at the data collected last year by the Spanish Electric Network (REE) the country's energetic diversity arises. As shown in Figure 1 in the beginning of this chapter, 60% of the share is divided between the 3 biggest suppliers: eolic, combined cycles and nuclear plants. A great deal of the energy is produced by renewable sources, but there are a few key differences between each case that can be relevant for this report.

The mentioned wind generation not only is the leader of the mix, but also one of the biggest gainers in the past couple of years. Its environmental benefits and the maturing of off-shore infrastructure are the basis of its present and, presumably, future growth. This continues the example of countries with similar capabilities, such as Denmark.

The following most present sources exhibit opposed conditions. Hydraulic power plants have already been constructed at the top of their potential, as they depend on pinpoint grounds with tall water jumps. From the 640 kWh per capita that comes on average from hydraulic sources, around 110 kWh are produced from pumping turbines, which make use of pumps and the energy price variability to recycle and storage water. This last ability to control the time of energy production aligns with the objectives of the energy plans proposed by the Spanish institutions and its ongoing development is arranged to continue in the next years, within each plant's adaptation's viability and the economic profitability. (REE, 2024)

With respect to the solar energy generation, some observations can be made. Despite the considerable potential of areas with high temperature gradients, photovoltaic parks supply more than 7 times more energy than thermal parks. There are two main reasons for this, the first being the lower initial investments of the photovoltaic plates and the second the development of both technologies in the last decades. Spain's solar capacities are second to none in the continent, though the low efficiencies of these energy sources are way behind those of other green sources. For instance, current photovoltaic plates count with a solar conversion efficiency of around 20% and it averaged at 15% just a few years ago. The rated power has noticeably expanded too, up to 370 W. The progress in the use of new materials and microstructures continues to improve the possibilities of the photovoltaic parks and their expansion through the mainland of the country is planned to maintain the growing trend. (Cambio Energético, 2019)

Unlike other European countries, nuclear energy remains a crucial part of Spain's energy mix, contributing about 55 TWh annually. Despite plans to phase out nuclear power in the long term, it currently provides a stable and substantial portion of the country's electricity supply. (REE, 2024)

Coming back to solar thermal parks, it must be commented that they have not seen the photovoltaics' proliferation, despite the efficiencies of about 80% they often display. This source shows some building and maintenance complexities that justify the government's lack of interest in the field. The attractiveness of this sector has increased the most in this decade, due to the energy storing capabilities some thermal plants show. This advantage is also taken into account within the country's imminent energy plans, as it will be discussed later in future sections of the report. (Cambio Energético, 2019)

As mentioned before, Spain relies significantly on natural gas for electricity generation, industrial processes, and residential heating. Currently, natural gas accounts for approximately 21.43% of the country's total energy supply. Due to limited local reserves, Spain imports most of its natural gas via pipelines from Algeria and France and through liquefied natural gas (LNG) shipments from other global suppliers. This heavy dependence on imports makes Spain vulnerable to geopolitical tensions and market fluctuations, impacting energy security and economic stability. To address these challenges, Spain's near- and long-future plans aim to reduce natural gas dependency by expanding renewable energy capacity, promoting energy storing technologies and enhancing energy efficiency. (Agence Ecofin, 2024)

Nowadays, very negligible hydrogen supports the energy mix and it must be noted that the used hydrogen does not display the future situation this report will dissect in upcoming sections. Within the hydrogen generation variation, Spain is as environmentally irresponsible as the rest of the EU, where 96% of the hydrogen comes from natural gas. Only a small production of the annual 500,000 tons of hydrogen is classified as green hydrogen, produced through renewable energy-powered electrolysis. The relevant types of hydrogen are later explained in more detail in this report. (European Commission, 2019)

## 2.3. Comparation between Present Spain and Denmark

Comparing Spain with Denmark reveals distinct approaches and contexts in their energy transitions. Denmark, known for its pioneering role in wind energy, generates 57% of its energy from wind and has a strong focus on biomass. With a total energy demand of 35 TWh and a per capita consumption of about 6000 kWh, Denmark is less reliant on fossil fuels compared to Spain. Still, both countries are dependent on non-renewable energy imports, though the nature of their dependencies differs. A more detailed dissection of both countries energy mix is shown in Figure 8, where is clear how much more diverse Spain's mix is. (Deloitte, 2016)

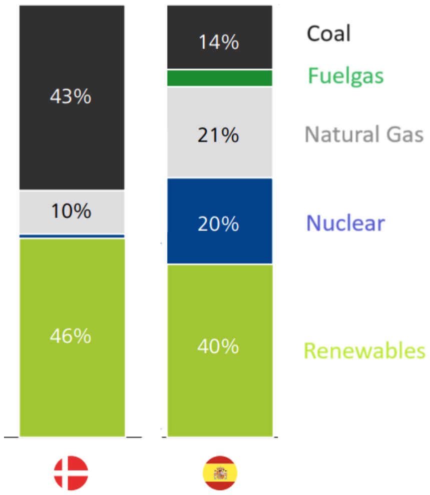



*Figure 8 Relative distribution of energy sources within each country's demand (Deloitte, 2016)*

Spain imports most of its natural gas from various international suppliers, which makes it vulnerable to geopolitical and market fluctuations. Similarly, Denmark relies on importing natural gas and biomass, mainly from the Baltic countries and Russia, to meet its energy needs. This import dependency highlights the importance of diversifying energy sources and increasing domestic renewable energy production in both countries to enhance energy security and sustainability.

Moreover, Spain faces significant cooling demand, especially during the hot summer months, which adds to its overall energy consumption. The high temperatures experienced in many regions, especially in the southern and central parts of the country, drive the need for air conditioning and other cooling technologies. This contrasts with Denmark's energy necessities, where heating demand is more predominant than in Spain due to colder winters. These differing climatic needs influence their respective energy strategies and infrastructure investments.

As mentioned before in this report, the heating and cooling networks are quite complex in Spain due to geographical variations between the mainland and the islands, the large dimensions of the country and its mediterranean location. Denmark's heating approach is less demanding and has invested significantly in district heating systems, which are highly efficient and can integrate various energy sources, including waste heat, biomass, and increasingly, renewable energy.

Different heating and cooling configurations ask for different investments. While Spain is focusing on improving energy efficiency in cooling systems and retrofitting buildings to reduce energy consumption during the hot summer months, Denmark emphasizes high standards of insulation and building efficiency to minimize heating demand and maximize the effectiveness of heating systems. Nevertheless, Spain's heating demand is still 3 times larger than the cooling demand, and the focus on the cooling networks improvements does not mean that the country is not equally approaching heating and heat insulation technologies with care. (ADHAC, 2023)

The other big differences between both countries' current state can be found in the transportation sector. On one hand, Spain's per capita energy demand for transportation is severely higher than Denmark's. The reasons behind this are not clear but it may be because of the different lifestyle or the fact that Denmark has a more developed public transport infrastructure. This report comes back to the possible assumptions of this circumstances later, after having analyzed Spain's related future policies in depth.

On the other hand, the electric vehicle adoption rate is way higher in Denmark (130,000 vehicles, around 5% of the total national vehicle fleet) than in Spain (250,000, approximately 1%) nowadays. This comes along with the charging and maintenance infrastructure required for the EVs to function correctly and be seen as attractive for the customers. The government support for this technology have come much later in the mediterranean country and severe economic investments in this matter have not been made until the last presidency. (Invest in Spain, 2021) (Nicholas & Wappelhorst, 2021)

## 2.4. Hydrogen Generation and the Role of Hydrogen in Denmark

Hydrogen is the most abundant element in the universe, known for its potential as a clean energy carrier. It exists naturally in compounds such as water and hydrocarbons, but not in a free state, requiring extraction for use as a fuel.

There are a few types of hydrogen classified by their origin. Gray hydrogen is that produced from natural gas through steam methane reforming processes. Blue hydrogen is also produced by the same machinery, but it incorporates carbon capture and storage (CCS) technologies to reduce environmental impact. Green hydrogen is produced through the electrolysis of water using renewable energy sources such as wind, solar, or hydropower. This method generates zero carbon emissions, making it the most sustainable option. Electrolysis consists of a process that splits water into hydrogen and oxygen using an electric current. There is a certain efficiency attached to the process, and thus, more energy than the one residing in the green hydrogen must be deposited initially. (H2lac, 2022)

Hydrogen plays a vital role in Denmark's strategy to achieve a sustainable and decarbonized energy system. Drawing insights from the study " The role of electrification and hydrogen in breaking the biomass bottleneck of the renewable energy system: a study on the Danish energy system ", hydrogen is integral to Denmark's efforts to reduce reliance on fossil fuels and enhance energy security. (Mortensen, et al., 2020)

Denmark's substantial wind energy capacity often results in a surplus of electricity production. Hydrogen provides a solution for storing this excess energy through electrolysis, converting it into hydrogen gas that can be stored and used later. This approach helps stabilize the grid and ensures a continuous energy supply even when wind energy production is low. Besides, the inexistence of hydraulic plants makes impossible to store energy by reverse pumping like in other countries. The reason behind this is orographic, so future turbine and pump installations are not planned to happen.

Hydrogen is crucial for decarbonizing sectors that are challenging to electrify directly, such as heavy industry, maritime transport, and long-haul aviation. By using hydrogen as a fuel or feedstock, Denmark can significantly reduce emissions in these sectors. The study emphasizes that hydrogen, combined with electrification, can break the reliance on biomass, thus providing a more sustainable and versatile energy system.

Denmark's hydrogen strategy is backed by strong policy frameworks and international collaboration, particularly within the European Union. Policies and funding support research, development, and deployment of hydrogen technologies, ensuring alignment with broader EU climate goals. (IEA, 2023)

Overall, hydrogen is a cornerstone of Denmark's comprehensive approach to achieving carbon neutrality, enhancing renewable energy integration, and driving economic development through green technology.

# 3. Methodology

## 3.1. General Research Approach

This report employs a systematic research approach to analyze and compare the energy transitions of Spain and Denmark, focusing on their current and future scenarios. In order to answer the two fundamental research questions for the study, a distinct approach is adopted to answer each of them, recognizing their divergent nature and requirements. Emphasis is placed on using the most reliable and official sources to ensure the accuracy and credibility of the findings.

The first question ("What are Spain's future plans and how aggressive must they be to follow Denmark's steps?") seeks the dissection of both quantitative and qualitative data. It must be considered that the measures proposed by the countries are flexible and their preciseness dependent in external factors. This is why the published policies for 2050 are not as detailed as those for 2030. This report will examine the upcoming steps to achieve the goals set for 2030 to fulfill two objectives. First, to gain more quantitative details about the path that Spain is going to follow until 2050, and second, to understand which measures are set for immediate appliance and which are designed for later. In order to ensure the trustworthiness of the results, an exhaustive recollection and analysis of the data in the plans published by the Spanish government and the European Commission will be carried out.

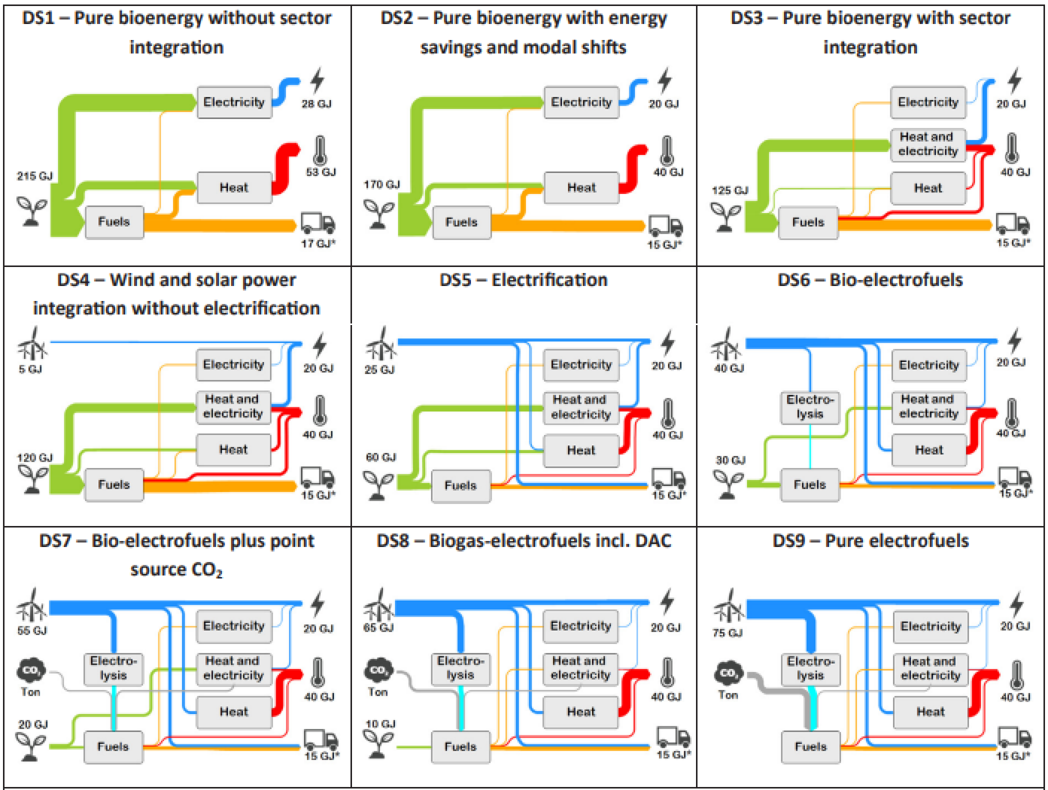
Following this, the second research question ("How much hydrogen demand and electrolysis capacity for 2050 would be required in order to fulfill the objectives set by EU and Spain?") pursues an approximate numerical and diagram-based answer. The calculations to estimate the hydrogen demand and the electrolysis capacity needed to achieve Spain's energy transition goals involve: the use of the current energy consumption analysis carried out in this project, the estimation of the amount of hydrogen required to replace fossil fuel energy based on energy equivalence, the calculation of the electrolysis capacity needed to produce the required hydrogen considering efficiency and technology advancements and the assessment of the potential for integrating hydrogen production with Spain's renewable energy resources and different ending-use sectors. A development of the methodology of the mentioned calculations is later explained in this report.

To sum up, following data collection, data analysis techniques are employed to extract meaningful insights and patterns. The ambitions of this report require of quantitative evaluation of official data and the transversal reasoning of the state of developing technologies and alterative policies.

### 3.2. Generic Design Strategies

As mentioned before, this project is built upon the insights presented in the article "The role of electrification and hydrogen in breaking the biomass bottleneck of the renewable energy system: a study on the Danish energy system”. This study outlines the so-called "Generic Design Strategies" aimed at achieving a sustainable and decarbonized energy system in Denmark. These strategies propose various combinations of electrification and hydrogen integration to optimize renewable energy use and reduce dependence on biomass and fossil fuels. (Mortensen, et al., 2020)

The Danish Generic Design Strategies provide a comprehensive framework for transitioning to a renewable energy system, focusing on maximizing the use of wind and biomass resources while incorporating hydrogen as a key energy vector. The designs are tailored to Denmark’s unique geographic and climatic conditions, which are highly favorable for wind energy production. The strategies that are supposed to align better with the upcoming times seek a higher integration of the hydrogen storage capabilities in both the electricity generation and as a transport propellant, along with a transversal connection between the renewable sources that should decrease the biomass overreliance. The recollection of the 9 Danish Generic Design Strategies diagrams is shown in Figure 9.




Legends/icons:
**Wind turbine**; wind power, solar power, and wave power, **cloud**; carbon dioxide from point sources and the air, **plant**; all types of biomass, **flash**; electricity demand, **thermometer**; heating demand, **truck**; all transportation demand in mechanical energy
**Blue**; electricity, **red**; heat, **orange**; fuels e.g. methane, jet fuel, methanol, etc., **grey**; carbon dioxide, **turquoise**; hydrogen
*Mechanical energy

*Figure 9 The 9 Generic Design Systems proposed in the study "The role of electrification and hydrogen in breaking the biomass bottleneck of the renewable energy system: a study on the Danish energy system" (Mortense, et. al., 2020)*

Unlike Denmark, Spain has already set a clear and ambitious path towards decarbonization, as outlined in its Long-Term Strategy for a Modern, Competitive, and Climate-Neutral Economy by 2050. Spain's strategy includes specific targets and measures to reduce greenhouse gas emissions, increase the share of renewable energy, and enhance energy efficiency. Given the existing framework and targets set by Spain's decarbonization plans, this project will focus on the Danish Generic Design Strategy that most closely aligns with Spain's strategic goals. This means that the hydrogen storage plants integration rate will be considered high and its mass-construction plausible within the proposed Spanish scenario. (Spanish Government, 2020)

For the calculations and the visualization of the results in later chapters of this report, three strategy diagrams have been designed. The first one reflects a case where the use of conventional sources is still fueling the system, in a similar structure as DS8. It will be depicted as a pseudo-DS8, where the main alterations are that the biomass is substituted by gas and coal, electricity has been separated into industrial and residential ending means and heating is divided into cooling and heating. The second case is represented as a pseudo-DS9 with the same alterations, the only difference with respect to the previous case being that the generation of fuels is only supplied by the renewable energy mix. The third type of strategy diagram represents the DS9 with the only alteration of expressing the ramification of the industrial sector. In all of them only GJ is shown to improve the readability of the Sankey diagrams.

### 3.3. Hydrogen Demand & Storage Capacity Calculation

Following the assessment of the current energy scenario in Spain and the path that it is arranged to follow, this report is set to determine the hydrogen demand required to replace Spain's current non-renewable energy sources by 2050. The calculations are based on the methodology observed in the article "The role of electrification and hydrogen in breaking the biomass bottleneck of the renewable energy system: a study on the Danish energy system”. (Mortensen, et al., 2020)

By integrating the insights from the Danish study with Spain's fixed decarbonization path, this project aims to provide a comprehensive analysis and actionable recommendations for Spain's transition to a sustainable and climate-neutral energy system by 2050. This approach ensures that the research aligns closely with Spain’s existing policies and leverages proven strategies from Denmark to enhance the effectiveness of Spain's energy transition. This means that it will be assumed that by 2050 only 10% of the small vehicles will be hybrid, almost no gas cars will be in distribution and only 20% of heavy vehicles will use conventional gas, as all trains will be electrified.

In order to approximate the attempted final values, some initial assumptions and hypotheses must be declared. The main assumption would be regarding the collected data. It will be considered that the values collected from the reports of 2023 and previous years’ summaries reflect the situation of the current situation. Additionally, it will be supposed that all the target valued proposed at PNIEC will be met, and thus, the decarbonization plan should also be fulfilled in the electrification and hydrogen generation capabilities it yearns for.

Furthermore, since quantitative results are the goal, a couple of numerical values must be set. These values are based on established scientific principles and industry standards. As a hypothesis, it will be stated that the energy equivalency of the hydrogen is 33.6 kWh/kg. This value represents the amount of energy that can be obtained as the output of one kilogram of hydrogen, providing a basis for calculating the total energy required to replace non-renewable sources. In addition, the electrolysis efficiency will be set at around 65%. This efficiency rate is typical for current electrolysis technologies and provides a realistic foundation for calculating the energy inputs required for hydrogen production. Even though the technology is still developing nowadays, different methods show efficiencies with the range of 60-70% and an average value is set to be used in this report. Additionally, it is assumed that hydrogen will be generated through 8,000 of annual operating hours. It must be also considered that the hydrogen capabilities remain stable through time, and so, hydrogen generated 20-25 years prior will maintain its energy generation potential. (García, 2023) (Troncoso, 2021) (The Danish Energy Agency, 2016)

Ultimately, it will be assumed that the Spain's population's size, consumption habits and transportation necessities will stay the same as at present. This will help setting a needed context for the results and will give veracity to the upcoming comparations and their conclusion.

The calculation of the hydrogen demand will be set to ensure all the energy sectors. Precisely, in this report it will be measured the limits of the required hydrogen demand in order to completely renounce on the gas, coal and nuclear plants. There are some countries that are planning on continue working with nuclear power due to being non-renewable but green source of energy, but this analysis is designed around Spain, where the future does not consider this technology adequate.

Alongside this, the electrolysis capacity to ensure this change's viability must be analyzed. The two limits of the demand will come from the worst-case scenario, where the plans for network interconnection and transportation electrification have been fulfilled but the energy mix has not shown any change toward renewability, to the best-case scenario, where the mix has been optimized to achieve the European goals and the needed hydrogen must only supply a minimum in the mix and transportation. This second limit is described in this report as "best-case" taking into account the current context; future technology breakouts or new stronger policies may achieve higher or more efficient hydrogen integration. These two limiting situations will be represented as the first to cases of the strategy diagrams, the pseudo-DS8 and pseudo-DS9, respectively.

With respect to the calculations themselves, just a few steps will be taken. Firstly, it is imperative to set the total energy that in each case will be covered by hydrogen. For this, the sum of the dissected pollutant energy in each case should be enough. Using the hypothesized energy equivalency value and the proposed generation efficiency, a few simple combination of unit change and divisions would give the weight of the hydrogen demand and the electrolysis capacity. The formulas represented in Figure 10 show the precise application of these concepts.

$$Hydrogen\ Demand\ [tons] = \frac{Non - renewable\ Energy\ [TWh] *\ 10^6}{33.6\ kWh/kg}$$

$$Hydrogen\ Demand\ per\ capita\ [GJ/pers.] = \frac{Non - renewable\ Energy\ [kWh]}{Population\ [pers.] * 277.77\ [kWh/GJ]}$$

$$Required\ Electrolysis\ Energy\ [TWh] = \frac{Non - renewable\ Energy\ [TWh]}{0.65}$$

$$Electrolysis\ Capacity\ [GW] = \frac{Required\ Electrolysis\ Energy\ [TWh] * 1000\ [GWh/TWh]}{8000\ [h]}$$

*Figure 10 The 4 main equations used in the later calculation of hydrogen demand and electrolysis capacity*

# 4. Results

## 4.1. Spain's Future Plans

### 4.1.1. National Integrated energy and Climate Plan 2030

Spain's National Integrated Energy and Climate Plan (PNIEC) 2021-2030 is designed to transform the nation's energy system, significantly reduce greenhouse gas emissions and enhance energy efficiency. This plan aligns with the European Union's overarching climate goals and sets ambitious targets for renewable energy adoption, the electrification of the transportation sector and the development of a hydrogen economy. These efforts are not only crucial for meeting different climate targets but also for ensuring long-term energy security and economic growth. (Spanish Government, 2023)

A cornerstone of the PNIEC is the aggressive expansion of renewable energy sources. By 2030, Spain aims to generate 74% of its electricity from renewable sources, a significant increase from the 40% achieved in 2020. This objective highlights the country's commitment to leveraging its abundant natural resources, particularly solar and wind energy. (Spanish Government, 2023)

Spain plans to substantially boost its solar photovoltaic capacity, aiming to reach 39 GW of installed power by 2030, up from approximately 10 GW in 2020. The nation's high solar irradiance, especially in southern and central regions, provides a strong foundation for this expansion. Alongside solar, wind energy remains a critical component of Spain's renewable strategy. The goal is to increase onshore wind capacity to 50 GW by 2030, with additional investments in offshore wind projects coasts to harness the consistent maritime winds at the Atlantic coast. Hydropower will continue to play a role, though the focus will be on modernizing existing facilities to improve efficiency. Biomass energy will be primarily used for combined heat and power (CHP) applications, supporting both energy generation and rural development. (Spanish Government, 2023)

To manage the intermittency of renewable sources, Spain aims to develop 6 GW of energy storage capacity by 2030. This will involve a mix of growing technologies, including pumped hydro storage, hydrogen batteries and solar thermal storage solutions; ensuring a stable energy supply even when renewable generation is low. (Spanish Government, 2023)

PNIEC places significant emphasis on the electrification of the transportation sector, a crucial area for reducing emissions and improving air quality. Spain targets having 5 million EVs on the road by 2030. This ambitious goal includes both private passenger cars and public transport vehicles. To support this transition, Spain has taken inspiration from neighboring countries. The plan provides various incentives, such as tax breaks and subsidies, to encourage the adoption of EVLs.

A robust network of EV charging stations is essential for this electrification effort. Spain plans to install at least 100,000 public charging points by 2030, ensuring accessibility across both urban and rural areas. The electrification of public transport is also a priority. Spain intends to transition its bus fleets to electric or hydrogen fuel cell buses, particularly in cities. This last step is politically the most complex one, as it depends in the commitment of local political institutions and the turbulent political fluctuations of some areas might suppose an obstacle. (Spanish Government, 2023)

Railway transport is another important area, with efforts to increase the share of electrified railway lines and promote the use of electric trains. This strategy aims to reduce the carbon footprint of long-distance and commuter rail services, further contributing to the overall decarbonization goals.

Hydrogen is identified as a key energy carrier in Spain's transition to a low-carbon economy. The PNIEC outlines specific targets and initiatives to develop a robust hydrogen infrastructure. By 2030 Spain aims to have a renewable hydrogen production capacity of 4 GW, supported by a robust network of hydrogen refueling stations and infrastructure to facilitate its use in transportation and industry. The hoped Hydrogen Roadmap also envisions significant investments in research and development to improve electrolysis efficiency and reduce costs. By 2050, Spain aspires to fully integrate green hydrogen into its energy mix, leveraging its abundant renewable resources to produce hydrogen sustainably. (AeH2, 2023)

Compared to other European countries, Spain is still catching up in terms of green hydrogen production capacity plans. For instance, Germany has set more advanced goals and infrastructure, aiming for 5 GW of electrolysis capacity by 2030. Similarly, France plans to invest heavily in hydrogen technology, targeting 6.5 GW of electrolysis capacity by 2030. Despite this, Spain has made significant strides in setting the foundation for a robust hydrogen economy. The country benefits from its abundant renewable energy resources, which are crucial for scaling up green hydrogen production. AeH2 reports that Spain could produce up to 1,000,000 tons of green hydrogen annually by 2030 if the current plans and investments are realized. This potential positions Spain as a key player in the European hydrogen landscape. (AeH2, 2023)

The plan promotes the creation of "hydrogen valleys," integrated clusters that encompass hydrogen production, storage and consumption. These hydrogen valleys, such as the Andalusian Green Hydrogen Valley, will serve as hubs for innovation and commercialization of hydrogen technologies. In industry, green hydrogen will be used to decarbonize processes in sectors like steel and chemicals, where direct electrification is challenging.

In the transport sector, hydrogen fuel cells are viewed as a complementary solution to battery electric vehicles, particularly for heavy-duty applications such as trucks, buses, and maritime vessels. The development of hydrogen refueling infrastructure is a critical component of this strategy, ensuring that hydrogen can be efficiently and widely used as a clean fuel.

Substantial investments in research and development are also planned to improve hydrogen production technologies and reduce costs. Collaborations with European and international partners are encouraged to accelerate advancements.

#### 4.1.2. Long-term Decarbonization Strategy 2050

Spain’s strategy for achieving carbon neutrality by 2050 is an ambitious and comprehensive strategy designed to transform the country's energy landscape. The planned efforts will not only mitigate climate change impacts but also enhance energy security, create jobs and contribute to economic growth in a sustainable way. The government sees this as an opportunity to improve social and economic aspects of the country. The core pillars of this strategy are the expansion of renewable energy, the electrification of transportation, the refinement of advanced heating and cooling networks, and the large-scale deployment of hydrogen technologies. These measures are detailed in Spain's Long-Term Decarbonization Strategy 2050. (Spanish Government, 2020)

By 2050, Spain aims to transition almost entirely to renewable energy sources, drastically reducing its reliance on fossil fuels. The country is leveraging its abundant solar and wind resources to achieve this transformation. Solar energy, particularly photovoltaic and concentrated solar power (CSP), will play a crucial role due to Spain's high solar irradiance. Southern and central regions are expected to become powerhouses of solar energy, with large-scale solar farms producing extensive amounts of clean electricity.

Wind energy, both onshore and offshore, is another cornerstone of Spain's renewable strategy. By 2050, the installed wind capacity is projected to be one of the highest in Europe, contributing significantly to the overall energy mix. The integration of advanced energy storage solutions, such as next-generation batteries and pumped hydro storage, will be essential to balance supply and demand, ensuring a stable and reliable energy supply. As previously mentioned, Spain is heavily dependent on importing non-renewable energy and the reconstruction of energy sources is planning on reducing it. Figure 11 depicts how achieving climatic neutrality is vital for this role. (Deloitte, 2016)

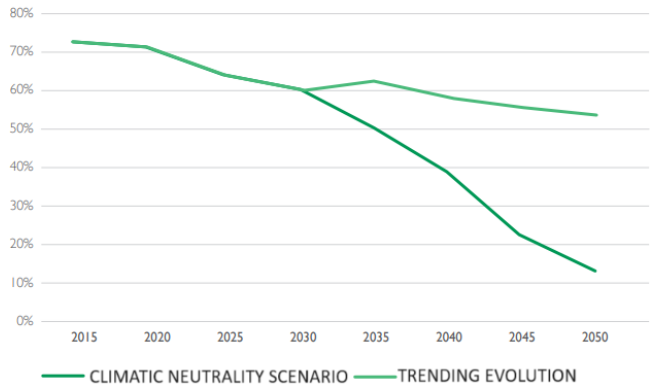



*Figure 11 Estimated evolution of energy dependency (Deloitte, 2016)*

Decarbonizing the industrial sector is critical for fulfilling Spain's 2050 plans. Industries are major consumers of energy and significant sources of emissions. The strategy mainly involves implementing state-of-the-art technologies to enhance energy efficiency and non-contaminant processes across all industrial processes. This includes optimizing production processes, employing smart energy management systems, encouraging industries to adopt on-site renewable energy generation and making use of green hydrogen in industries where direct electrification is not feasible. Hydrogen produced from renewable sources will be especially useful as a feedstock in chemical industries and as a clean fuel for industrial heat applications.

As mentioned before, the approach of this scheme is transversal and plans to interconnect the ending sectors with the hydrogen supply. Within Spanish industry, there are 5 areas where green hydrogen can be implemented in ways outside of electricity generation. On one hand, the high temperatures required in the furnaces of the steel, cement and glass industries could be accomplished by electric means. On the other hand, some select compounds used in chemical and petrochemical industry processes could be substituted by green hydrogen and E-fuels. (Opina360, 2023)

The transportation sector is also a major focus of Spain's decarbonization plan. By 2050, the target is to have virtually all vehicles on the road powered by electricity or hydrogen. This transition involves several key initiatives: Firstly, Spain aims to achieve full penetration of electric vehicles in the passenger car market. The government is supporting this shift with incentives for EV purchases, extensive charging infrastructure, and policies favoring electric mobility over internal combustion engines. Secondly, in heavy and long-distance transport, hydrogen fuel cell vehicles will be crucial. To make this work, Spain plans to develop a nationwide network of hydrogen refueling stations to support this sector. Lastly, in public transport systems are planned to be predominantly electric or hydrogen powered. In the decarbonization plan, the current description of this measure is not as detailed as the others, as its fulfilment heavily depends on regional political situations and the economic viability analysis that different national institutions will carry in the following years. Figure 12 shows the predicted evolution of the electrification of vehicles in the country. (Spanish Government, 2020)

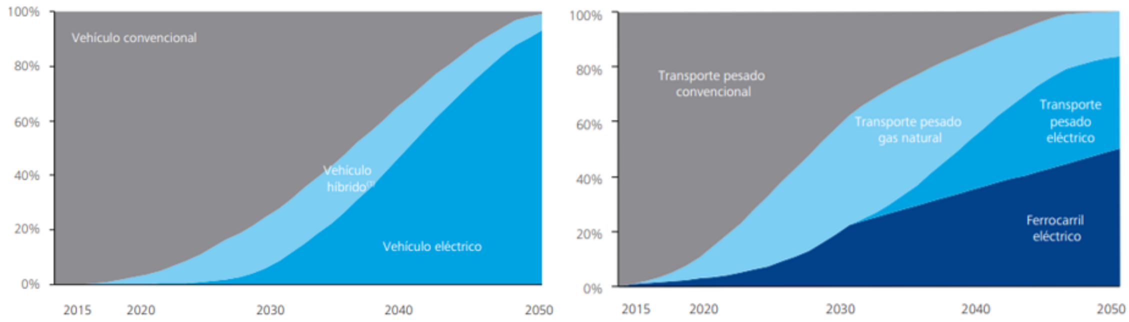



*Figure 12 Evolution of the distribution of electric vehicles within the road transport (left) and heavy-duty or railway transport (right). Light blue shows respectively hybrid road vehicles and natural gas heavy-duty vehicles. Darker blues show variants of EVs (Spanish Ministry of Ecologic Transition)*

Efficient heating and cooling systems are vital for reducing emissions in residential and commercial buildings. By 2050, Spain aims to have implemented broad networks of district heating and cooling that utilize renewable energy sources. Between the planned policies, the simplest measure would be expanding district heating networks that use biomass, geothermal energy and solar thermal energy. The more complex operations can be grouped in two. On one hand, building large-scale retrofitting of existing buildings to improve energy efficiency. This includes installing advanced insulation, energy-efficient windows and modern heating systems. On the other hand, promoting the national use of heat pumps, which are highly efficient for both heating and cooling applications. The execution of these two last measures is heavily influenced by the country's diverse climatic conditions, with northern regions focusing more on heating solutions and the warmer southern regions prioritizing cooling technologies. Adjusting the implementation strategies to regional climate variations will be essential to maximize the efficiency and effectiveness of these decarbonization efforts.

Hydrogen is at the forefront of Spain's long-term decarbonization strategy. The country aims to become a leading producer and consumer of green hydrogen by 2050. In order to achieve this, Spain plans to achieve up to 11 GW of installed electrolysis capacity by 2050. The management of this hydrogen will be developed in hydrogen valleys, which are integrated ecosystems for hydrogen production, storage and consumption. These valleys drive innovation and scale in the hydrogen sector. The Spanish Hydrogen Association (AeH2) estimates that 1.5 to 2 million tons of green hydrogen will be produced annually by 2050. The Spanish ministries claims that this measurement could be even bigger, up to the 3.5 million tons, but this numbers are uncertain and bound to several external factors. (AeH2, 2023)

This technology is planned to seek applications along all sectors crossways. It is stated that green hydrogen will be used extensively in the industrial sector, for heavy-duty transport, and as a backup power source. The establishment of hydrogen refueling infrastructure and the integration of hydrogen in various sectors will be critical for achieving the 2050 targets. During the R+D stages of the upcoming years, collaboration with European and international partners will be crucial for pushing forward technological advancements and creating a robust hydrogen economy.

Another technology set go gain importance in the following years are the carbon capture, utilization and storage (CCS) devices. These will be deployed in hard-to-abate sectors such as cement, steel, and chemical industries. These sectors are significant contributors to Spain's CO2 emissions, and the deployment of CCS is seen as essential to achieving net-zero emissions by 2050. The government is willing to economically invest in the research of the technology and will work in partnership with other European and international bodies. (Spanish Government, 2020)

From the governments point of view, the economic impact that the hydrogen sector will bring is significant. It is expected that approximately 200.000 jobs will be created across numerous sectors. For the resolution of this goal, the budget for the hydrogen industry has been measured to be around €15-20 billion by 2030, scaling up further towards 2050 as the infrastructure and production capacity expand.

#### 4.1.3. Comparation between Future Spain and. Denmark in 2050

As fellow members of the European Union, the ultimate goals of both Spain and Denmark align in matters of sustainability, environmental impact and energy security. Nonetheless, there are key differences induced by each land's characteristics and contemporary energy issues. Some of these are already present today and have been analyzed in ta previous section of this report. For instance, the wind generation predominance in Denmark and the heterogeneity in Spain's renewable energy mix are bound to continue existing in 2050.

One of the biggest contrasts will keep up being in the heating and cooling installations. Denmark already has a well-established district heating system, one of the most advanced in the world. This is why its future efforts will be focused on expanding this system further and optimizing the existing networks into being more efficient and even less contaminant. The situation in Spain is much more complex and much more work has to be put into the implementation of new technologies based in renewable sources into the heating and cooling networks. Aside from this, the large-scale retrofitting buildings with more efficient insulation is nowhere to be found in the Danish plans, as there is no need for it. Logically, al the operations regarding the cooling systems exclusively are only seen in Spain.

The other biggest difference is seen in the transportation sector and follows a similar example. The end goal of both countries is similar regarding every kind of vehicle, but the strong foundation of electric vehicles and well-developed public transport are the reason why Denmark's policies are follow-ups of existing measures and Spain needs to deploy a variety of changes regarding both private and public transport.

By 2050, these two countries should have more similarities than now, at the end of the day, both traced their plans around the European energy goals. In both countries the electrification and implementation of hydrogen are clear objectives among all the sectors, the latest being dependent on the buildout of the technology in the upcoming years. The machinery behind transportation is planned to be the same and the substitution of hydrogen into different industries depend on the industries themselves following the same criteria.

Analyzing each country's plans for the forming of hydrogen parks, both nations will follow the same procedure following the potential they have to invest into it. Even though the difference in size of the land and population are significant, Denmark is planning to produce 15 TWh of green hydrogen by 2030, expanding this demand to 79 TWh by 2050. As calculated in the following section of this project, Spain is set to ensure just about 67 TWh by 2050, which leaves a per capita value of around 9 times smaller. (IEA, 2023)

Denmark's plans to reduce its reliance on biomass by expanding its offshore wind and hydrogen capacities significantly. A critical challenge Denmark faces is the "biomass bottleneck," where over-reliance on biomass can lead to sustainability issues. This kind of situation cannot be seen in the present Spain, and thus the hydrogen generation is not as prioritized.

While both countries' strategies include developing a robust hydrogen infrastructure and transversally integrating green hydrogen production into the energy grid, Denmark is planning on establishing international pipelines to export hydrogen to neighboring countries such as Germany. This approach is set not only supports Denmark's domestic decarbonization goals but also positions it as a key exporter of renewable energy within Europe. On the other hand, Spain's international proposals are centered around the research and developing of the art.

This brief comparative analysis shows how, between two developed countries with the same set of energy goals, the current state of the used technologies in each sector and the progress in the forward-thinking policies are the main reasons that condition future actions. These two qualities seem to be more valuable that the context of the nations in matters like climate and geography, even though there is an obvious connection between the present situation and each country's external circumstances. This does not go against the proposed hypothesis of the project per se, but it does confirm that the weight of the climate and geography are not the exclusive factors if the goals are the same and depend on technological resources.

Nevertheless, both nations seem to follow a hopeful path, where all the environmental and economic targets are set to be accomplished. This kind of conclusions are believed to have the potential to be useful for future research about similar European countries, not only the case of Spain and Denmark. The upcoming energy analysis has been carried out to deepen even more in this conclusion and the viability of the analyzed plans.

#### 4.1.4. Hydrogen Demand & Electrolysis Capacity Calculation

Hydrogen is rapidly emerging as a pivotal component of Spain's energy transition strategy, driven by its potential to decarbonize hard-to-electrify sectors and improve energy generation management. Currently, Spain is in the early stages of developing its hydrogen infrastructure. The limited existing hydrogen use is concentrated in industrial applications, such as refining and chemical production, where it serves as a crucial feedstock.

In order to gauge the dimensions of the future hydrogen demand in Spain in 2050, two limiting situations have been established. Firstly, there is the worst-case situation, where no advances have been achieved in the construction of more and better renewable sources, but other goals have been completed following the Decarbonization Plan.

For this proposed sample, as there is ideal transversal electrification for transportation or industrial means; the sum of natural gas, coal, nuclear and non-renewable waste will amount to the maximum hydrogen demand the country should be able to provide. These three sources sum about 127 TWh of non-renewable non-green energy. Following the energetic equivalency described in the methodology, little above 3,78 million tons of hydrogen would be required to substitute the environmentally unfriendly energy production. This value is clearly superior to the 1,5 to 2 million tons reported by the Spanish Hydrogen Association's (AeH2), even though this measurement is subjected to fluctuate significantly in the nest decades. (REE, 2024) (AeH2, 2023)

Taking the calculated hydrogen demand, the predicted maximum hydrogen generation and the assumptions about the operation of the energy grid; this case can be represented in a variant of the Generic Design Strategy diagram DS8, a pseudo DS8. The version of this strategy diagram supposes the transversal electrification pursued by the country's future plans. This means that industry, cooling, heating and transport will be feed from both renewable energy sources and fuel generated by hydrogen storing technologies and the capture of disposed carbon dioxide. It is assumed that the whole electricity supply of particular use is provided by the renewable plants. Figure 13 shows this Sankey diagram with the data from the calculations made for this section and the demand data for each final use. In order to normalize the analysis for further comparisons; the data is shown in GJ per person per year, national averages have been sorted out and the ending numerical figures have been rounded.

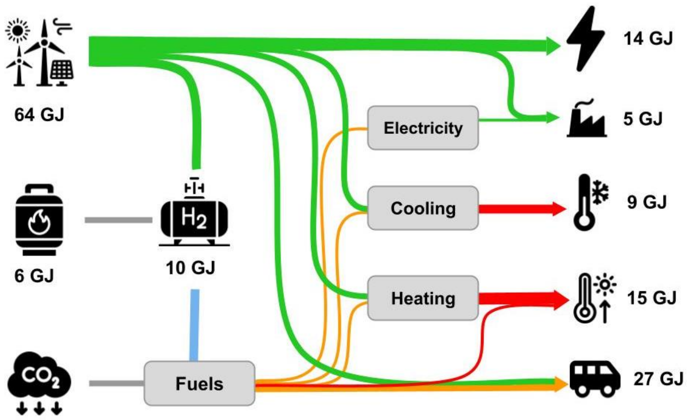



*Figure 13 Pseudo-DS8 strategy diagram, illustrating the worst-case scenario for Spain in 2050*

As can be seen, the impossibility of the high hydrogen demand of 10 GJ/pers./year forces the system to depend on non-renewable sources. The sourcing of this hydrogen demand is set to require a national electrolysis capacity of 24 GW. To supply this huge value, it is estimated that around 6 GJ/pers./year of energy from conventional energy sources would be needed if no progress is done in the improvement of the renewable parks, even though the rest of the main measures are carried out correctly.

The predictions of the plans for 2030 support the unlikelihood of bigger hydrogen generation for a more favorable result in this case. As mentioned previously, by 2030 Spain aims to have a renewable hydrogen production capacity of 4 GW, which is not enough as a waypoint if Spain would have wanted to achieved this non-viable measurement later in 2050. (AeH2, 2023)

Analyzing the reasons behind the optimistic previsions of Spain, its geography and climate provide significant advantages for the generation of green hydrogen. The diversity of green sources caused by these factors is one of the biggest assets for the country's hydrogen plans, compared to other European countries like Denmark. To study how this ideal prediction would exactly work, the best-case scenario has also been quantified. As mentioned, for this case all the main proposed initiatives have been executed, including the 2000 tons of green hydrogen refilling generation. This hydrogen is estimated to require every installed electrolyzer for its generation, all provided by renewable sources. With the value of the 2000 tons of hydrogen in mind, the contribution of around 67 TWh can be gauged, which can be represented as 5 GJ/pers./year. This, along the general performance of the energy networks, can be found in Figure 14.

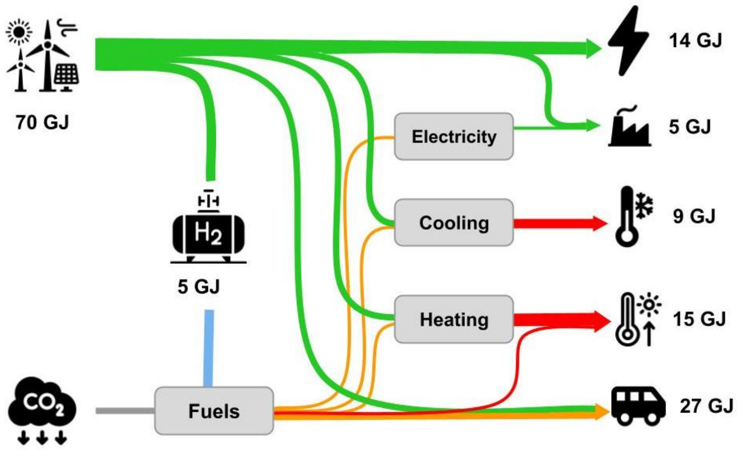



*Figure 14 Pseudo-DS9 strategy diagram, illustrating the best-case scenario for Spain in 2050*

Compared to the first situation, the extra help from more renewable sources supposes the viability of finishing with the significant dependency of Spain with natural gas and nuclear plants. Therefore, it has been proven that the construction of more and better photovoltaic and eolic parks is imperial and the goals set for 2050 will not be achieved if this is neglected. Nonetheless, this does not mean that other measures can be ignored. Ultimately, the optimal exploitation of the hydrogen storing system is closely tied to the ability to wield it for the final use of energy that requires its help. This is why in this report, as a way of analyzing the capabilities of hydrogen, cases where the technology is optimized is examined.

In a previous chapter of this report, it has been explained how green hydrogen would benefit industry and transportation with policies like specific industrial processes improvements and for hydrogen refueling stations construction. Actions like this are not represented in the strategy diagrams shaped in this section of the project. Even so, it is obvious that the hydrogen used for fuel generation will impact these two energies branches. For starters, even though the required energy that must be supplied has not been affected, the vehicles powered with this technology (directly or indirectly through electricity) will not emit pollutants the same way conventional vehicles do.

In the case of industry, the use of green hydrogen for the generation of electricity may affect the functioning of certain plants. Steel production, chemical industry, cement manufacturing, glass production and the petrochemical industry would be strongly affected by the electrification operation. These 5 take up to the 27.4% of the total actual Spanish industry. This significant share underscores the importance of targeted decarbonization efforts within these sectors to achieve Spain's broader climate goals, as it means that around 1.5 GJ/pers./year of green hydrogen would be used in totally renewed industrial processes. (Opina360, 2023)

However, the situation in the transportation sector is different. As of now in 2024, due to the lack of details in 2050 plans with respect to the number of vehicles that are planned to function by hydrogen cells, there is no way to dissect the hydrogen necessity that will go straight to that final use. Looking at PNIEC, 150-200 buses and 5000-7500 cars are predicted to work on this technology. By taking this data as the minimum hydrogen vehicles, it can be seen that their total energy demand is completely negligible (less than 0.05 GJ/pers./year) compared to the bigger picture. This means that, until a more solid plan is published by Spanish authorities, the methods applied in this report cannot dimension the impact of hydrogen cells in the national grid in neither the worst- nor best-case scenarios. (Spanish Government, 2023)

Data like this adds importance to the efforts that Spain must carry out to achieve its hydrogen demand target. Moreover, this sets clear how the construction of more renewable sources is not enough and the policies designed for the renovation of the Spanish industry are indispensable for the country’s green transition, thus confirming the hypothesis proposed before in this report.

#### 4.1.5. Energy Strategy Comparison with Denmark

This ideal case can be set side by side with the optimal future explained in Denmark’s plans for 2050. The northern country’s following energy system can be idealized trough the DS9 diagram from “The role of electrification and hydrogen in breaking the biomass bottleneck of the renewable energy system: a study on the Danish energy system”, as shown in Figure 15. (Mortensen, et al., 2020)

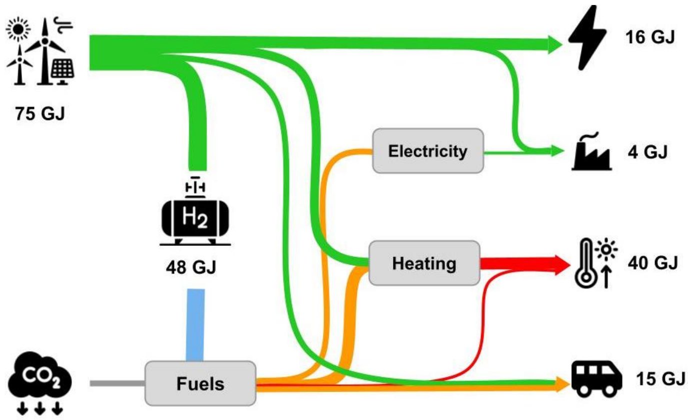



*Figure 15 DS9 strategy diagram, illustrating the planned scenario for Denmark in 2050*

This diagram shows two values there were not expressed in the mentioned Danish study. On one hand, the energy share of the industrial sector can be seen. This was calculated the same way as in the analyzed Spanish cases, taking as reference the present weight of the sector in the national grid. On the other hand, the predicted 79 TWh of hydrogen demand have been quantified as yearly GJ per capita, in order to normalize the data and make the following analysis realized in this section clearer. (IEA, 2023)

There are three main differences between the two country's planned cases. Firstly, the polarity in cooling and heating needs discussed trough previous chapters of this report are very visible in the diagrams. Not only does Denmark require of negligible cooling power but the utilized final heating is much larger than the sum of the average heating and cooling wielded in Spain. This is a surprise as, even if Spain is not the hottest place on Earth, Denmark is far less cold than other Baltic countries. A difference this big sets clear that heating requirement will suppose a bigger energy generation to a nation.

In contrast, transportation seems to consume a lot more energy in Spain. There are a couple of reasons that may be behind this. The first would be the derivation of the measure value for Spain's demand. As explained before, it is assumed that the mass deployment of EVs and the rest of the measures related to road private transport and other means of transportation will not suppose any change with respect to today's energy demand in this sector. Spain has a much bigger share of conventional gas or diesel vehicles than Denmark, which may justify the more voluminous consumption. This aligns with the conclusions from the comparison between both nation's plans carried out previously in this same report. The other reason may lay on the variance in lifestyle between both countries' population. The opportunities a more extensive country with warmer climate offers can be behind the more prolific use of every kind of transport. These reasons are suggestions after a situation that, as mentioned in this report, is happening nowadays and is not planned to change drastically, even though Spain's future policies will most-surely reduce the energy consumption and near the gap between these two countries' circumstances. (Spanish Ministry of Transport, 2020)

Last and most notably, as anticipated in the 2050 plans comparison, the hydrogen demand per capita Denmark is intended to implement is more than 9 times bigger than in the Spanish best-case scenario and even almost 5 times greater than in the worst case where green hydrogen is supplemented by grey hydrogen. This will ensure the constant supply of renewable energy throughout the nation with a bigger margin for working with unfavorable conditions during the energy generation.

This also proves how the hypothesis of these two countries having similar hydrogen demand is wrong. It was assumed that the research and development stages of the hydrogen technology would ensure both countries to advance with a similar pace, since these are carried out as an international effort, but the dissection of the energy mixes have set clear that other factors have to be taken into account. Nonetheless, it must be noted that Denmark has two reasons why it needs a lot more of hydrogen reserves than other European countries like Spain. (AeH2, 2023) (IEA, 2023)

The first reason is no other than the problem that gave value to the base report of this project, the study "The role of electrification and hydrogen in breaking the biomass bottleneck of the renewable energy system: a study on the Danish energy system". Denmark has a sustainability problem with its dependency of its use of biomass. The urge to substitute this source with hydrogen storing technologies is not found in Spain. The other reason is the dominance of eolic parks in future Denmark, as the country is relying completely on hydrogen as energy storing technology. There is a smaller urge for hydrogen in Spain, where hydropower plants with reverse pumping and CSP solar parks will also contribute to energy storing. (Mortensen, et al., 2020)

Taking this last analysis and the countlessly times mentions Danish study into account, it can be concluded that energy storing technologies have clear advantages that are vital for countries trying to accomplish the European environmental goals related to the national grid, but hydrogen is not the sole technology. Even if this report proves that hydrogen is necessary for ensuring the functioning of completely renewable sourcing and the upcoming change of sectors like transport and industry, other storing technologies are also advantageous and their collaboration can reduce the imminent need for green hydrogen that European countries face. (Mortensen, et al., 2020) (Spanish Government, 2023)

It can be stated that, numerically at least, the rest of the energy grid's fixture is quite similar in both countries. Industry's percentual share may be bigger in Spain's strategy but ending values ae not big enough to suppose any kind of conclusion with respect to the population or companies in neither land. In addition, the levels of hydrogen are big enough so that an analysis of which industries will be affected more would not have any important consequence in the analysis of the whole situation.

## 5. Conclusions

The main objective of this study has been to provide comprehensive, up-to-date information on the energy transition strategy in Spain, focusing on the role of renewable energy, hydrogen storing technology and achieving carbon neutrality by 2050. This analysis has been grounded on a Danish study and, thus, a comparative point of view has been executed through the whole analysis process. This study has provided valuable insights into the future projections and policy framework, and to approach this, the study has been structured in two parts, which are closely interrelated but aim to answer each of the two main research questions proposed individually.

The first part consisted of a qualitative and quantitative analysis of the latest published strategies. With the objective of evaluating what Spain's proposal to achieve the European goals by 2050 and the impact that this would have in each sector; the plans for Spain 2030, Spain 2050 and Denmark 2050 were analyzed side by side.

It was found that, contrary to the presented hypothesis, the main factor that differentiates each approach is the present state of the national energy grid. It was seen that the current circumstances of the electrification stages of the industry, the EV integration level into the transportation sector, the actual distribution of cooling and heating networks, and the insulation technologies implementation into buildings were the reasons behind the difference between plans.

Even though been catalogized as less critical, some other observations were carried out. On one hand, the main difference seen between Spain's PNIEC 2030 and decarbonization strategy for 2050 was due to the uncertainty that new technologies suppose.

Due to some aspects like the functioning and efficiency of hydrogen storing technology still being in developing stages, the plan for 2050 is forced to work with less precise assumptions and not commit to specific values in some aspects. On the other hand, the factors that enlarger the difference between Spain and Denmark would be the geography and climate, even though they were proven to be less relevant that though before.

Focusing into the differences themselves, this report points how the scale to the planned hydrogen generation is completely different and why this is. The dependency on the wind parks as almost the sole renewable source supposes working with the uncertainty of the weather, something that does not take place in Spain this strongly, as this second nation is planning on a more diverse mix. In addition, the scale of hydrogen generation is prioritized in Denmark more because the biomass bottleneck problem they currently are fighting to erase. To detail even more on the planned hydrogen demand, the next part of the report was carried out.

On the second part of the report, three cases were numerically and graphically represented. These were the Spain of 2050 if no progress was made in the building and reforming renewable sources, the ideal Spain of 2050 were all the proposes policies fulfill their targets and the Denmark of 2050 were the electrification and hydrogen integration is completely achieved. There were two main conclusions that followed the calculations and their analysis.

Proving part of the hypothesis to be true, it was seen that the current renewable sources in Spain will not be enough to supply green energy to all the ending uses. There is at least 6 GJ/pers./year worth of energy demand to be supplied by new renewable plants if the carbon neutrality goals want to be achieved. Both renewable sources and hydrogen storing must work together, as it was seen that the planned hydrogen demand levels are also vital for a future green Spain.

Moreover, it was proven that the industrial sector needs the implementation of the hydrogen technologies and the restructuration of several industrial processes. With per capita demands as high as 1.5GJ/pers./year, this part of the industry must completely be renovated for the ultimate environmental goals to be achieved.

The other main conclusion is that hydrogen, even if indispensable, is not the sole technology advantageous for the energy transition. Other storing technologies like reverse pumping have been seen to be able to substitute hydrogen in some rate and not suppose any change in the appropriate functioning of a nation with smaller hydrogen reserve.

Overall, this report proves that Spain and Denmark are both set in a hopeful path, where measures adequate to each one's present circumstances will be able to ensure the sought European environmental goals. It is proved how current plans are trustworthy and measured what impact hydrogen storing will have in a nations grid; conditioned by the state of the energy sourcing, infrastructure and external factors intrinsic to each country.

## References


ADHAC. (2023). *Censo de redes de calor y Frío 2023.*

AeH2. (2023). *Análisis del Censo de Proyectos.*

Agence Ecofin. (2024, April 26). *Argelia se convierte en e primer proveedor de gas natural de España*. Retrieved from https://www.ecomnewsmed.com/en/2024/04/26/argelia-se-convierte-en-el-primer-proveedor-de-gas-natural-de-espana/

Cambio Energético. (2019, June 11). *Energía Solar Térmica: ¿Merece la Pena?* Retrieved from https://www.cambioenergetico.com/blog/energia-solar-vs-termica/#:~:text=Eficiencia%3A%20Los%20equipos%20de%20energ%C3%ADa,dif%C3%ADcilmente%20supera%20el%2020%25).

Deloitte. (2016). *Un modelo energético sostenible para España en 2050.*

EMBER. (2024). *European Electricity Review 2024.*

Endesa. (2023, July 31). *El crecimiento imparable del autoconsumo fotovoltaico*. Retrieved from https://www.endesa.com/es/la-cara-e/energias-renovables/aumento-autoconsumo-fotovoltaico-espana

European Commission. (2019). The European Green Deal., (pp. 4-24). Brussels.

European Commission. (2023, November 20). *European Union - Energy, Climate Change, Environment*. Retrieved from Renewable Energy Directive: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en

García, J. A. (2023, June 25). *LinkedIn*. Retrieved from El poder del hidrógeno: Explorando el potencial energético de 1kg de hidrógeno: https://www.linkedin.com/pulse/el-poder-del-hidr%C3%B3geno-explorando-potencial-de-1-kg-rold%C3%A1n-garc%C3%ADa/

H2lac. (2022, July 20). *Los tipos de hidrógeno*. Retrieved from https://h2lac.org/noticias/infografia-los-tipos-de-hidrogeno/

IDAE. (2020). *Comunidades Energéticas*. Retrieved from https://www.idae.es/ayudas-y-financiacion/comunidades-energeticas

IEA. (2023). *Denmark 2023 Energy Policy Review.*

Invest in Spain. (2021, July 21). *Invest in Spain News*. Retrieved from Spain launches electric vehicle project to become EU eletromobility hub: https://www.investinspain.org/content/icex-invest/en/noticias-main/2021/spain-electric-vehicle-project.html

Mortensen, A. W., Mathiesen, V. B., Hansen, A. B., Pedersen, S. L., Grandal, R. D., & Wenzel, H. (2020). *The role of electrification and hydrogen in breaking the biomass bottleneck of the renewable energy system – A study on the Danish energy system.* Elsvier Ltd.

Nicholas, M., & Wappelhorst, S. (2021). *Spain's electric vehicle infrastructure challenge: How many chargers will be required in 2030?*

Opina360. (2023). *¿De dónde viene la energía que usa la industria?*

REE. (2024, May). *Datos*. Retrieved from Demanda: https://www.ree.es/es/datos/demanda

REE. (2024, May). *Datos*. Retrieved from Generación: https://www.ree.es/es/datos/generacion

Spanish Government. (2020). *Estrategia de Descarbonización a Largo Plazo 2050.*

Spanish Government. (2023). *Plan Nacional Integrado de Energía y Clima 2023-2030.*

Spanish Ministry of Transport. (2020). *Sostenibilidad Ambiental*. Retrieved from Consumo y Eficiencia Energética: https://otle.transportes.gob.es/inform/es/2020/sostenibilidad-ambiental/-consumo-y-eficiencia-energetica

The Danish Energy Agency. (2016). *Tehnology Catalogues.*

Troncoso, F. (2021, August). *InduAmbiente*. Retrieved from Claves del Hidrógen Verde: https://www.induambiente.com/informe-tecnico/calderas/claves-del-hidrogeno-verde#:~:text=La%20electr%C3%B3lisis%20tiene%20una%20eficiencia,producir%201%20Kg%20de%20H2.

United Nations. (2023, July 11). *United Nations*. Retrieved from Our Growing Population: https://www.un.org/en/global-issues/population#:~:text=Our%20growing%20population&text=The%20world's%20population%20is%20expected,billion%20in%20the%20mid%2D2080s.