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Production of hydrogen from renewable energy sources – case study

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RESEARCH PROJECT

Production of hydrogen from renewable energy sources – case study

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1. Scope

This Research Project seeks to review methods for hydrogen production utilizing renewable fuels, with a specific approach to their use and sustainability within the landscape of Spain. Through a critical analysis of the current energy scenario and renewable energy applications in Spain, the project aims to evaluate the viability and benefits of hydrogen production as a new source, contributing to a greener future.

1.1. Objectives

- Overview of hydrogen production technologies: to review existing the most common hydrogen production technologies, such as steam methane reforming, water electrolysis, biomass gasification and oxidation, focusing on their process's conditions, environmental impacts, and differences.
- Explore integration in Spain's energy market: evaluate the potential of hydrogen as a transformative renewable energy resource in Spain, considering current challenges, such as climate, energy security and decarbonization targets. Examine how hydrogen can be beneficial in the future for the country and in which fields of industry it could be implemented.

2. Introduction

The exponential growth of population globally is a highly demanding challenge that plays a vital role in the increased demand for energy worldwide. As a result, the study of environmentally harmless methods to generate enough energy has become extremely relevant nowadays, providing an extensive field of research.

Hydrogen is an emerging source of renewable energy in the quest for sustainable solutions, making it an extremely attractive option due to its capacity to generate energy without harmful emissions. Unlike conventional fossil fuels, hydrogen combustion produces water vapor mostly, resulting in a cleaner source. This attribute is key to reducing air pollution and climate change, leading to a great investment in this industry by many countries.

As shown in Fig. 1, hydrogen production will increase over the next decade, in countries of Asia and Oceania. The demand of hydrogen production is predicted to become diversified by 2040, being the manufacturing industry the lead in consumption of this energy. [1]

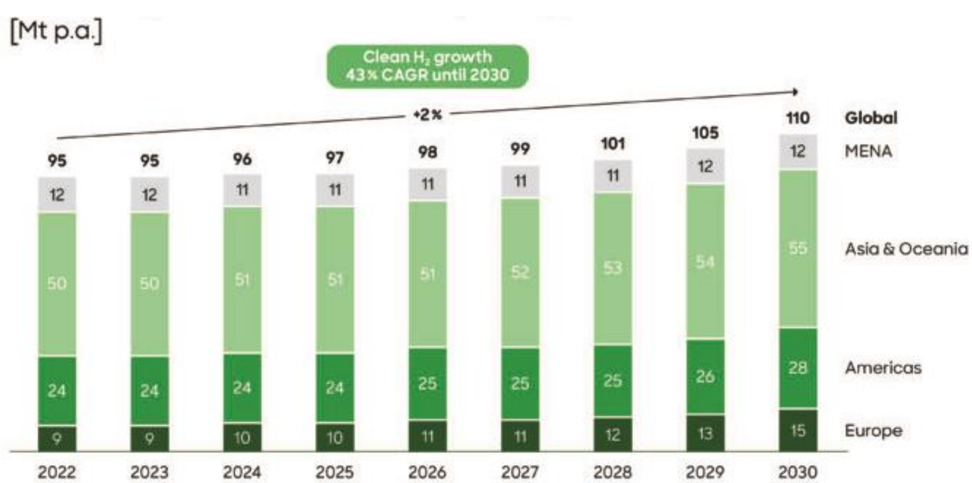

Fig. 1. Global production of hydrogen 2022-2030. [1]

As of now hydrogen is already a versatile source that comes in various forms, primarily depending on the production process. The main categories utilized in large scale industries are classified as blue, green, and grey hydrogen, all of which are represented in Fig. 2.

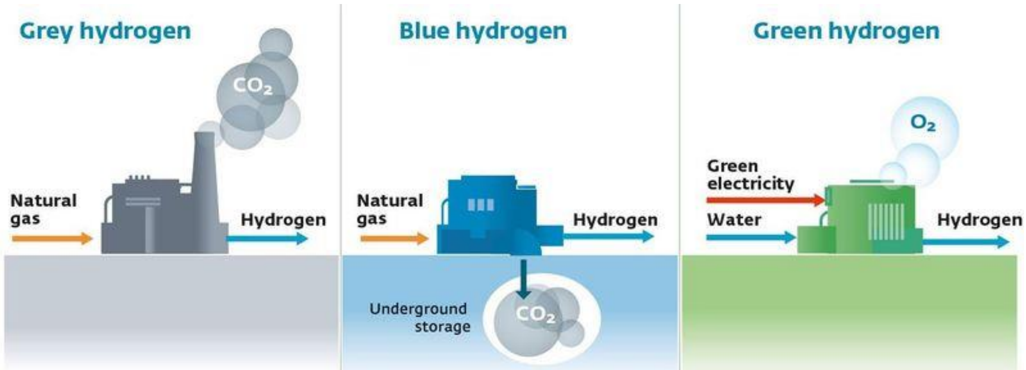

Fig. 2. Depict of grey, blue, and green hydrogen production. [2]

Green hydrogen is produced using fossil fuels (natural gas or coal), and currently the most common type, around 95% of the total hydrogen production nowadays. The principal techniques for production are steam methane reforming and coal gasification. Due to its liberation of carbon dioxide in both processes, grey hydrogen is not the most environmentally friendly alternative.

Similarly to grey hydrogen, during the production of blue hydrogen the emission of carbon dioxide is still present, however in the case, carbon capture and storage technology (CCS) is utilized. Instead of releasing gas into the atmosphere, it is stored underground, which significantly reduces the environmental impact. The production methods are the same as grey hydrogen, yet due to the CCS this method is more expensive. [2]

The ideal representation of sustainability comes from green hydrogen, which is considered to have low or zero emissions due to its utilization of energy from sources such as wind and solar. In the process of production of this hydrogen variety, water is split into hydrogen and oxygen, known as electrolysis. Even though it is the cleanest method of production, there is the need for an energy input for electrolysis, causing this to be quite an expensive process. [2]

When it comes to the methods of production of hydrogen, there are other technologies besides electrolysis, methane steam reforming and coal gasification. Among them partial oxidation, autothermal reforming and plasma reforming can be found and biomass gasification. [3,4]

In addition to the commonly known blue, grey and green hydrogen, which are the most used types in the industry, there are several other types as well, each distinguished by its production method and environmental impact. Fig. 3 shows a representation of the other types of hydrogen that can also be encountered nowadays.

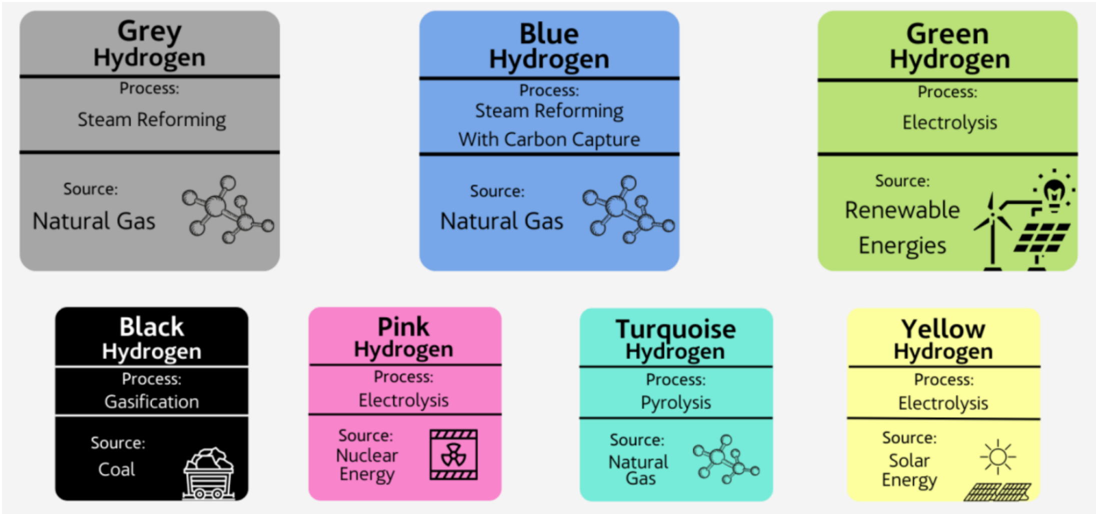

Fig. 3. Hydrogen types by colors. [5]

Pink hydrogen is produced using nuclear energy, and it offers a low-carbon alternative by harnessing the energy from nuclear reactors. Turquoise hydrogen is generated through the thermal process of splitting methane, which results in solid carbon as a byproduct instead of carbon dioxide which makes it a more sustainable option. On the other hand, white hydrogen, or natural hydrogen, occurs in geological formations that do not need industrial processes for its harvest. Black and brown hydrogen are the most environmentally damaging because they are made from fossil fuels, such as coal. [5]

Each type of hydrogen presents its own benefits and challenges, which contributes to the diverse landscape of hydrogen production technologies aimed at reducing carbon emissions and generating more sustainable energy solutions.

Hydrogen offers various advantages as a clean source of energy, as well as a versatile and diverse field of application in many industries. Fig. 4 shows the great variety of applications of hydrogen, such as petrochemical, energy sectors, transportation and fuel, fertilizers, and clean processes.

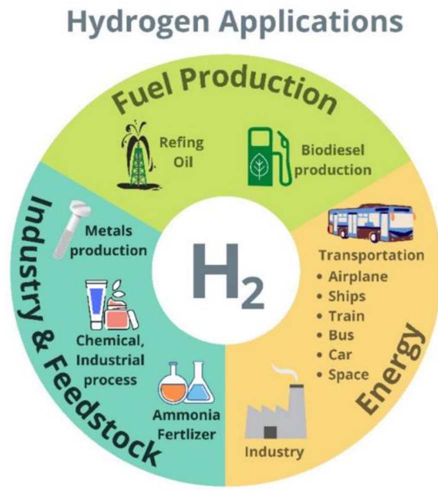

Fig. 4. An overview of the applications of hydrogen. [6]

As the world faces an increasingly necessity to transition to cleaner energies, hydrogen offers an efficient solution to face decarbonization by replacing fossil fuels, combat climate change and as a result provide a new global market for companies to invest in and capitalize on this new growing industry. In the following chapters, the different methods of production of hydrogen and the main industry applications will be covered.

2.1. Applications of hydrogen

Hydrogen plays a critical role in various industries nowadays, contributing to both traditional and emerging technologies. Historically, it has been most employed in oil refining, ammonia production and methanol synthesis, however nowadays its fields of application are growing considerably. Fig. 5 represents the main industries where it is employed and the percentage of hydrogen of the world that is dedicated to each of them.

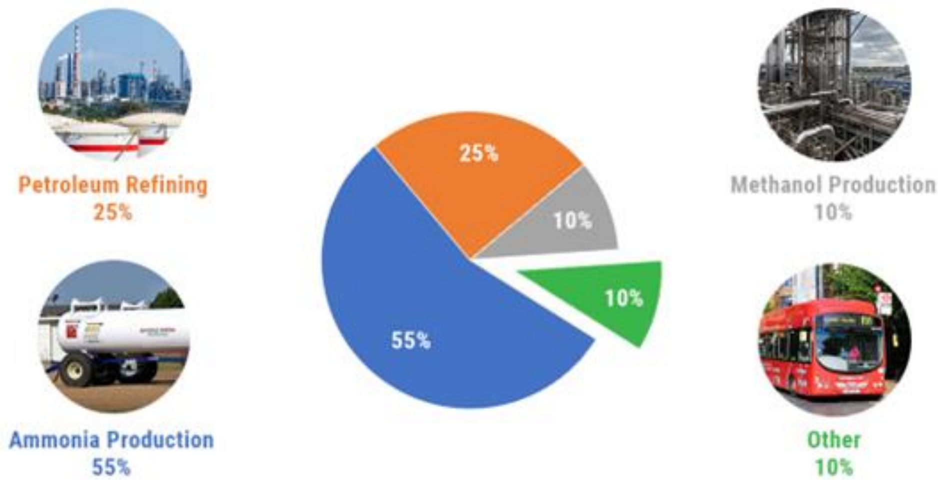

Fig. 5. Global hydrogen consumption by industry. [7]

The ammonia field relies heavily on hydrogen for Haber Bosch process, fertilizer production, and on the making of environmentally friendly refrigerant, corresponding to 55% of all the hydrogen consumption around the world.

Other applications use less hydrogen, such as renewable energies which account for only 10% of its consumption worldwide. Following the ammonia production industry, the leaders in use of hydrogen are petroleum or oil refining industry with a 25% of consumption, used for processes like hydrocracking and sulfur removal to produce cleaner fuels, and lastly methanol production corresponds to a 10% of hydrogen use for chemical processes. [7]

Moreover, methanol production generates formaldehyde and hydrogen, in which hydrogen is crucial in the refining process of chemical products that rely on methanol as a key component. This integrates hydrogen in the chemical manufacturing industry as well. [8]

As shown in Fig. 6, hydrogen obtained from hydrolysis and combined with nitrogen in the Haber-Bosh process results in green ammonia, which is extremely important for fertilizers production. For this reason, the ammonia production industry is responsible for a great part of the utilization of hydrogen in the world. [8]

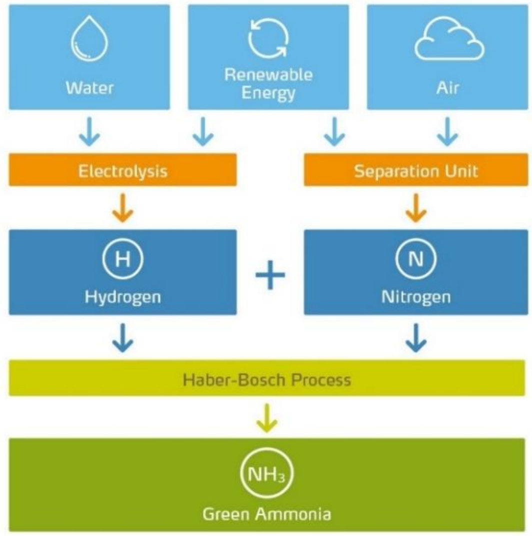

Fig. 6. Green ammonia process scheme. [9]

With the growing need to reduce carbon emissions, hydrogen's applications are expanding into new areas. One of them is the steelmaking industry, which is exploring hydrogen as a substitute for coal, aiming to reduce the carbon footprint of steel production. Similarly, the concrete production sector is also investigating hydrogen-based methods to decarbonize the process, addressing the emissions associated with traditional cement manufacturing. Furthermore, hydrogen's versality extends to sectors like food processing, metalworking, welding, flat glass production, electronics manufacturing, and medical applications. In the food processing field, hydrogen is employed to hydrogenate vegetable oils. When it comes to metalworking and welding, it enhances the properties of materials and enables high-precision techniques. [7,8]

As hydrogen economy develops, its application also diversifies even further. Clean hydrogen, produced via renewable energy sources or combined with carbon capture technologies, promises to transform industrial processes, making them more sustainable. The transition to hydrogen-based methods in various sectors leads to a reduction in emissions of carbon and creates a new path for a cleaner future in many industrial fields.

2.2.Methods of hydrogen production

2.2.1. Steam reforming

Steam reforming consists of an endothermic conversion of hydrocarbons in contact with water steam into synthesis gas. Typically, the hydrocarbon utilized is methane (CH_4) in the presence of steam (H_2O) to produce carbon monoxide. Fig. 7 represents a scheme of the process of steam reforming with methane.

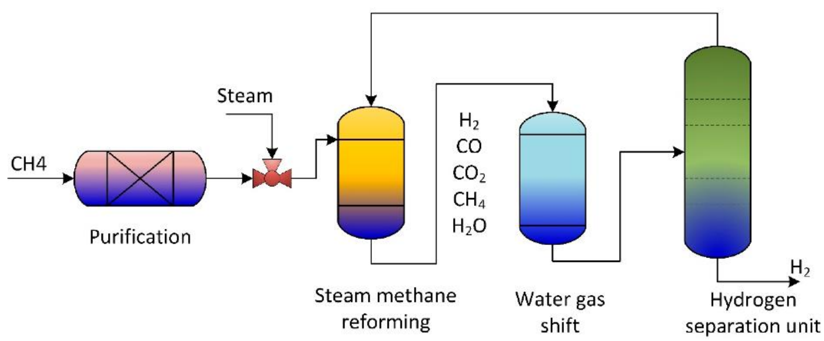

Fig. 7. Schematic of traditional methane reforming unit for hydrogen production. [10]

The process consists of five main steps: feedstock preparation, steam methane reforming, water gas shift reaction, gas separation and hydrogen purification. Firstly, the natural gas used in the process, commonly methane, is purified to remove sulfur compounds that could interfere in the catalyst performance. Secondly, comes the steam reforming reactor, in which methane reacts with steam in the presence of the catalyst, producing 'syngas,' mixture of hydrogen and carbon monoxide. The global chemical reaction can be expressed as follows:

$$CH_4 + H_2O \rightarrow 2CO + 2H_2 \qquad \Delta H^{o}{}_{298K} = 247.3\frac{kJ}{mol}$$ [1]

Afterwards, the syngas produced goes through a water-gas shift reaction to reduce the hydrogen content and reduce carbon dioxide. In the hydrogen separation unit methods such as membrane separation are employed to separate and purify the hydrogen from other residual gases.

Depending on the reactants, the temperature employed in the process may exceed 180ºC degrees for oxygenated hydrocarbons and above 500ºC for conventional hydrocarbons. There are numerous factors that influence steam reforming besides the temperature, for instance the pressure, the molar steam-to-ratio (S/C) and the catalyst. Pressure and S/C ratio can affect the chemical reaction in an equivalent way, if either the pressure or the ratio is increased the hydrogen yield production will also be elevated.

The catalyst commonly used is fundamentally composed of nickel since it facilitates the kinetic reaction and therefore decreases the reforming temperature required. The effect of poisoning by sulfur is the main cause of catalyst deactivation, meanwhile there are other less common causes of deactivation such as halogen compounds, heavy materials, and an excess of carbon. Despite the presence of the catalyst, steam reformation has a low effectiveness rate due to the great mass and heat transfer limitations in the reactors. This leads to a preferred choice of low-cost nickel catalysts during the industrial process instead of inverting on noble metals catalysts, for instance Rh, that present a much higher specific activities site. [4]

This process requires heat input since its process is of endothermic nature, this has led in the development of new processes that utilize the presence of oxygen and as a result do not require temperatures as high as the steam reforming. [4,11]

Steam methane reforming is a large-scale industrial process, presenting a complex and expensive set of equipment and strict operational conditions. Fig. 8 shows the magnitude of the equipment utilized in a steam methane reforming industry.

Fig. 8. Steam methane reforming industry. [12]

2.2.2. Partial oxidation

During the partial oxidation process oxygen reacts with natural gas (hydrocarbons) in a high-temperature reactor (HTR), resulting in the formation of carbon monoxide and hydrogen. Fig. 9 represents a scheme of a high-temperature reactor and how the process of partial oxidation occurs inside of it.

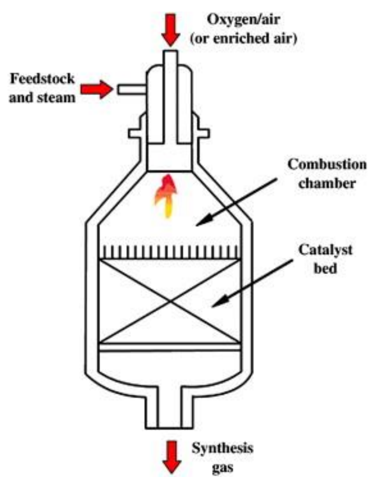

Fig. 9. Diagram of a HTR reactor. [13]

In the HTR reactor, combustion and steam reforming reactions occur simultaneously in the catalyst bed. The chemical reaction can be summarized as:

$$C_mH_n + \frac{1}{2}mO_2 \rightarrow mCO + \frac{1}{2}H_2 \qquad [2]$$

This consists of an exothermic reaction, meaning it releases heat internally without an external source. To establish optimal conditions and complete conversion for this reaction the temperature needed is in the range of 1300ºC-1500ºC. Due to the extremely elevated temperatures, catalysts such as nickel (Ni) or rhodium (Rh) can be used, even though they can lower the operating temperature, nickel tends to form coke, while Rh has an inflated cost. [4]

This technique has provided solutions to challenges presented by steam reforming, specifically since on the previous method it was necessary to have an external heat input which leads to a high energy consumption, and now there is no need for external heat. Regardless of that, the presence of undesirable compounds such as coke, nitrogen oxides and sulfur remain unsolved. [14]

2.2.3. Autothermal reforming

The process of autothermal reforming, as illustrated in Fig. 10, combines the techniques of steam reforming and partial oxidation. In this method, the hydrocarbon feedstock undergoes a reaction with both oxygen and steam. This is contrasted with the partial oxidation process, where the hydrocarbon feedstock reacts only with oxygen and not steam, which leads to the production of carbon monoxide and hydrogen.

Autothermal reforming is characterized by a thermally neutral reaction, which is achieved by the combination of endothermic reactions from steam reforming and exothermic reactions resulting from partial oxidation. This balance directly impacts the design of the reactor used in the process, creating the necessity for a specific division into two zones so these reactions can take part effectively. This zoning is crucial for maintaining the stability and efficiency of the reaction within the reactor. [4]

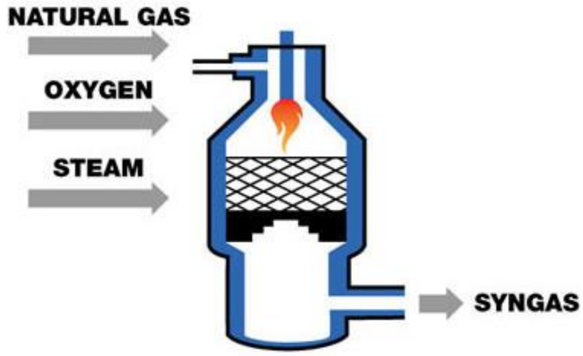

Fig. 10. Autothermal reforming process scheme. [15]

The reactor is divided into two zones, such as represented in Fig. 10, the thermal zone where the partial oxidation occurs and generates the heat needed eliminating the necessity for an external heat source; and the catalytic zone which corresponds to the steam reforming. The second zone operates at a lower temperature due to the endothermic reactions. [4]

The recommended operating conditions are 750ºC - 950 ºC, an O_2/C ratio of 0.25, a S/C of 1.75 and a constant heat supply. Compared to the previous methods, the temperature and ratios needed are lower and consequently it results in reduced energy consumption. This enables the steam reformer to have a reduced size and overall softens operation conditions. [11,15]

2.2.4. Plasma reforming

Plasma is generated with electricity or heat, through a process of injection of water or steam with fuel. Therefore, radicals O, OH and H in addition with electrons are created through microwaves, which produces optimal conditions for reductive and oxidative reactions to occur. Fig. 11 shows a schematic view of the equipment used in plasma reforming and how the plasma is generated during the process.

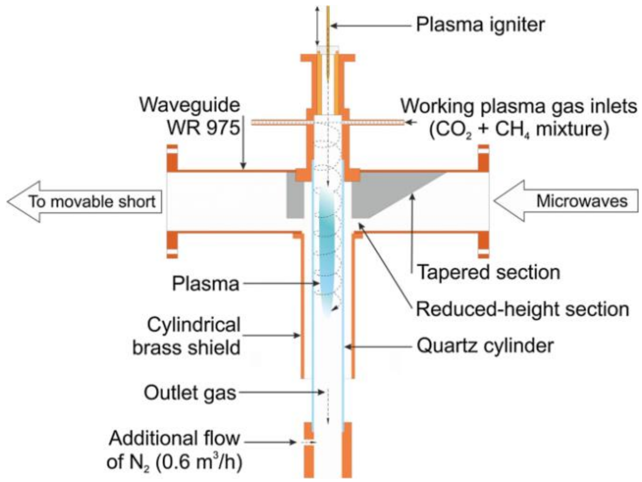

Fig. 11. Schematic view of the waveguide-supplied metal cylinder-based type MPS. [16]

This technique consists of gas ionized by a high frequency electromagnetic field (0.3-300 GHz) responsible for energizing electrons that will create plasma through the ionizing of neutral atoms and molecules. [16]

For thermal plasma, the consumption of electrical power is especially elevated, causing a rise in electrons and other neutral species to extremely high temperatures of 5000-10.000K. Meanwhile, in non-thermal plasma the temperature of neutral species is notably lower, around 68-76K. The electrons still operate at the same temperature, however the power required is much less. [4]

The major challenge of this method is the power consumption and elevated temperatures required, on the other hand it does present advantages when it comes to the limitations of the previous methods such as size and weight requirements of the reactor, cost of catalysts and hydrogen production from certain types of hydrocarbons.

2.2.5. Biomass gasification

The growth of population in the past years has promoted the excessive production of waste from every type of facility, industries, local stores, restaurants, universities, and others. One way to provide a purpose for all the waste produced is to employ it in new environmentally friendly technologies, such as biomass gasification. Gasification is a highly efficient way to convert waste into gas that can be used to generate electricity and power. Unlike incinerators that can generate emissions of harmful gases.

The procedure of gasification may be realized through different methods, such as microwave, catalytic, multi-step and chemical looping gasification being the most common ones. The process of gasification involves a controlled supply of oxygen or steam to produce syngas, which is mostly composed of hydrogen, carbon monoxide, carbon dioxide, traces of methane and other gases. It occurs at different temperatures according to its stages, firstly dehydration at 100ºC-200ºC, then pyrolysis at 250ºC-500ºC, followed by combustion and reduction. The application of an oxidizing agent helps produce gaseous products, hydrogen, and carbon monoxide from syngas. Fig. 12 presents the process of biomass gasification from the industrial view until the reception by the customer. [17]

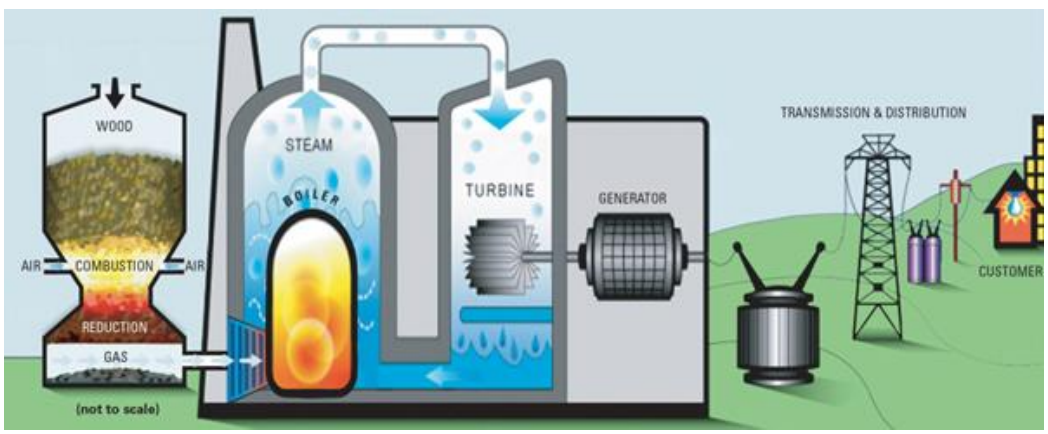

Fig. 12. Biomass gasification system. [18]

After biomass being gasified, the syngas obtained can be a versatile source of energy and display various applications in industry, including heat and power generation, hydrogen production. Utilizing syngas in these applications also helps prevent waste from accumulating on Earth and polluting the environment. Besides that, the composition of syngas can vary depending on the biomass feedstock, operating conditions of the gasifier and its design, but its use can reduce the reliance on fossil fuels and provide cleaner energy.

2.2.6. Water electrolysis

The dissociation of water molecules occurs at the electrodes, and it is caused by an electric current that results in positively charged hydrogen ions (H+) and negatively charged hydroxide ions (OH-). This process is one of the main technologies used for clean hydrogen production, particularly characterized by the zero emission of greenhouse gases as the electricity employed comes from renewable sources.

The method involves two electrodes that are submerged in the water as shown in Fig. 13. Both are made of conductive materials that allow the electric current to go through the water, for instance platinum (Pt) and graphite (C).

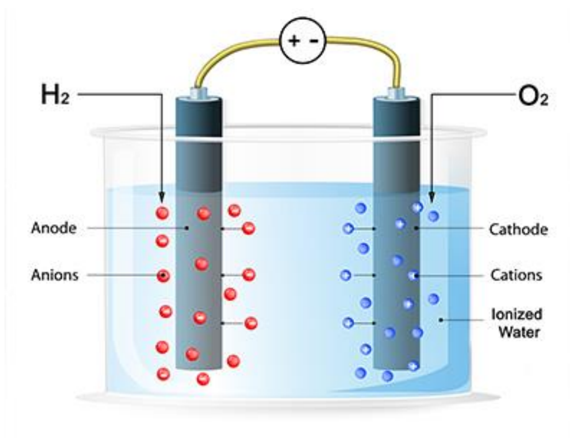

Fig. 13. Electrolysis of water. [19]

Hydrogen and oxygen are continuously produced at the electrode during the electrolysis due to the migration of hydrogen ions to the cathode (negatively charged electrode), while the hydroxide ions migrate towards the anode (positively charged electrode), resulting in the following reactions:

$$\text{Cathode:} \quad 2H^+ + 2e^- \rightarrow H_2 \qquad [3]$$

$$\text{Anode:} \quad 4OH^- \rightarrow O_2 + 2H_2O + 2e^- \qquad [4]$$

Global reaction: $2H_2O \rightarrow 2H_2 + O_2$ [5]

The operation of water electrolysis typically involves the following main types of electrolyzers: alkaline electrolyzers, polymer electrolyte membrane (PEM) and solid oxide electrolyzers, each characterized by different operating parameters.

In the case of alkaline electrolyzers, the operating pH conditions are on a high range, using liquid alkaline solutions like potassium hydroxide (KOH) as the electrolyte. This requires pure water and a cautious handling of the caustic electrolyte; however, it is also a durable material that allows the use of non-precious metals as catalysts. On the other hand, PEM electrolyzers utilize a solid polymer electrolyte, allowing a compact design and rapid response time to sudden changes in the electricity current, which turns them into suitable for integration with intermittent renewable energy sources and a high-cost material. [20]

Solid oxide electrolyzers operate at elevated temperatures, ranging from 500ºC to 800ºC which enhance efficiency by facilitating the process of splitting water molecules with lower electrical energy input. This range of operating temperature also causes the use of less expensive catalytic materials; however, it presents difficulties in terms of material stability. [20]

The efficiency of this process is affected by the purity of water, type of electrodes, current density, and other factors such water flow rate, presence of membrane or other type of selective separation in between electrodes to prevent the formation of undesired products [21]. Moreover, the efficiency of this process is based on the yield of energy conversion, which can be optimized through new advancements in electrolyzing technologies that operate at varying temperatures which leads to higher efficiencies. Besides that, the use of robust catalysts to lower activation energy and increase reaction rates also influences positively the overall efficiency of the process. Such developments are crucial to make water electrolysis a more economical process and suitable option for large scale hydrogen production. [20]

2.2.7. Comparison of methods of production

All methods of production of hydrogen offer different advantages and challenges, however it is important to evaluate them to choose the best method of production in each industry.

When it comes to seeking a greener future, the key aspect is that the method of production utilized offers the cleanest and most sustainable solution. In Table 1 the methods previously mentioned are gathered in a comparison of economical and efficiency parameters.

Table 1. Comparison of the methods of production of hydrogen. [43][43][11]

Method	Economics	Efficiency
Steam Methane Reforming (SMR)	Cost-effective due to natural gas abundance; significant CO2 emissions unless coupled with CCS.	65-75%
Partial Oxidation	Relatively cost-effective; less common; high-temperature process.	60-70%
Autothermal Reforming (ATR)	Balanced cost; combines steam reforming and partial oxidation; requires precise control.	70-80%
Plasma Reforming	High operational costs due to power and temperature requirements; suitable for decentralized production.	50-90%
Biomass Gasification	Sustainable but costly; depends on feedstock and pre-treatment.	50-70%
Water Electrolysis	Most expensive; costs expected to decrease with technology advancements and scale; cleanest method.	60-80%

The table above shows how each method differs from the other, highlighting the most important economic and efficiency aspects. In this case, water electrolysis stands out for being the cleanest method of all, which despite being expensive offers a great solution for generating hydrogen in the most sustainable way possible. Besides that, it also presents some of the highest levels of efficiency among other methods.

3. Renewable energy landscape in Spain – case study

3.1. Current infrastructure

Spain is a leading country in the sustainable energy transition global race, committed to invest in renewable energy, the country has a national policy to achieve carbon neutrality by 2050. The aim is to minimize the impacts of climate change and change the way the country produces energy, while maintaining its economy competitively. This section explores the current scenario of Spain's renewable energy production, focusing on its mains sources of energy, and how the environmental conditions influence its outcome. The current panorama of renewable energy sources in the country can be summarized by the chart in Fig. 14.

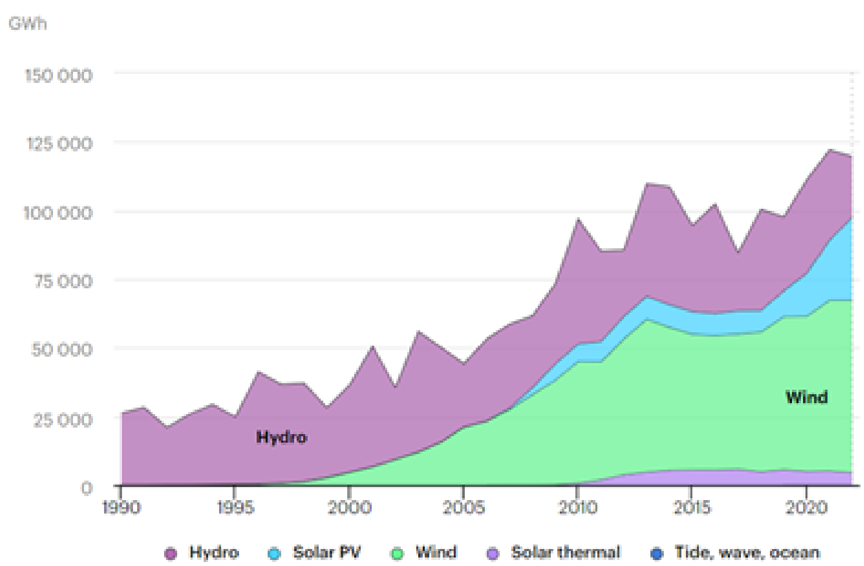

Fig. 14. Renewable electricity generation by source in Spain. [22]

The country's geographical diversity and climate conditions offer a great advantage for the use of solar and wind energy. As shown in Fig. 14, the main renewable energy sources in Spain are hydropower, solar photovoltaic (PV), and wind, representing the highest generation of electricity in the recent years.

As of 2023, Spain has installed 25.549 MW of solar photovoltaic power which shows an increase of 28% compared to 2022. Currently, this is the source of renewable energy that has been experimenting with the greatest growth in the past year, representing 20,3% of the total national capacity. Within the Spanish country, the regions that have most installations of solar PV are shown in Fig. 15, standing first Extremadura (25,1%) and Castilla-La Mancha (24%). Nonetheless, as represented in Fig. 15, the distribution of this energy is expanding to northern parts of Spain as well. [23]

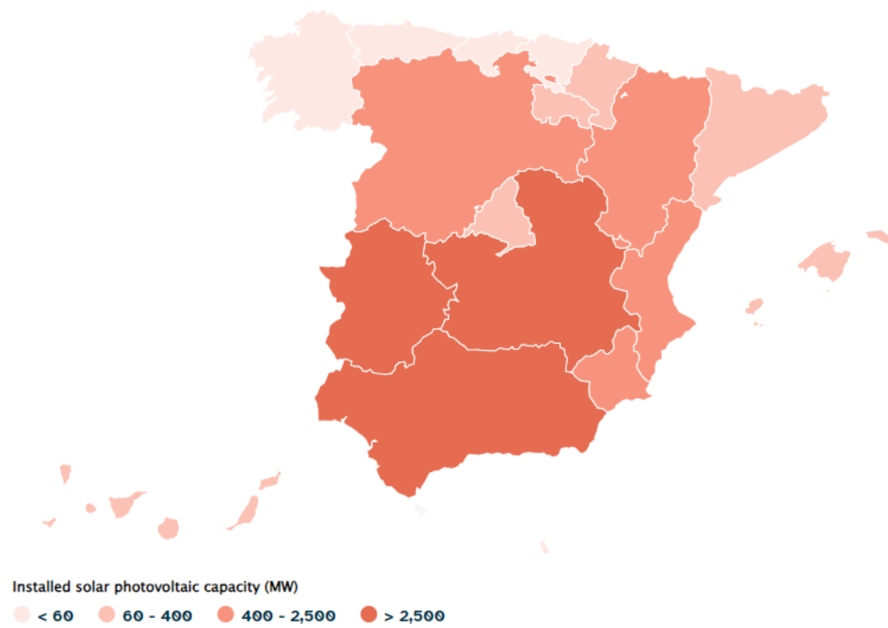

Fig. 15. Installed photovoltaic solar power as of 12/31/2023. [23]

The solar energy market takes advantage of the favorable climatic conditions of the country, specifically the extensive sunny days in the south of Spain, where it´s clear the highest concentration of solar PV. This distribution is strategical to maximize the energy produced and efficiency.

When it comes to the wind infrastructure, the Spanish energy market in one of the global leaders with most installed capacity, standing only after China, the United States of America, Germany, and India. With more than 30.810 MW of installed capacity, this remains the main renewable source in Spain, representing a total share of 25.2% of the national power capacity. [24,25]

According to Fig. 16, the regions of Castilla y León and Aragón have the most installed wind power capacity of the country, even though other regions such as Galicia and Castilla La Mancha experienced a great increase in wind power capacity. This is a result of the of rainy and windy conditions on the north of Spain, where these regions are located.

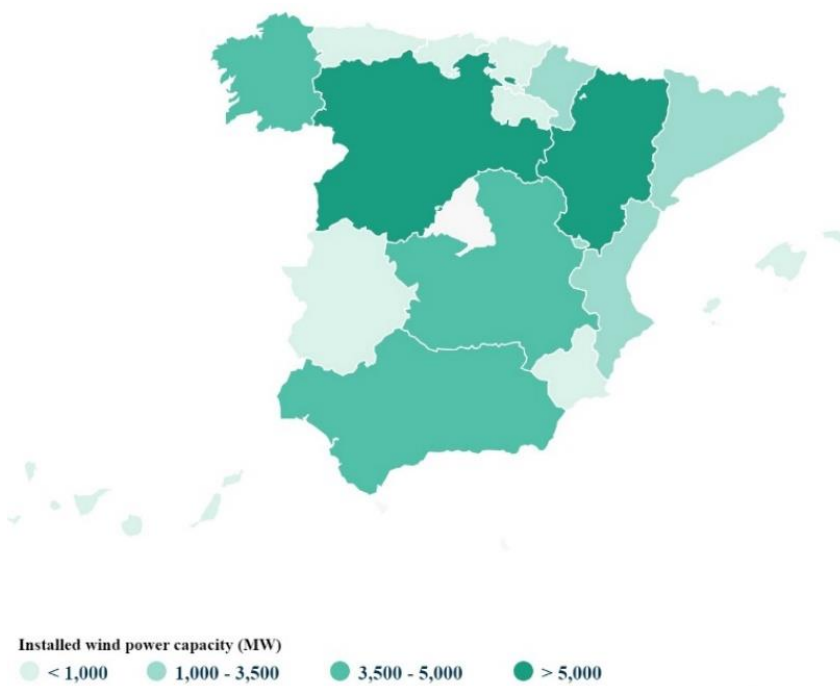

Fig. 16. Installed wind power capacity on December 31, 2022. [25]

Despite of the growing installation capacity of solar photovoltaic energy and wind power, a great part of the Spanish energy comes from other sources, such as fossil fuels (oil, natural gas, and coal). This poses a relevant influence on the economy and political decisions of the country since it has become more vulnerable due to its lack of self-supply capacity and dependance on importation.

As shown in Fig. 17, Spain is highly dependable on importation of energy from other countries, standing globally on the 14th place on the rank for countries that import energy the most.

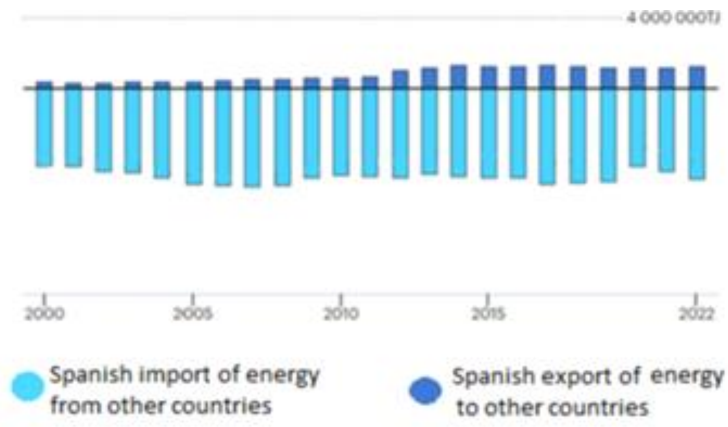

Fig. 17. Trade in energy, Spain. [26]

The fact that Spain is a country that is so dependent on the importation of energy from other countries can be a great challenge, since it makes the country vulnerable to economic and political disruptions from outside, besides external events such as the war in Ukraine, the Covid-19 pandemic and price inflation. Consequently, the transition to renewable sources of energy could be the key to providing more independence to the country in the future. [27]

3.1.1. Climate and geographical conditions

Spain is characterized by its Mediterranean climate, meaning hot summers, and mild and rainy winters. As a result, during some months of the year the energy produced through solar photovoltaic energy and wind power sources can be higher than other months of the year.

To perform an analysis of how the climate influences the energy production in Spain, the average temperature, sun hours and wind speed in the regions of Extremadura and Aragón will be studied. As mentioned earlier, these are the regions with the most solar PV and wind power installed, respectively. Fig. 18 indicates the regions that will be studied in this analysis, which are Extremadura and Aragón.

Fig. 18. Map of Spain by Autonomous Communities. [28]

Extremadura is in the central-western part of the Iberian Peninsula, and as mentioned before, has the best climatic conditions for the use of solar photovoltaic technology. On the other hand, Aragón in the northeastern Spain presents great climatic conditions for the application of wind power. For this reason, these will be the regions studied in the energy production analysis of 2023.

Fig. 19 shows the yearly variation of temperature in Cáceres, Extremadura, representing the average daily range of temperatures in the grey bars, the lowest in blue and the highest in red.

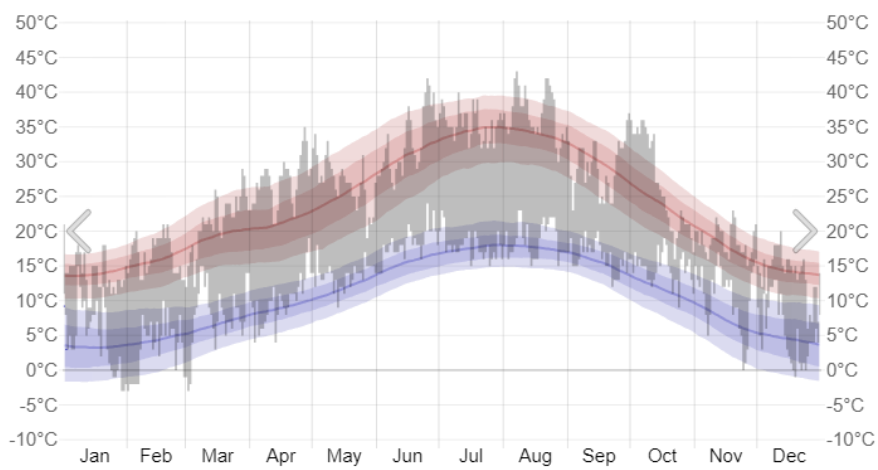

Fig. 19. Cáceres, Extremadura, Temperature History, 2023. [29]

During the months of May until the end of September the temperature can reach more than 30 Celsius degrees, with a maximum of 43 Celsius degrees. Despite presenting warm conditions during most of the year, there is another key aspect related to the high temperatures in Cáceres that is ideal for the use of solar panels: sun hours.

As represented in Fig. 20, the maximum hours of daylight occur in the months of summer, reaching almost 15 hours a day. On the other hand, during the months of winter there is a decay in sun hours, however it still reaches 9 hours a day.

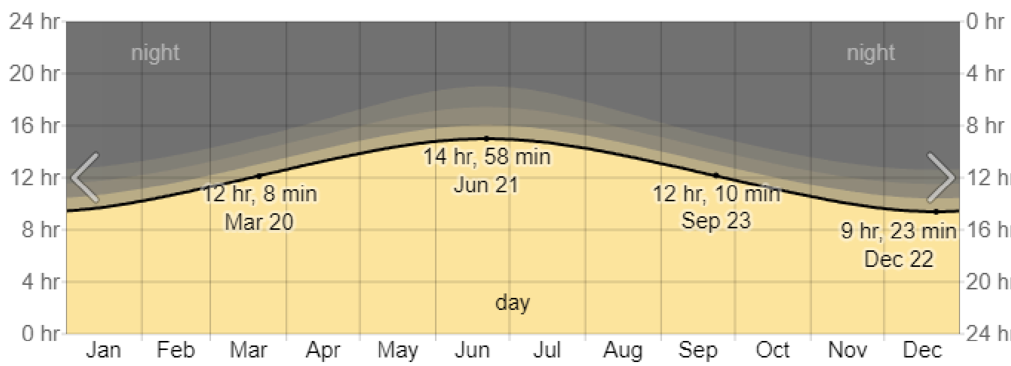

Fig. 20. Hours of daylight and twilight in 2023 in Cáceres, Extremadura. [29]

Overall, the great amount of daylight hours all year round and the warm climate in Extremadura offer great conditions for the installation of solar panels since these work by absorbing sun rays via their photovoltaic cells and generate electricity. Even during winter there is enough sunshine to produce electricity through the panels. This scenario is not exclusive of Extremadura only, as shown in Fig. 15, various other regions of the south and central Spain have invested in the installation of Solar PV, due to similar climate conditions. [30]

Regarding the installation of wind power, a minimum wind speed of 12-14 km/h is required to start generating electricity. In the case of Huesca, in Aragón, the annual averages of wind speed reach enough capacity to generate intense winds. [31]

Fig. 21 represents the annual evolution of wind speed in Huesca, with maximum gust speeds being the red ticks in the image.

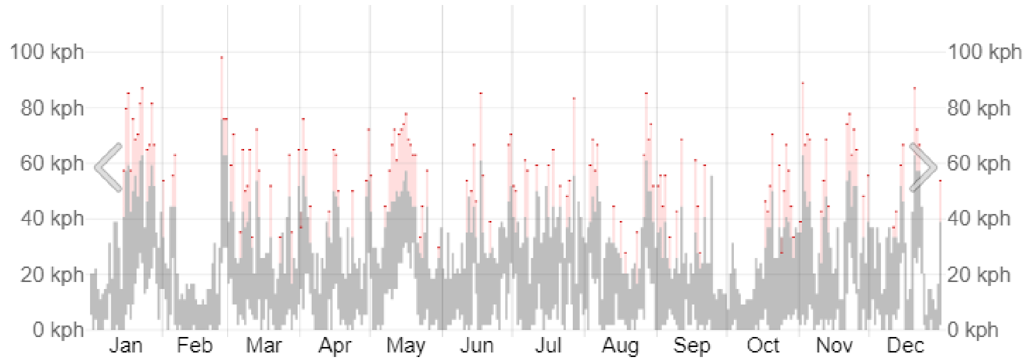

Fig. 21. Wind speed in 2023 in Huesca, Aragón. [32]

Speeds of more than 50-60 km/h are observed frequently through the year, meaning that the presence of such strong winds in the region can generate at full capacity most of the year, providing optimal conditions for the installation of wind power technologies, mainly during the months in which is more likely to have peaks of maximum wind speed. [33]

3.1.2. Regulatory overview

In Spain's transition towards a sustainable future, regulatory policies play a fundamental role in developing the market for renewable energy sources. Currently the country is focused on the 2050 Objectives of national climate neutrality, including the implementation of a totally renewable electricity system, Spain has ambitious targets for the growth of the renewable energy sector.

Carbon neutrality is achieved through equaling the amount of carbon dioxide (CO_2) emitted into the atmosphere with the amount removed from the atmosphere, resulting in a net zero carbon print. There are several ways to accomplish this goal, however Spain plans to apply various actions for green transition including an investment of 12 billion euros in the energy efficiency of public and private buildings, 13.2 billion euros in sustainable mobility in urban and long-distance, 6.1 billion euros in the decarbonization of the energy sector and a Renewable Hydrogen Roadmap, which consists of a series of policies to build energy storage, decarbonization and rehabilitation for renewable electricity. [34]

Overall, Spain will be converted into a clean energy hub, investing in total an amount of 2.5 trillion euros in green technologies and processes in general by 2050. This means 85 billion euros per year in which the main areas of investment will be transport, power, and buildings, as mentioned previously. Moreover, this investment will lead to creating one of the most competitive markets of Europe in Spain, since the country already has the second highest wind generation after Germany and great solar climate conditions and resources. The production of renewable energy in Spain can be at a lower cost than other European countries and therefore, result in an extremely rapid decarbonization. [35]

In the short term, the National Integrated Energy and Climate Plan 2021-2030 (PNIEC) plans to reduce emissions from 23% to 32% by 2030, promoting ambitious climate and energy objectives. The aim is to increase the share of renewable energy consumption to 48%, being 81% in electricity, besides that the project plans to have 62 GW of wind power installed, 76 GW of solar photovoltaic, 4.8 GW of solar thermal power and 1.4 GW of biomass power. Moreover, the plan to increase indigenous energy production until 49% will result in savings of approximately 90 billion euros in fossil fuel importation. [36]

To achieve the necessary investments, PNIEC suggests a mobilization of 294 billion euros in investment, of which 85% come from private sources and the rest from public sources and European funds. From this inversion, a share of 40% will be destined to renewable energy, 29% towards energy savings and efficiency and 18% to energy networks. With that thousands of jobs will be created across sectors of industry, energy and construction, an estimation of 430,000 to 522,000 jobs in the periods of 2025 to 2030. [36]

To complement the financial subsidies, the PNIEC also implements various tax incentives to reduce the cost of transitioning to renewable energy for business and households. To begin with, the Value Added Tax (VAT) on household electricity will be reduced at a rate of 10%, a notable change from the past value of 21%. Also, the VAT for natural gas and biomass derivatives will also be 10%. This applies from January to March of 2024 for gas and extends until the end of June for biomass products. Additionally, the Special Electricity Tax (IEE) will be set at 2.5% for the first quarter and increase to 3.8% for the second quarter of 2024, meanwhile for electricity producers the IEE will be reinstalled at 7%, with expectations to gradually reintroduce the tax base as electricity market normalizes. [37]

Furthermore, the Tariff of Last Resort (TUR) will continue to be regulated so that the price in raw materials does not increase more than 5%, ensuring that the prices annually do not rise over 15%. As a reflection of the government's commitment to stabilizing energy costs, the maximum price for butane will be limited to 19.55 euros per canister, and charges related to electricity consumption will remain 55% lower than in 2021. Also, the reduction in tolls for electro-intensive industries by 80% will be extended for an additional six months, promoting sustainable industrial practices. All together these measures seek to support economic growth and stability meanwhile incentivizing the sustainable energy transition of household and business in the country. [37]

3.2. Energy production analysis (2023)

This analysis seeks to address the possibility of exceeded production of electricity from solar photovoltaic panels and wind turbines during certain months of the year in Spain. Excess energy production occurs when the energy generated by power sources surpasses the consumption need of the grid at certain times. To evaluate if this phenomenon is occurring in Spain, this analysis will focus on key regions in Spain mentioned before, which are Extremadura and Aragón, which present the highest levels of wind speed, temperature levels and daylight hours.

3.2.1. Solar photovoltaic analysis

In Spain the climatic conditions favorable to wind and solar power lead to variations in productions across the year. Firstly, to evaluate the veracity of this, a study of monthly generation of energy from each source mentioned previously will indicate the concrete months that had most electricity generation from solar PV in 2023. Fig. 22 demonstrates that the month of July marked the peak of electricity generation, resulting in 4,552.26 GWh.

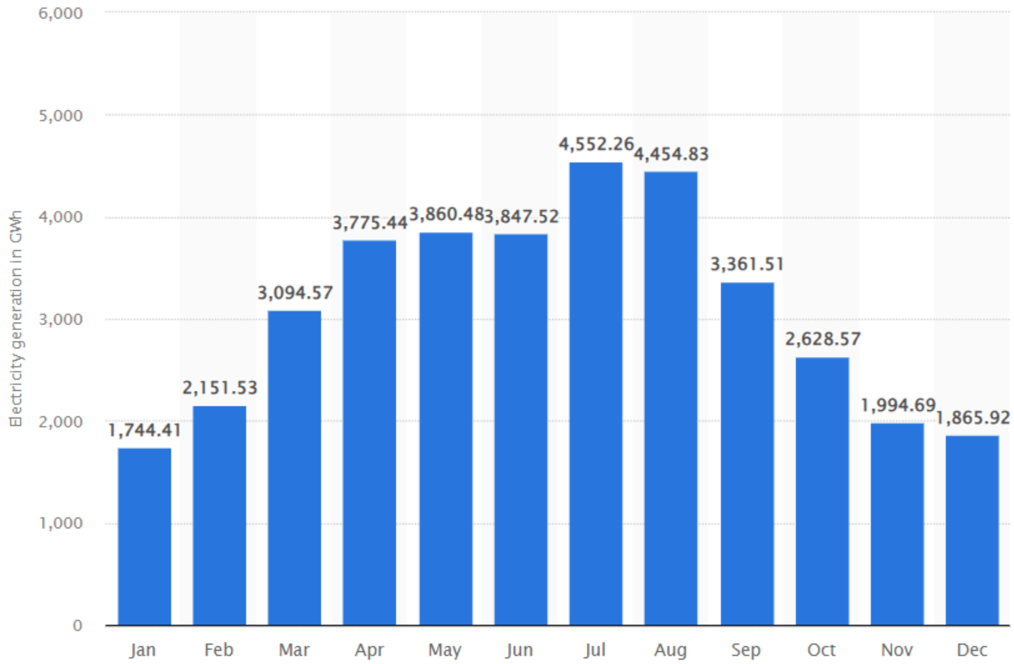

Fig. 22. Solar photovoltaic energy generated in Spain from January to December 2023. [38]

Given the extended daylight hours and increased solar radiation during this month, it is highly likely that periods of excess energy production occurred throughout the day. To address this, a comparison between the energy generation from solar PV in July in Extremadura and the demand for energy in the same month at same region will indicate if there has been more electricity production during this period.

According to Red Eléctrica, the monthly generation of energy due to solar photovoltaic in July of 2023 technology is responsible for generating an average of 1.018.195 MWh per month. Now it is necessary to assess the demand during the same period in Extremadura to prove if all the electricity produced from solar PV was entirely used or if there was an excess. [39]

The demand of energy in July of 2023 in Extremadura was equivalent to 416.618 MWh, a value much lower than the energy produced. Therefore, in the period analyzed there is exceeded energy being produced. [40]

Moreover, solar overproduction in having an unintended effect on consumers that installed panels in their residential homes: the energy produced that is not consumed and is sold back to the grid is not generating a profit for surplus production, consumers with regulated market contracts had to pay for the excess energy they fed into the network. [41]

3.2.2. Wind turbine analysis

When it comes to wind power generation, a similar study was conducted to analyze if this source generating an overproduction of energy. Next the data encountered will be discussed evaluating the national demand of energy and energy production for the month that presents the highest electricity generated from wind energy.

As shown in Fig. 23, January recorded the peak production value of wind energy generation in Spain in the year of 2023, with a total of 7,457.3 GWh generated.

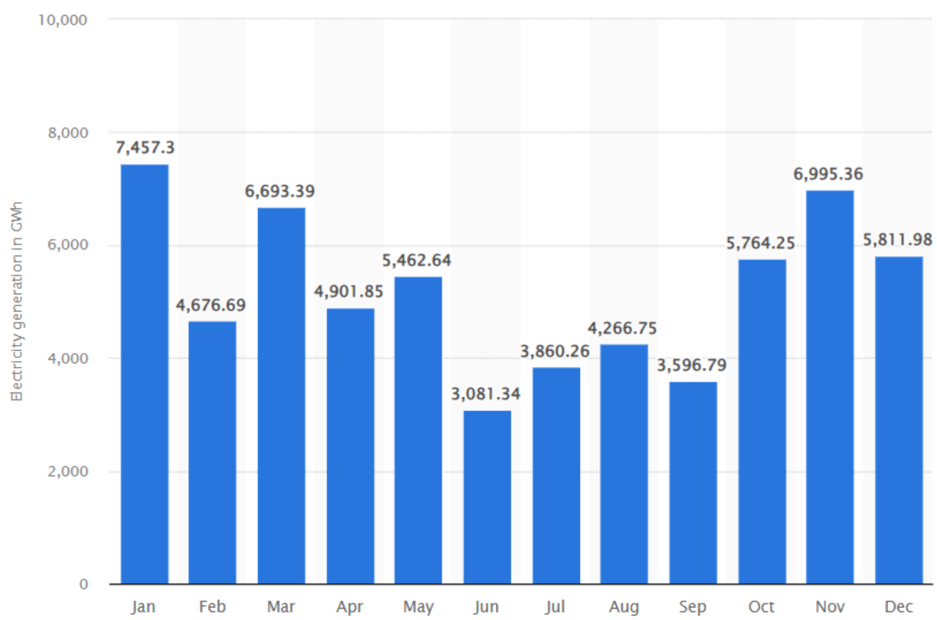

Fig. 23. Wind energy generation in Spain from January to December 2023. [42]

The peak registered in January presents the highest output throughout the year, and it is primarily due to the favorable windy conditions of the month. Consequently, the analysis of surplus energy will focus on the days within January to evaluate moments of excess generation.

Therefore, the production of energy from wind power sources will be studied for the month of January of 2023 in the region of Aragón. According to Red Eléctrica, the production of energy from wind power results in an equivalent of 1.614.539 MWh. [40]

Despite winter months typically having higher electricity demand due to heating needs, the wind energy output during this month exceeds the demand, mostly during certain periods of the day on occasions when wind speeds are exceptionally high.

On the other hand, the demand of energy in January corresponds to 878.380 MWh in total. Comparing the values of demand and generation of energy in this month, it is possible to see that wind power produces energy enough to attend the demand of 878.380 MWh during the indicated period, but it has also produced an excess of energy equivalent to 736.159 MWh. [39]

The alignment of climatic optimum conditions with technological capacity in January for wind and July for solar PV in Spain demonstrates the high potential for renewable sources and highlights the excess production. These periods of surplus are critical for energy policy as it brings out the necessity for energy storage or redistribution to prevent wastage and stabilize the grid. Furthermore, such excesses offer a great opportunity to power processes like hydrogen production via electrolysis for instance, which can provide a purpose to manage the surplus as well as an economic opportunity.

4. Assessment of excess energy production

In this section the generation of energy during the year 2023 by solar photovoltaic and wind turbine will be analyzed in Extremadura and Aragón. Besides that, the demand of energy for each month of the year in the respective regions will be utilized to evaluate in which months the energy produced by those renewable sources presented an excess of generation, after attending the demand. Therefore, the possibility of using the excess energy generated for production of hydrogen will be considered through the most efficient method mentioned earlier in this project, which is water electrolysis.

Table 2 shows the amount of energy that was generated each month in 2023 in Aragón and the demand for energy in the same period and location. With these values it is possible to calculate the exact value of energy produced that was exceeding each month, meaning that the entire demand was attended and still an amount of energy was available to be used.

Table 2. Wind power generation and total demand of energy in the year of 2023 in Aragón.

Wind Power in Aragón		
Month	**Generation (MWh)**	**Demand (MWh)**
January	1,614.539	878.380
February	647.693	822.063
March	1,156.474	843.589
April	1,006.496	758.289
May	1,369.560	814.034
June	653.750	800.324
July	874.522	836.874
August	942.646	794.644
September	479.501	759.679
October	753.421	763.863
November	1,351.292	794.897
December	1,153.644	812.829

As observed in the table above, during most of the months of 2023 the generation of energy was superior to the demand. However, in certain months the demand was higher, for example February, June, September, and October.

In Table 3 the same data of values of energy generation and demand are shown for the region of Extremadura. Once again, the comparison between energy generated by solar PV and the demand in the region will be evaluated.

Table 3. Solar power generation and total demand of energy in the year 2023 in Extremadura.

Solar photovoltaic in Extremadura		
Month	**Generation (MWh)**	**Demand (MWh)**
January	443.738	442.677
February	619.317	404.495
March	792.626	398.690
April	1,015.718	341.259
May	1,032.609	342.226
June	936.765	380.511
July	1,018.195	416.618
August	1,093.250	487.092
September	804.311	372.290
October	569.675	378.116
November	418.587	378.538
December	422.460	418.336

The information provided by both tables reveal that during the year of 2023 there was a great amount of energy being produced by wind power and solar PV that was not all designated to attend the local demand of Extremadura and Aragón, since with the values obtained each month, it was possible to satisfy the demand and there still be an excess of energy.

Table 4 provides a detailed account of the monthly excess energy generated by solar PV and wind power in the regions of Aragón and Extremadura throughout 2023. The data reveals significant variations in energy production between the two renewable sources, with solar PV consistently producing a surplus each month, peaking at 690.383 MWh in May.

Table 4. Excess of energy produced from renewable energy sources 2023.

Excess of energy (MWh)		
Month	**Solar PV**	**Wind Power**
January	1.061	736.159
February	214.822	-174.370
March	393.936	312.885
April	674.459	248.207
May	690.383	555.526
June	556.254	-146.574
July	601.577	37.648
August	606.158	148.002
September	432.021	-280.178
October	191.559	-10.442
November	40.049	556.395
December	4.124	340.815

During the months of February, June, September, and October the results obtained for energy excess are negative, meaning that there of no excess of energy being produced from wind power in Aragón, this is expected since in Table 2 it was possible to observe that the demand of energy was higher in Aragón in those months. This could have been caused due to a higher demand for energy in February from the lower temperatures in winter, and because of climatic conditions that were not optimal in the other months, as it can be seen in Fig. 21, the wind speeds were indeed a lot lower in the period of February, September, and October mainly. However, during the other months of the year there has been an excess of energy being generated from wind power, and during all months from solar PV.

With the energy exceeding data from the months of 2023 in Table 4, it is possible to calculate how much hydrogen could be generated through water electrolysis. Firstly, the amount of energy using water electrolysis depends on the efficiency of the electrolyzers. Most electrolyzers range between 60-80%, therefore the energy required to produce hydrogen will be based on a 70% efficiency electrolyzers, which is a mid-range value. For electrolyzers operating at 1000 K temperatures, utilizing one stage, and with an efficiency of 70% it can operate at 26.63 kWh kg^{-1} of electrical input. [43]

The amount of hydrogen produced per MWh of excess energy form wind or solar can be calculated with the following equation:

$$P_{H_2} = \frac{E_{excess}}{E_{required}} [Mg] \qquad [6]$$

where:

- E_{excess} is the excess energy calculated in Table 4 (MWh).
- $E_{required}$ is the energy required to produce 1 kg of H_2 at the given efficiency of the electrolyzer, in this case it is worth 26.63 kWh kg^{-1} for an electrolyzer of 70% of efficiency.

Table 5 presents the results of using equation 6 to calculate the amount of hydrogen that can be produced from the excess energy presented in Table 4. The results of the study demonstrate that by using water electrolysis, it is feasible to produce thousands of kilograms of hydrogen on a monthly basis. This production leverages the excess energy generated from renewable energy sources in the regions that were examined. The implications of these calculations are significant, as they suggest a notable potential for sustainable hydrogen production.

Given this potential, it is crucial to assess whether the quantities of hydrogen that can be produced through this method can be effectively used in the primary industries that heavily rely on hydrogen. These industries are discussed in detail in earlier chapters of this document. This evaluation is essential to ensure that the produced hydrogen could meet the needs of these industries, or contribute to them, thereby creating a more sustainable and efficient use of renewable energy sources. By considering the compatibility of hydrogen production and its industrial applications, it is possible to better understand the practical benefits and the magnitude of their impact on implementing such a strategy on a larger scale.

Table 5. Hydrogen production from renewable sources.

Hydrogen Production (Mg)		
Month	**Solar PV**	**Wind Power**
January	0.040	27.644
February	8.067	
March	14.793	11.749
April	25.327	9.321
May	25.925	20.861
June	20.888	
July	22.590	1.414
August	22.762	5.558
September	16.223	
October	7.193	
November	1.504	20.894
December	0.155	12.798
Annual value	244.200	110.238

Firstly, the ammonia production industry, which is the leading industry in consumption of hydrogen worldwide, needs a total of 177 kg of H_2 and 823 kg of N_2 to produce 1 ton of ammonia according to the following equation: [27]

$$3H_2 + N_2 \rightarrow 2\,NH_3 \qquad [7]$$

However, the modern ammonia synthesis Haber-Bosh efficiency is around 50-55%. For this reason, the real amount of hydrogen needed in the process is twice the value indicated above. The following equation represents the relationship between the theorical amount of hydrogen obtained from equation 7 with the real-world efficiency of the process to achieve the hydrogen truly needed in the process. [44]

$$H_2\ needed = \frac{Theoretical\ H_2\ required}{\eta} \qquad [8]$$

In this case, considering an efficiency of 52.5% and using the theorical amount of 177 kg of H_2 based on stochiometric calculations, the conversion rate equals 337 kg of hydrogen necessary to produce 1 Mg of ammonia. [44]

Therefore, with the results from Table 4 it is possible to calculate how many tons of ammonia could be produced with the hydrogen from exceeded energy. The values obtained from this operation are gathered in Table 6.

Table 6. Ammonia production from hydrogen.

Ammonia Production (Mg)		
Month	**Solar PV**	**Wind Power**
January	0.000	0.082
February	0.024	
March	0.044	0.035
April	0.075	0.028
May	0.077	0.062
June	0.062	
July	0.067	0.004
August	0.068	0.017
September	0.048	
October	0.021	
November	0.004	0.062
December	0.000	0.038
Annual value	79.224	0.328

A typical commercial scale of ammonia production can be of a scale around 200 ton/day of NH_3, according to the results obtained the amount of ammonia that could be generated from the hydrogen obtained from renewable sources is equivalent to a small percentage of the typical commercial scale of ammonia production. However, this still represents the integration of a green alternative to be used in the ammonia industry, which already uses 55% of the worlds hydrogen consumption and could benefit from hydrogen produced from renewable energy, which is wind power and solar photovoltaic in this case. [27]

When it comes to electrical cars, a growing tendency mainly in Europe and North America, for every kilogram of pure hydrogen it is possible to drive one hundred kilometers. [45] This information is based on the efficiency of current hydrogen FCEVs like Toyota Mirai; however, it may vary according to the car. In Table 7 it is possible to visualize how many kilometers it could be possible to drive with the amount of hydrogen obtained from Table 5. [45]

Table 7. Kilometers that can be driven with hydrogen production.

Kilometers		
Month	**Solar PV**	**Wind Power**
January	3.98	$2.76 \cdot 10^3$
February	$3.98 \cdot 10^2$	
March	$1.48 \cdot 10^3$	$1.17 \cdot 10^3$
April	$2.53 \cdot 10^3$	$9.32 \cdot 10^2$
May	$2.59 \cdot 10^3$	$2.09 \cdot 10^3$
June	$2.09 \cdot 10^3$	
July	$2.26 \cdot 10^3$	$1.41 \cdot 10^2$
August	$2.28 \cdot 10^3$	$5.56 \cdot 10^2$
September	$1.62 \cdot 10^3$	
October	$7.19 \cdot 10^2$	
November	$1.50 \cdot 10^2$	$2.09 \cdot 10^3$
December	$1.55 \cdot 10^1$	$1.28 \cdot 10^3$
Annual value	$1.66 \cdot 10^4$	$1.10 \cdot 10^4$

As the results show, with the hydrogen produced from renewable sources such wind power and solar PV in only two regions of Spain, it is possible to generate enough electricity to charge electric cars enough to drive more than thousands of kilometers in one month. This puts to evidence the exciting potential that using the excess of energy production from renewable sources to produce hydrogen can have on other essential fields of the industry, in this case replacing fuel cars for a greener alternative such as electric cars.

As a last example of the possible applications of hydrogen comes methanol industry, in this field the hydrogen is used for methanol synthesis, which consists of separating it from water and residual gases and purified through distillation. To produce 1000 kg of methanol it is needed around 200 kg of hydrogen, among other compounds. Evidently, the amount of hydrogen produced from exceeded energy is not enough to produce a great share of methanol, but it still can offer an important contribution to the process by employing a hydrogen that comes from renewable sources, which has zero or low carbon emissions and contributes overall to more sustainable industrial process. [46]

In conclusion, hydrogen offers great versatility and a multifaceted solution to many industries, bringing a more sustainable and environmentally friendly approach to important industrial processes. By using hydrogen in big industries, Spain can achieve significant objectives towards a carbon-neutral future, setting an example for other countries to follow.

5. Conclusion

The transition to hydrogen as a key energy source signifies a great shift towards sustainable and environmentally friendly solutions to industry. This research project has demonstrated the potential that renewable energy sources such as solar photovoltaic and wind power must generate hydrogen in Spain, which can be applied to many different industrial fields. Hydrogen's unique ability to produce energy without harmful emissions makes it an attractive option for reducing air pollution and combating climate change worldwide. By incorporating hydrogen in more industrial processes, Spain can significantly increase its energy security and contribute to global decarbonization efforts.

Hydrogen production methods such as steam methane reforming (SMR), partial oxidation, autothermal reforming, plasma reforming, biomass gasification, and water electrolysis are typically utilized in the industries nowadays, however each one presents different advantages and challenges. SMR remains the most widely used method because of its cost effectiveness, despite having a negative environmental impact. Water electrolysis is currently the most expensive method, but it is highly effective, and it offers the cleanest hydrogen production when powered by renewable energy. The production of hydrogen through water electrolysis from renewable sources aligns with Spain's goal of achieving carbon neutrality by 2050 and it can also have a significant impact on the country's economic market by reducing its dependence on imported fossil fuels.

The assessment of excess energy production from renewable sources in the regions of Extremadura and Aragón shows the feasibility of using surplus renewable energy for hydrogen production. The study revealed that during certain months of 2023, these regions produced more energy than was consumed, particularly in July for solar photovoltaic and January for wind energy. For example, the surplus energy generated from solar PV in Extremadura in July 2023 was significantly higher than the regional demand, resulting in an excess of approximately 601,577 MWh. Similarly, in Aragón, wind energy generation in January 2023 exceeded demand by about 736,159 MWh.

Using the surplus energy for hydrogen generation offers an optimized use of renewable resources and provides a sustainable solution for hydrogen production that can be used in various industries, such as transportation, ammonia production, methanol synthesis, and the petroleum industry. For instance, the hydrogen produced from excess energy in Extremadura and Aragón reached values that could contribute to the industry of ammonia production and methanol production, supporting the industry's decarbonization efforts and providing a totally clean share of hydrogen to be used in those process, since these industries take up of 55% and 10% of the whole consumption of hydrogen worldwide, respectively.

Furthermore, the hydrogen produced from renewable sources could also be used to power fuel cell electric vehicles (FECVs). For example, the hydrogen produced from excess energy in one month could enable electric cars to drive thousands of kilometers, providing a greener alternative to traditional fossil fuels, and depicting potential to have a significant impact on the growing industry of electric vehicles in Spain.

The future of hydrogen as an energy source is promising, driven by technological advancements and the need for a sustainable alternative. As Spain continues to invest greatly in renewable energy infrastructure and regulatory frameworks, hydrogen can play a crucial role in the country's energy transition. The combination of favorable climatic conditions of certain regions, technological innovation and policy initiatives positions the country as a potential leader in the global hydrogen economy.

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