Universidade de Aveiro
2021

**Alberto Rafael Silva Peixoto**

# Análise económico-financeira de projetos: energias renováveis e eficiência energética

Economic and financial analysis of projects: renewable energy and energy efficiency

**Universidade de Aveiro**
**2021**

**Alberto Rafael**
**Silva Peixoto**

# Análise económico-financeira de projetos: energias renováveis e eficiência energética

Economic and financial analysis of projects: renewable energy and energy efficiency

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Sistemas Energéticos Sustentáveis, realizada sobre a orientação científica da professora Marta Ferreira Dias, professora auxiliar do departamento de Economia, Gestão, Engenharia Industrial e Turismo, e co orientação científica da professora Mara Teresa da Silva Madaleno , professora auxiliar do Departamento de Economia, Gestão, Engenharia Industrial e Turismo da Universidade de Aveiro.

**o júri**


presidente

Prof. Doutora Margarita Matias Robaina
Professora auxiliar da Universidade de Aveiro

Prof. Doutor Nuno Miguel dos Santos Carvalho Figueiredo
Professor Auxiliar Convidado, Universidade de Aveiro

Prof. Doutora Marta Alexandra da Costa Ferreira Dias
Professora auxiliar da Universidade de Aveiro

**agradecimentos**

Desejo exprimir os meus agradecimentos a todos aqueles que, de alguma forma, permitiram que esta dissertação se concretizasse.

À professora Mara Teresa da Silva Madaleno e à professora Marta Alexandra da Costa Ferreira Dias, pela orientação, apoio e disponibilidade, pelas opiniões e críticas, assim como a partilha do saber, e por todas as palavras de incentivo.

A todos os meus amigos e colegas, que estiveram ao meu lado durante esta fase, pelo companheirismo, força e apoio nos momentos mais complicados.

À minha namorada por ter caminhado ao meu lado, por toda a paciência e compreensão, quando sacrificava os dias, os fins-de-semana em prol da realização desta etapa.

Dirijo um agradecimento especial aos meus pais, Joaquim e Madalena, por serem o meu maior exemplo de coragem e determinação, pelo seu apoio com palavras de encorajamento valorizando o meu potencial nos momentos mais complicados, pela paciência demonstrada pela minha ausência nos momentos de família. Sem vocês não teria esta oportunidade de lutar pelos meus sonhos e objetivos. A eles dedico este trabalho!

Agradeço ainda aos restantes familiares com principal destaque para a minha querida avó, por todas as refeições, doces e pequenos-almoços que preparou para ter a certeza que não perdia tempo, um agradecimento à minha tia e à minha Madrinha, sem o vosso apoio e compreensão também nada disto seria possível.

**palavras-chave**

Células de combustível, Emissão de gases de efeito de estufa, Economia de hidrogénio, Eletrólise da água, Energia, Sustentabilidade.

**resumo**

A cresceste procura por energia, a emissão de gases de efeito de estufa, o aquecimento global e consequentemente as alterações climáticas são temas importantes sobre a sustentabilidade do nosso planeta. Parte importante para a solução deste problema pode surgir da utilização do hidrogénio.
Esta dissertação procura realizar um estudo de viabilidade económica da produção de hidrogénio em Portugal através de energias renováveis em regime de autoconsumo. Em primeira instância foi realizada uma revisão bibliográfica ao contexto atual global relativamente à energia e sustentabilidade, com foco no enquadramento do hidrogénio na economia global, europeia, e portuguesa e as suas oportunidades, desafios, utilizações atuais e futuras. Em toda a cadeia de valor é salientada uma perspetiva de custo, uma vez que esse é um dos principais impedimentos para o desenvolvimento de uma economia global baseada no hidrogénio.
Posteriormente foi realizada uma análise de viabilidade económica da produção de hidrogénio em Portugal, onde foram tidos em conta os equipamentos necessários e o seu custo. Uma vez que o estudo é realizado através de autoconsumo de energia elétrica através de fontes renováveis de modo a ser possível realizar uma análise sensitiva, o mesmo foi realizado em quatro localizações diferentes, de modo a analisar o impacto da localização em que o projeto irá ser realizado. O impacto de diferentes fontes de financiamento foi também simulado.
Resultados obtidos demonstraram que as disponibilidades de recursos energéticos renováveis têm um grande impacto no custo de produção do hidrogénio, sendo a escolha da localidade importante para a viabilidade económica do projeto, resultados demonstraram também que atualmente sem financiamento externo não é possível realizar um centro de produção de hidrogénio com venda a preços competitivos onde o retorno de investimento seja inferior a 10 anos.
No melhor cenário, 100% energia solar com investimento externo de 70% em Faro, é expectável um payback inferior a 5 anos e um valor atualizado líquido entre 682 403€ e 476 640€ em um período de 10 anos.

**keywords** Energy, Greenhouse gas emissions, Hydrogen economy, Sustainability, Water electrolysis.

**abstract**

The growing demand for energy, the emission of greenhouse gases, global warming, and consequently climate change are important issues regarding the sustainability of our planet. An important part of solving this problem can arise from the use of hydrogen.

This dissertation seeks to carry out an economic feasibility study to produce hydrogen in Portugal through renewable energy in a self-consumption regime.

Firstly, a literature review was carried out on the current global context regarding energy and sustainability, focusing on the framework of hydrogen in the global, European, and Portuguese economy and its opportunities, challenges, current and future uses. A cost perspective is highlighted throughout the value chain, as this is one of the main impediments to developing a global economy based on hydrogen.

Subsequently, an analysis of the economic feasibility of hydrogen production in Portugal was carried out, considering the necessary equipment and its cost. Since the study is carried out through self-consumption of electricity from renewable sources, to carry out a sensitivity analysis, it was studied in four different locations, to analyze the impact of the location where the project will be implemented. The impact of different fundings sources was also simulated.

The findings revealed that the availability of renewable energy resources has a significant impact on the cost of hydrogen generation and that the site chosen is critical for the project's economic sustainability. They also revealed that without external funding, it is unfeasible to create a hydrogen production center with competitive costs and a return on investment of fewer than ten years.

In the best scenario, 100% solar energy with an external investment of 70% in Faro, it is expected a payback inferior to five years and a net present value between €682,403 and €476,640 over a period of 10 years.

# Contents

# List of Figures

# List of Tables

## Acronyms

**AFC** Alkaline Fuel Cell

**APFS** Perfluorosulfonic Acid

**CCS** carbon Capture and Storage

**EU** European Union

**GDL** Gas Diffusion Layers

**GGND** Galp Gás Natural Distribuição

**HHV** Higher Heating Value

**LHV** Lower Heating Value

**NDC** National Determined Contributions

**PEM** Proton Exchange Membrane

**PEMFC** Polymer Electrolyte Membrane Fuel Cell

**PTFE** Polytetrafluoroethylene

**RDD** Research, Design, and Development

**SCP** Superior Calorific Power

**SOFC** Solid Oxide Fuel Cell

**TWh** Terawatt-hour

# Chapter 1

# Introduction

There is a growing interest among policymakers, scientific community, environmental organizations, and industries in searching for alternatives to fossil fuels. Our reliance on fossil fuels is unsustainable, both economically and environmentally. There is an energy security risk of relying on finite oil and gas. In the past, the increase of prices in fossil fuels have led to a growing insight that the world is starting to run out of cheap fuel, rushing the need to move to cleaner and sustainable energy technologies. Hydrogen is an energy carrier that presents an opportunity for the substitution of fossil energy sources, which may be stored for long periods time unlikely batteries and electricity, and be transported by pipeline, truck, ship, or even be blended into existing natural gas grid (Brändle et al., 2021).

There are a variety of ways to produce hydrogen. For the purpose of this analysis hydrogen is only considered green if it is produced through water electrolysis driven by electricity from renewable energy sources, therefore there are no direct carbon emissions in this process (Federal Ministry for Economic Affairs and Energy, 2020). Hydrogen can be converted back to electricity using a fuel cell, producing only water as a result (Yuan et al., 2021). Therefore, hydrogen may play a key role in achieving greenhouse gas neutrality in almost all sectors of the economy (Brändle et al., 2021). However the production of green hydrogen still cannot compete in price against other types of hydrogen production, being mostly influenced by the price of electricity (Hydrogen Council, 2020). Besides that, there are a lot of technical, environmental, and cost challenges to overcome in the way hydrogen is produced, transported, and stored (Sdanghi et al., 2020).

The objective of this dissertation is to carry out an economic feasibility study on the production of hydrogen in Portugal through renewable energies in the self-consumption regime and search through companies and budgets for the real cost of producing hydrogen in Portugal. In light of this, the study is carried out through self-consumption of electric energy through renewable sources to be able to carry out a sensitivity analysis. This analysis was carried out in four different locations, to analyze the impact of the location in which the project will be carried out, where the impact of different sources of financing was also simulated. Spreadsheets were made to simulate the course of production over ten years, from 2020 to 2030. The main results shows that green hydrogen production, with current equipment costs and efficiency, is unfeasible at less than 3€/kg of hydrogen without funding even with the best meteorologic conditions in Portugal.

In the following chapters, a bibliography review is carried out on the current global context regarding energy and sustainability, contextualization and framing of hydrogen in the global, European, and Portuguese economy, and its opportunities, challenges, current and future uses. A cost perspective throughout the value chain is always taken into account, as this is the biggest obstacle to the development of a global economy based on hydrogen.

Following that, an economic analysis of the possibility of hydrogen generation in Portugal was carried out, considering the necessary equipment and its cost. Because the study is conducted through self-consumption of electric energy from renewable sources to perform a sensitivity analysis, it was run in four separate places to assess the influence of each location where the project is implemented. Different financing sources' effects were also simulated.

This dissertation ends with an appropriate conclusion and results from the discussion, pointing limitations and directions for future research.

# Chapter 2

# Energy and Sustainability

Population growth associated with fast technologic evolution and consequently major access to it, stand serious questions about sustainability. Advancements to a technologic world, with several countries reaching similar levels of development leads to a higher search for energy, both primary energy and its useful forms like, for example, electricity. We may see the evolution curve in primary energy consumption in the World and more relevant actors in Figure 2.1 (BP, 2020).

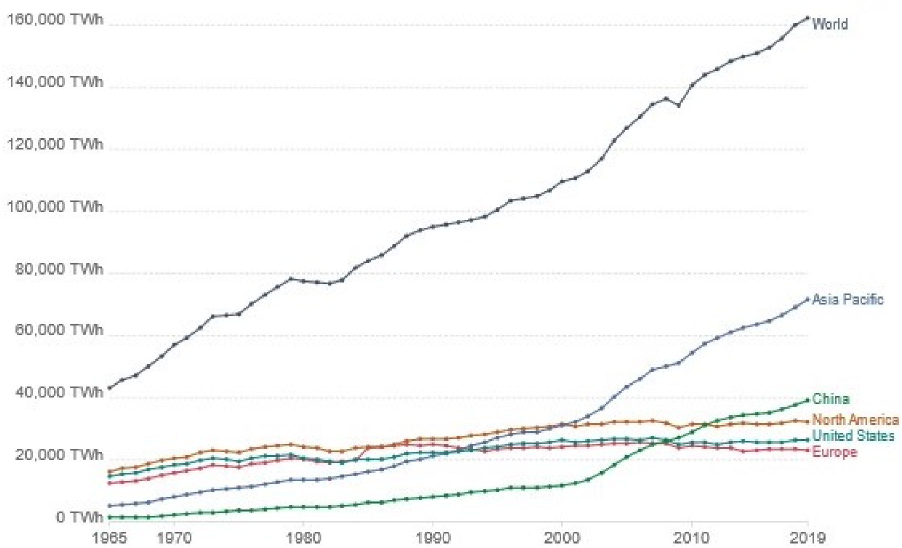


**Figure 2.1:** World primary energy consumption [TWh] (Biomass not included) (adapted from Bp, 2021)

Primary energy may be transformed from multiple sources, fossil, nuclear, and renewables. Sustainability in energy production may be analyzed considering multiple factors such as utilized materials in production and extraction of the fuel, transport of materials, territory occupation, and storage.

The tendency is the increase of production from renewable sources, as we may see in Figure 2.2. Although it is important to mention that the need for primary energy consumption in the World was 162,194 TWh in 2019, and in the same year the amount of primary energy consumption generated from renewable sources was 18,504 TWh, it accounts for only 11,4%.

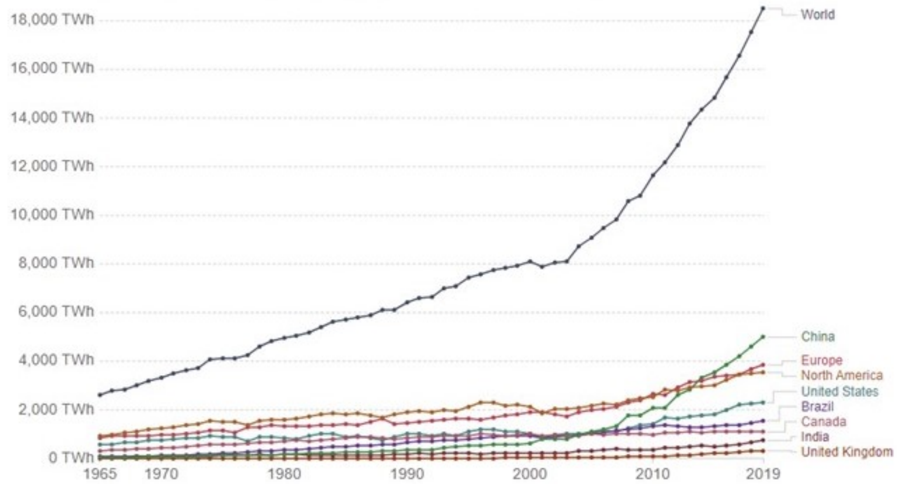


**Figure 2.2:** Primary energy consumption from renewables [TWh] (adapted from Bp, 2021)

---

Use of fossil fuels to produce energy generate greenhouse gases including carbon dioxide, methane, and nitrous oxides. The amount of carbon dioxide in earth´s atmosphere stores extra heat near the surface of earth, inducing temperatures to rise. A growing number of societal actors from activists, scientists and concerned consumers are pushing for stronger policy action to limit carbon emissions.

For that reason, on 12 December 2015, has been achieved a landmark agreement to combat climate change and to accelerate and intensify the research and development of technologies needed for a sustainable low carbon future, that agreement is called "The Paris Agreement".

The Paris Agreement is a legally binding international treaty adopted by 196 countries, to limit the increase in the world temperature to below 2ºC compared to pre-industrial levels before the end of the century. The origin of a more ambitious target is the 1.5ºC Paris Agreement limit derived from the concern amongst vulnerable areas of the world about the adverse consequences of a 2ºC warming level.

If $CO_2$ emissions continue current at levels, we have only ten years remaining in the global carbon budget before we breach the 1.5ºC threshold, emphasizing the need for immediate action (Hydrogen Council, 2020). Parties to the agreement submit climate action plans known as nationally determined contributions (NDCs) for the climate action. National determined contributions includes an enhanced governance system related to integrated planning, reporting and monitoring in climate and energy policy fields, including with respect to climate and energy targets, policies, measures, projections, and provisions for multi-level public participation as well as public consultations to be held by Member States in the preparation of the integrated national energy and climate plans that implement their policy targets up to 2030 (Energy and climate inteligence unit, 2021).

Along with companies, cities and financial institutions, 131 countries have now set or are considering a target of reducing emissions to net zero by 2050. While net zero is a critical longer-term goal, steep emissions cuts especially by the largest greenhouse-gas emitters are imperative in the next 5 to 10 years in order to keep global warming to no more than 1.5ºC and safeguard a livable climate. To keep warming to 1.5ºC, countries must cut emissions by at least 45% compared to 2010 levels (Energy and climate inteligence unit, 2021).

## 2.1 Why 1.5ºC?

In the Paris Agreement, governments committed to keep global warming below 2ºC, and make efforts to keep it below 1.5ºC. These replaced the previous politically-agreed target of 2ºC.

Stabilizing global warming at 1.5ºC since 2015 results in a lower level of impacts and reduced risks compared with stabilizing at 2ºC. Besides 1.5ºC does not seem relevant on our daily basis the warming in different countries and regions can be a lot more than the global average. Accordingly to a study conducted by Seneviratne et al., (2016) global warming of 2ºC is projected to increase the warmest temperatures in the Mediterranean by 3ºC, and the coldest Arctic temperatures by 5.5ºC.

It is expected more extremes of temperature at 2ºC of global warming than at 1.5ºC for longer periods and frequently. Reaching the 1.5ºC target would mean that fewer people are exposed to regularly (at least once every five years) to severe heatwaves. In Europe, summers as hot as 2003, which brought excess deaths, are expected to occur three years in five under 2ºC of warming, two years in five at 1.5ºC. For central England, the hottest summers seen so far are expected to happen every third year at 1.5ºC, every second year at 2ºC (Dosio et al., 2018).

Heavy rainfall is expected to increase. Incidence is forecasted to be significantly higher at 2ºC than at 1.5ºC in countries around the Arctic and high altitudes. By contrast, limiting warming to 1.5ºC is forecast to bring droughts of lower severity to the Mediterranean and North Africa.

Limiting global warming to 1.5ºC rather than 2ºC is projected to result in about 10cm less of sea-level rise by the end of the century. That would mean that in 2100, 10 million fewer people would be at risk of coastal flooding from extreme sea level events under 1.5ºC of warming as compared with 2ºC. The lower target also reduces the risk that either the Greenland or West Antarctic ice sheet will be destabilised, leading to sea-level rise of several meters. The global warming threshold for triggering runaway melting is not known precisely, but one credible estimate for Greenland is 1.6ºC (Robinson et al., 2012).

Scarcity of Food, water and health is also expected to increase, keeping global warming to 1.5ºC is forecast to result in about half as many people facing water scarcity as at 2ºC. The number of people exposed to severe levels of heat in Southern Asia and Eastern Africa is forecast to increase by a factor of 4 at 1.5ºC of global warming, and a factor of 16 at 2ºC (Harrington and Otto, 2018).

Both the smaller extent and slower speed of climate change associated with the 1.5ºC target are forecast to result in a smaller threat to nature. However, in some cases it would still be severe. About 70-90% of coral reefs are expected to experience severe degradation at 1.5ºC of global warming, increasing to 99% at 2ºC (Warren et al., 2018).

Globally, 2ºC of warming is projected to affect economic growth significantly, such that average gross domestic product per capita would be 5% lower in 2100 at 2ºC than at 1.5ºC (Pretis et al., 2018).

## 2.2 National determined contributions [NDC]

Now that it has been established the importance to limit the emission of greenhouse gases to contribute positively to global warming, where we can look at the percentage of contributors of greenhouse gas emissions in Figure 2.3.

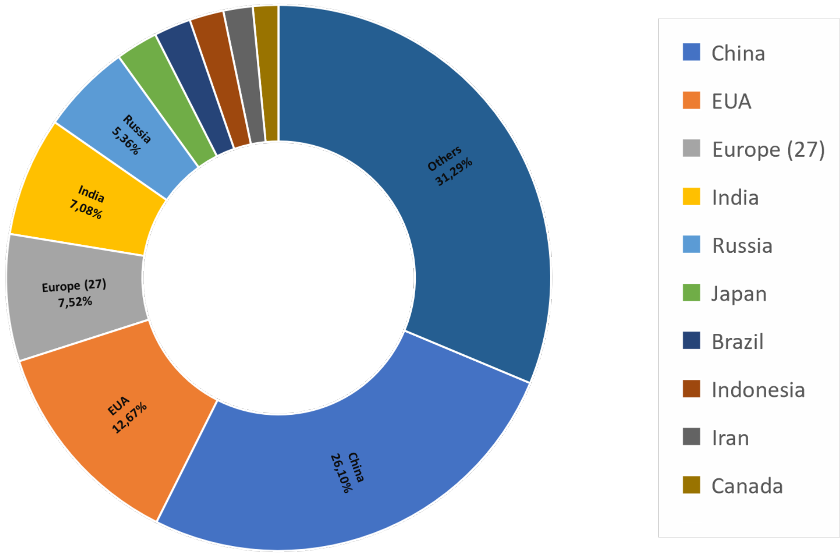


**Figure 2.3:** Top 10 greenhouse gases Emitters (Friedrich et al., 2020, accessed on 1 June, 2021 from https://www.wri.org/insights/interactive-chart-shows-changes-worlds-top-10-emitters)

The top 3 greenhouse gas emitters contribute 16 times the emissions of the bottom 100 countries, totalizing more than 46% of the global emissions. Let´s take a brief resume of the national determined contributions of the top 3 emitters (Friedrich et al., 2020).

### 2.2.1 China

Accordingly to the National Development and Reform Comission of China, 2016 has nationally determined its actions by 2030:

-Reach the peaking of carbon dioxide emissions around 2030 and making best efforts to peak sooner, as we can see in Figure 2.4 China annual emissions of $CO_2$ is still increasing.

-Diminish and control carbon dioxide emissions per unit of gross domestic product by 60% to 65% from the 2005 level.

-Increase the share of non-fossil fuels in primary energy consumption to around 20%.

-Increase the forest volume by around 4.5 billion cubic meters from the 2005 level.

In order to achieve targets on climate change, National Development and Reform Comission of China, 2016 has to take action on policies and measures implementing proactive national and regional strategies on climate change to strengthen laws and regulations.

### 2.2.2 United States of America

United States is setting an economy-wide target of reducing its net greenhouse gas emissions by 50% to 52% below 2005 levels in 2030 (United States of America, 2021), Figure 2.4.

In order to achieve these objectives, United States considered sector by sector emissions reductions pathways.

United States has set a goal to reach 100% carbon pollution-free electricity by 2035. To reach that objective there is a need to cut energy waste, shift to carbon pollution-free electricity, electrifying and driving efficiency in vehicles, buildings, and parts of the industry, ling up new energy sources and carriers such as carbon-free hydrogen.

The largest sources of emissions from transportation are light-duty vehicles like SUVs, pickup trucks, and cars, followed by heavy trucks, aircraft, rail, and ships. These modes of transport are highly dependent on fossil fuels with more than 90% of transportation energy use coming from petroleum. There is a great potential to improve greenhouse gas emissions of transports. There is a pathway that includes incentives for zero-emission personal vehicles, funding for charging, infrastructure to support multi-unit dwellings, public charging, and long-distance travel, and research, development, demonstration, and deployment efforts to support advances in very low carbon new-generation renewable fuels for applications like aviation, and other cutting-edge transportation technologies (United States of America, 2021).

The United States government will support research, development, demonstration, commercialization, and deployment of very low- and zero-carbon industrial processes and products. For example, the United States will incentivize carbon capture as well as new sources of hydrogen to power industrial facilities. In addition, the United States government will use its procurement power to create demand and support early markets for these very low and zero-carbon industrial goods (United States of America, 2021).

### 2.2.3 European Union 27

European Union set a new target for increasing renewable energy in final energy consumption has been set to reach at least 32% by 2030 (European Commission, 2020).

In transport, binding targets will reduce $CO_2$ emissions per kilometer from passenger cars sold in the EU on average by 37.5% from 2021 levels by 2030, and new vans on average by 31% from 2021 levels by 2030, $CO_2$ emissions per kilometer from new large lorries must be reduced on average by 30% from 2019/2020. European Union enacted, in 2015, also regulations to reduce emissions from Fluorinated gases emissions by 66% by 2030 compared with 2014 levels.

Member States have prepared Integrated National Energy and Climate Plans for the period 2021 to 2030 that include their national contributions to achieve the combined energy and climate targets as well as related commitments under the Paris Agreement. Combined, these policies will deliver by 2030 an at least 40% reduction in greenhouse gas emissions as compared to 1990 levels. The European Union Members, acting jointly, are committed to a binding target of a net domestic reduction of at least 55% in greenhouse gas emissions by 2030 compared to 1990, Figure 2.4 (European Commission, 2020).

Emissions from electricity and associated heat generation in co generation plants contributed about 22% of the EU27 + United Kingdom total emissions. Emissions from this sector witness the fastest reduction of any sector, between 1990 and 2018, emissions fell down by 34% (European Environment Agency, 2020). It is expected that this reduction continues to fall mainly due to a collapse in power generation from coal and the increasing share of renewables.

Besides the ambitious plans to decarbonize the top 3 emitters of greenhouse gases, almost every country in the world has a bold and ambitious plan to reduce emissions dramatically, we can see in Figure 2.5 a world map with the countries with net-zero commitments until 2050 and with updated National determined contributions.

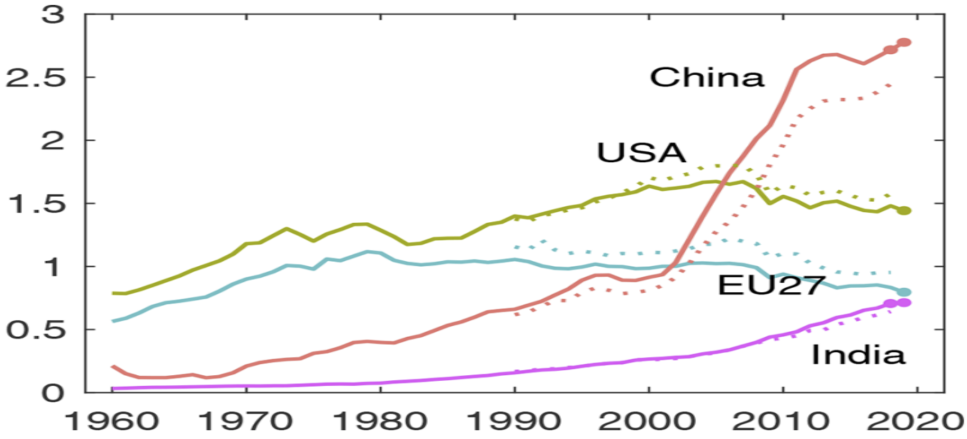


**Figure 2.4:** Gigatone of carbon emissions, (Friedlingstein et al., 2020, p.3294)

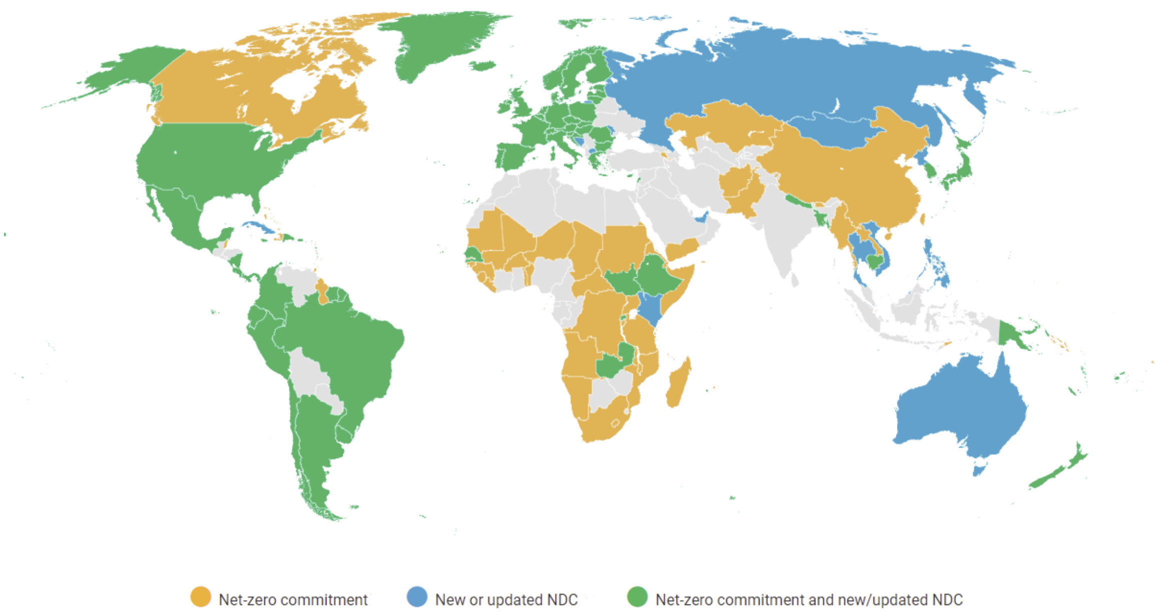


**Figure 2.5:** Net-zero commitments (Energy and climate inteligence unit, 2021, accessed on 1 June, 2021 from https://www.un.org/en/climatechange/net-zero-coalition)

# Chapter 3

# Hydrogen as an energy solution

In order to achieve full decarbonization, a multidimensional strategy is required, which has incited renewed interest in hydrogen. Governments are recognizing hydrogen´s ability to decarbonize sectors that are otherwise impossible or difficult to slacken, such as transports, industrial heating, industry feedstock, and energy security and storage systems. Meanwhile, industries of all sectors are looking to hydrogen as an alternative to reach their substantial sustainability objectives (Hydrogen Council, 2020).

Hydrogen is the lightest, and most abundant element in the universe, is made up of one electron and one proton being, therefore, the first element in the periodic table as we can see in Figure 3.1 (United Nations Environment Programme [UNEP], 2006).

On Earth there is no hydrogen in its pure state, it is always associated with other elements, to be obtained it is necessary energy to dissociate their molecules. Therefore, it may not be considered as a primary energy source but as an energy carrier (Miguel et al., 2016).

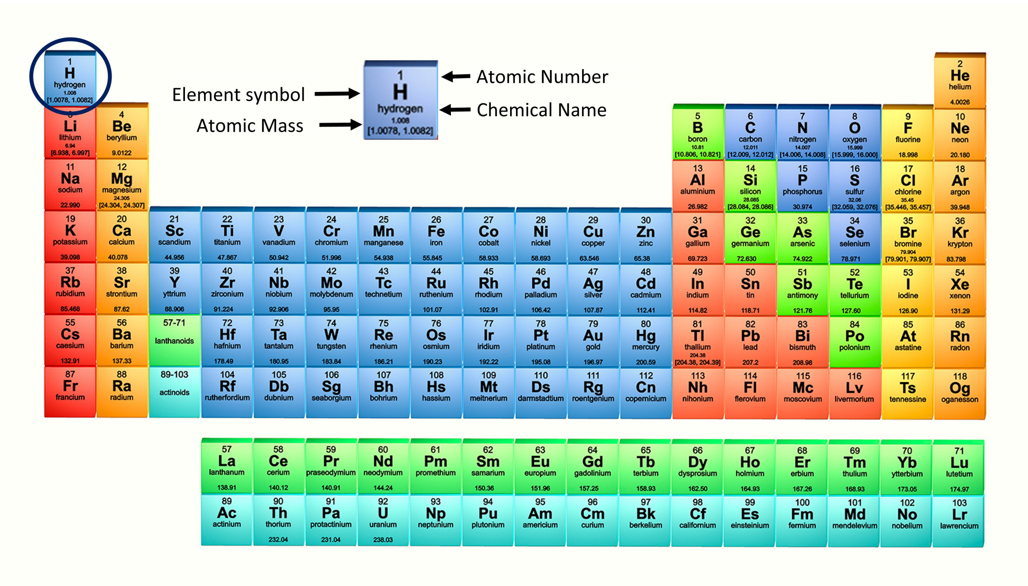


**Figure 3.1:** Periodic table of the elements (adapted from Pasieka, 2017, accessed on 20 October, 2021 from https://physicsworld.com/a/an-unelementary-affair-150-years-of-the-periodic-table/)

In its pure state at a standard temperature and atmospheric pressure, hydrogen is tasteless, colorless, odorless, and non-toxic. Its liquefaction temperature is 20,38 K and Solidification temperature is 13,95 K (United Nations Environment Programme [UNEP], 2006).

Hydrogen is highly flammable when in contact with air (burning when it makes up to 4% to 74% of air by volume) and has a high energy content by weight. We may see in Table 3.1 the comparison of superior calorific power and lower calorific value between some of most known combustibles (United Nations Environment Programme [UNEP], 2006).

**Table 3.1:** Comparison between calorific values of different fuels (Miguel et al., 2016, p.253)

| **Fuel** | **High Heating Value (HHV)** 298.15 K and 1 atm | **Lower Heating Value (LHV)** 298.15 K and 1 atm |
|---|---|---|
| Hydrogen | 141,86 $KJ/g$ | 119,93 $KJ/g$ |
| Methane | 55,53 $KJ/g$ | 50,02 $KJ/g$ |
| Propane | 50,36 $KJ/g$ | 45,6 $KJ/g$ |
| Gasoline | 47,5 $KJ/g$ | 44,5 $KJ/g$ |
| Diesel | 44,8 $KJ/g$ | 42,5 $KJ/g$ |
| Methanol | 19,96 $KJ/g$ | 18,05 $KJ/g$ |

The calorific power is the amount of energy released by a unit of mass in the oxidation of a fuel, the difference between the higher heating value and the lower heating value represents the energy needed to vaporize the water. By contrast, due to it minor weight, hydrogen has a low energy density by volume at a standard temperature and atmospheric pressure. In those conditions one gram of Hydrogen occupies around eleven liters of space. Hydrogen can be an energy carrier both in liquid, solid, or compressed gas (Miguel et al., 2016).

Hydrogen, instead of traditional fossil fuels must need to be produced with an external energy source and, therefore the nature of that source determines the *color* of hydrogen.

***Grey hydrogen:*** *Grey hydrogen is based on the use of fossil hydrocarbons. Grey hydrogen is mainly produced via the steam reforming of natural gas. Depending on the fossil feedstock, its production entails considerable carbon emissions.*

***Blue hydrogen:*** *Blue hydrogen is hydrogen which is produced using a carbon capture and storage (CCS) system. This means that the CO2 produced in the process of making hydrogen does not enter the atmosphere, and so the hydrogen production can be regarded on balance as carbon neutral.*

***Green hydrogen:*** *Green hydrogen is produced via the electrolysis of water; the electricity used for the electrolysis must derive from renewable sources. Irrespective of the electrolysis technology used, the production of the hydrogen is zero-carbon since all the electricity used derives from renewable sources and is thus zero-carbon.*

***Turquoise hydrogen:*** *Turquoise hydrogen is hydrogen produced via the thermal splitting of methane (methane pyrolysis). This produces solid carbon rather than CO2. The preconditions for the carbon neutrality of the process are that the heat for the high-temperature reactor is produced from renewable or carbon neutral energy sources, and the permanent binding of the carbon.*

Source: (Federal Ministry for Economic Affairs and Energy, 2020, p. 28)

Hydrogen holds the potential to act as an energy carrier and has the possibility to replace all the forms of final energy providing energy services to all sectors of the economy. Hydrogen may offer storage options and may be converted back to electrical energy efficiently using fuel cells, may be produced from a variety of energy sources (fossil, nuclear and renewable), Figure 3.2, all this makes it interesting even for remote communities which are not supplied through electrical grid. Besides hydrogen may reduce the dependence on imports and improve energy security, and it may be produced without emitting any greenhouse or harmful gases if produced with energy from renewable sources (United Nations Environment Programme [UNEP], 2006).

In the early stage of transition to a hydrogen economy, hydrogen would compete with electricity, gas, and oil in final energy uses, but might also complement them offering means to store electricity, obtaining an energy system more flexible, diversified, and secure. That could be one of the most attractive solutions to handle unpredictable fluctuations in outputs from intermittent sources of energy generations such as renewables and control dealing variations during the day (United Nations Environment Programme [UNEP], 2006).

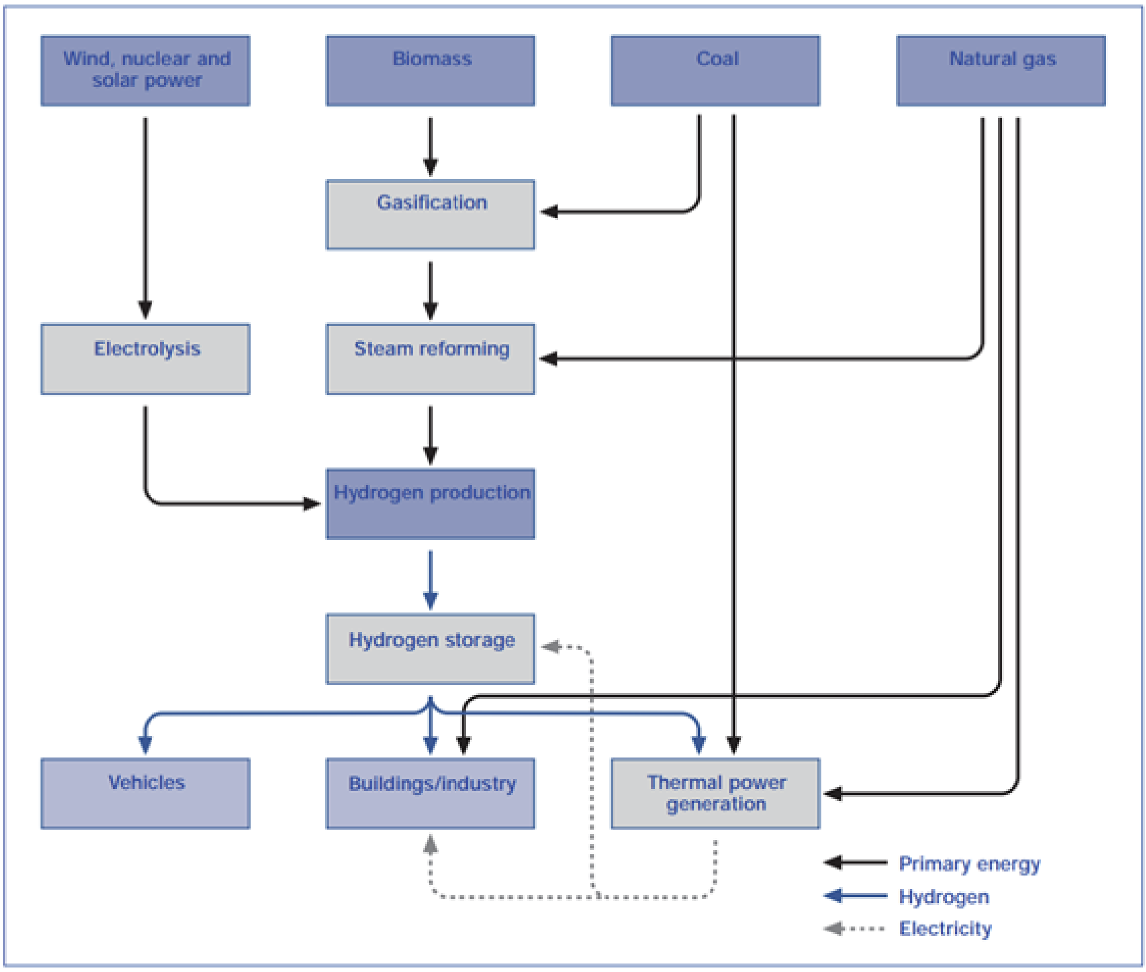


**Figure 3.2:** Linkages between Hydrogen and the rest of energy system (United Nations Environment Programme [UNEP], 2006 p.22 adapted from Menecon Consulting analysis)

## 3.1 Hydrogen Production

Hydrogen may be produced in many ways assigning different colors of hydrogen as mentioned before, in this dissertation the purpose is to produce green hydrogen via water electrolysis, however, processes mentioned in Figure 3.2 will be briefly approached, (biomass gasification and pyrolysis, and steam reforming).

### 3.1.1 Biomass gasification and pyrolysis

Obtaining hydrogen through biomass gasification and pyrolysis is a thermochemical process that will form the synthesis gas, which, followed by catalytic synthesis and fermentation, makes it possible to obtain hydrogen among other compounds (hydrocarbons, alcohols, ammonia).

Synthesis gas is the name given to a mixture of hydrogen and carbon monoxide, this represents an increasing source of clean fuels, being an important fuel for the production of electricity free from air pollutants (Silva et al., 2012).

It has applications in industrial processes of production of hydrogen for fuel cells, methanol, and multiple chemical products, as we may see in Figure 3.3.

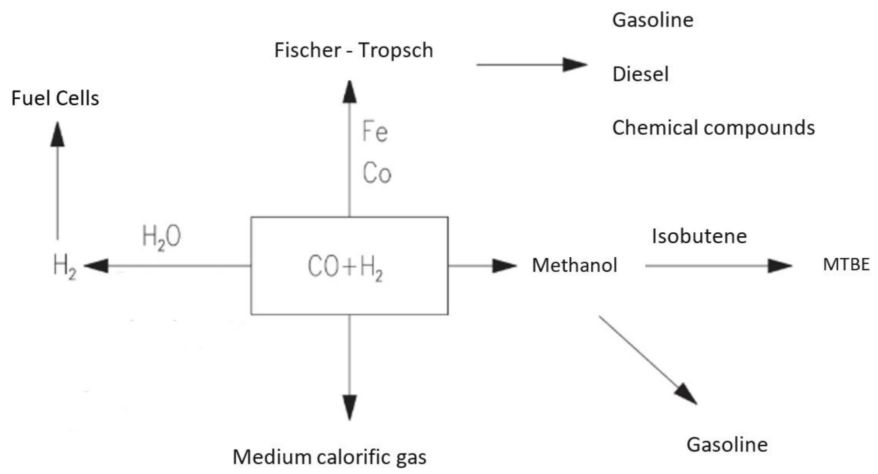


**Figure 3.3:** Synthesis Gas Transformations (adapted from Wender, 1996, p.190)

FE - Chemical element, Iron
CO - Chemical element, Cobalt
$H_2$ - Chemical element, Hydrogen
$H_2O$ - Chemical compound, Water
MTBE - Chemical compound, Methyl tert-butyl ether

### 3.1.2 Steam reforming

This technique consists of exposing hydrocarbons to steam at high temperatures, being this type of technology used mainly by the industry, with the majority of the hydrogen obtained by processing natural gas:

$$Methane \longrightarrow CH_4 + H_2O = CO + 3H_2 \tag{3.1}$$

$$Ethane \longrightarrow C_2H_6 + 2H_2O = 2CO + 5H_2 \tag{3.2}$$

The formation of Hydrogen from methane is feasible from 895.15 K at $1atm$, while the ethane is only 753.15 K at the same conditions. Efficiency of this process is influenced positively by the raise of the temperature, and negatively by the raise of the pressure (de Souza and Silveira, 2004).

Afterward the carbon monoxide is converted with steam to produce the additional hydrogen, thus resulting in the highest yield of the process.

$$CO + H_2O = CO_2 + H_2 \tag{3.3}$$

This method has some disadvantages, such as the use of fossil fuels, release of carbon dioxide and price per energy unit. The production of hydrogen for later consumption by this method is more expensive than if the primary fuel is simply used for combustion (Miguel et al., 2016; de Souza and Silveira, 2004).

### 3.1.3 Water electrolysis

Producing hydrogen through water electrolysis presents an energy solution that combines several environmentally favorable characteristics, such as being a clean and reproducible energy carrier, only emitting water in transport or stationary applications, and having a high energy capacity (Liu et al., 2010).

In order to obtain hydrogen using water electrolysis, it is necessary to use energy in the form of electricity to separate water atoms, using an electrolyser.

$$2H_2O + electricity = 2H_2 + O_2 \tag{3.4}$$

It is possible to observe the estimated production of hydrogen in Portugal, Figure 3.4, increasing emphasis on water electrolysis production.

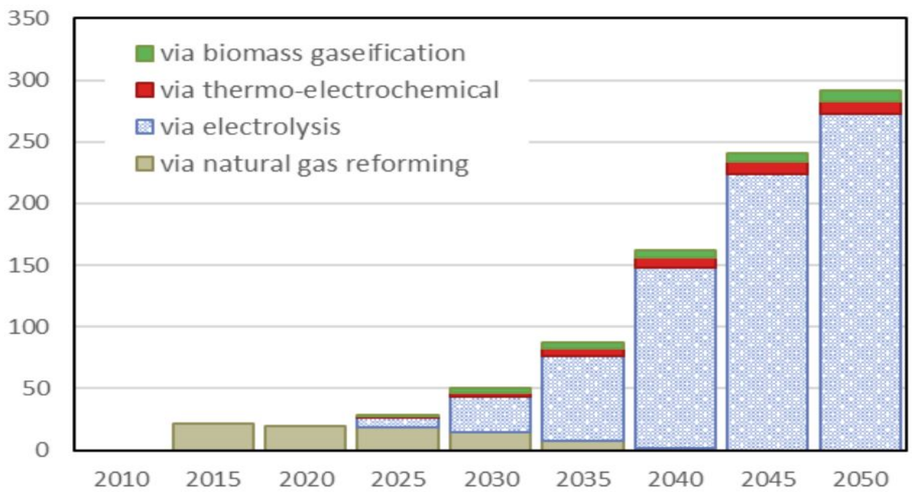


**Figure 3.4:** Estimated hydrogen production [Pj] (Aguiar et al., 2020, p.34)

## 3.2 Fuel Cells and Electrolyzers

Energy stored in hydrogen can be transformed back into electrical energy, hydrogen internal combustion engines and fuel cells are generally used. Total efficiency of fuel cells is typically between 30% and 70% depending on the technology, while internal combustion engines is usually less than 40% (Wang et al., 2019).

Fuel cells are emerging as an alternative to internal combustion engines. Fuel cell is a device that generates electricity by electrochemical reaction of hydrogen and oxygen and differs from batteries in the aspect that batteries store energy, while fuel cells can produce electricity continuously as long as fuel and air are supplied. Thus, the only emission of this cell is water, being considered a production of clean energy.

$$2H_2 + O_2 = 2H_2O + electricity \tag{3.5}$$

This process includes the supply of hydrogen as fuel and oxygen as a oxidizer, the electrons from Hydrogen are conducted through a circuit, producing electrical current and heat, then water is produced by combining oxygen, protons, and electrons, Figure 3.5 (Schmidt et al., 2017).

Fuel cells are categorized according to their electrolyte witch also determines their operating temperature, range of applications, price and efficiency. It is described those analyzed in Table 3.2 the main properties of Polymer electrolyte membrane fuel cell (PEMFC), Alkaline fuel cell (AFC), and Solid oxide fuel cell (SOFC), including the main differences (Schmidt et al., 2017).

In Figure 3.5 there is a scheme of the operating mode of these three different fuel cells, in spite of cells are categorized according to their electrolyte, that is not the only difference between them, differing also in the operation mode.

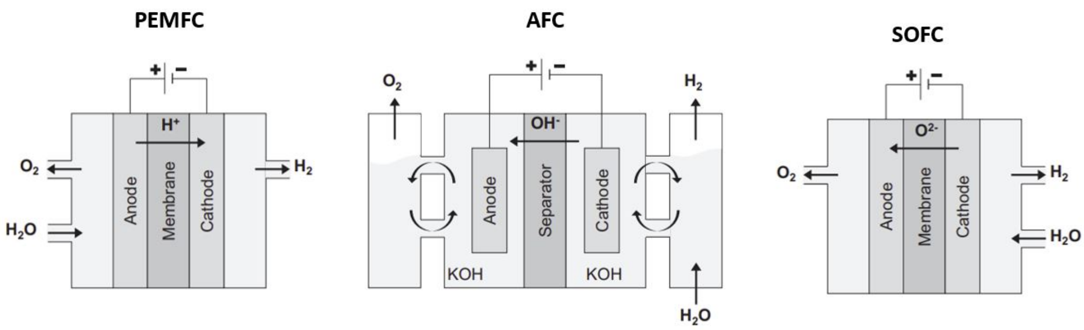


**Figure 3.5:** Functioning of different fuel cells (Schmidt et al., 2017, p.3047)

As we may see in Table 3.2 polymer electrolyte membrane fuel cells due to their lower operating temperature with fast response of system components and a lower cold start time without impacts on gas purity are the best suited to operate with intermittent power sources, supporting the dynamic operation. However, are still evolving, provided durability and capital costs are still far from the ideal goal, but are expected to improve with technology breakthrough and economics of scale (Schmidt et al., 2017).

Alkaline fuel cells and Solid oxide fuel cell can also be successfully engineered to operate with an intermittent power supply, although AFC characteristics seem interesting the search for this technology has stopped, being difficult to even quantify his expeditions in after 2018, however SOFC expeditions are growing favoured by their higher efficiency and improvements slowly reducing system costs (Schmidt et al., 2017).

**Table 3.2:** Main characteristics of PEMFC, AFC, SOFC (Schmidt et al., 2017, p. 30472; E4tech, 2021)

| | PEMFC | AFC | SOFC |
|---|---|---|---|
| Electrolyte | Polymer membrane [1] | 20 - 40 wt % KOH [2] | $O_5Y_2Zr$ [3] |
| Cathode | Pt, Pt - Pd[4] | Ni, Ni - MO alloys[5] | Ni/YSZ |
| Anode | $RUO_2$[6], $IrO_2$ | Ni, Ni - Co Alloys | LSM[7]/YSZ |
| Cell area ($m^2$) | < 0.3 | < 4 | < 0.01 |
| Operating temp. (ºC) | 50 - 80 | 60 - 80 | 650 - 1000 |
| Operating pressure (bar) | < 200 | < 30 | < 25 |
| Gas purity (%) | 99.99 | <99.5 | 99.9 |
| System response | Milliseconds | Seconds | Seconds |
| Cold Start Time (min.) | < 20 | < 60 | < 60 |
| Stack Lifetime (h) | 20,000 - 60,000 | 60,000 - 90,000 | < 10,000 |
| Development Maturity | Commercial | Mature | Demonstration |
| Capital Cost (€/$kW_{el}$) | 1860 - 2320 | 1000 - 1200 | >2000 |
| Expedition in 2019 | 948 MW | — | 107 MW |

1 e.g Nafion ($C_7HF_{13}O_5SC_2F_4$)
2 KOH - Potassium hydroxide
3 Yttria stabilised Zirconia
4 platinum (Pt) and palladium (Pd)
5 Nickel-Molybdenum alloys
6 Ruthenium oxide
7 LSM - Perovskite-type lanthanum strontium manganese

### 3.2.1 Electrolyzer and polymer electrolyte membrane fuel cell (PEMFC)

Among the options for fuel cells and electrolyzers, PEM main characteristics make them best suited for this study, his range of applications differ from motor vehicles to portable devices.

As we already discussed electrolyzers convert electrical energy into hydrogen and fuel cells hydrogen into electrical energy. Its main functioning is the same as we may see in Figure 3.6.

With the goal of becoming more durable, sustainable, and cheaper, the main parameters that determine these three aspects is the choice of materials used. To achieve the price competitiveness, it is necessary to analyze each component of the fuel cell to reduce costs that may be associated with very expensive (and rare) materials, as well as possible ways to increase the life span of each cell (Schmidt et al., 2017).

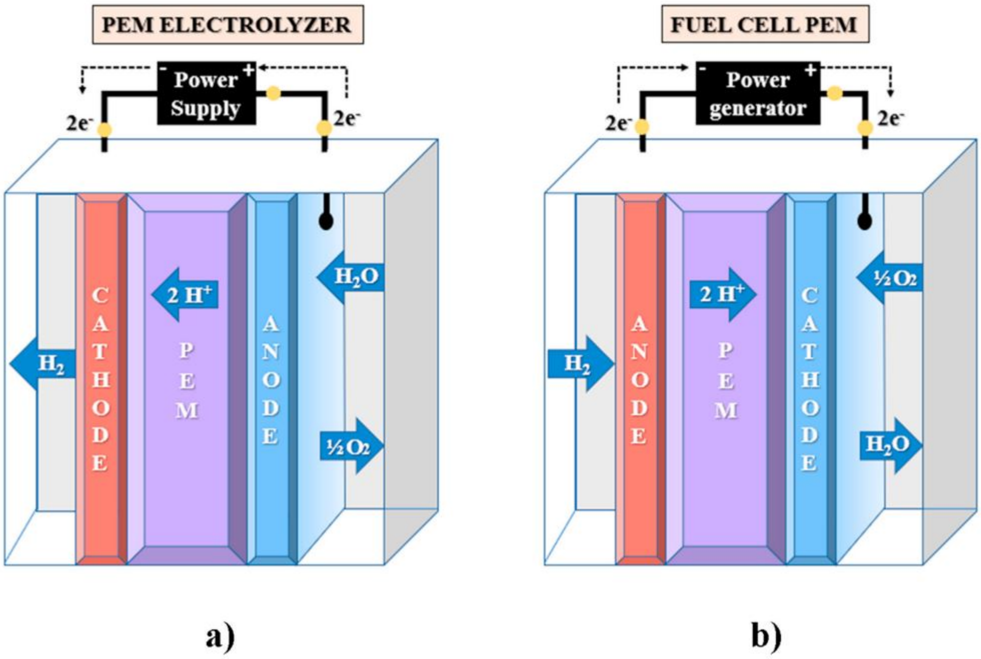


**Figure 3.6:** Illustrative diagram of a) PEM electrolyzer and b) PEMFC (Escobar-Yonoff et al., 2021, p.3)

---

### PEM components and their main functioning

PEM cells are composed of six major components with very distinct functions, as we may see in Figure 3.7, where a brief approach is made for the most relevant components of these cells, proton exchange membrane, catalyst layers, and gas diffusion layers.

Also known as PEM (Proton Exchange Membrane), is a membrane that conducts only positive ions and blocks electrons, therefore being found between the catalyst layers of the anode and cathode. The most used material for the membrane is perfluorosulfonic acid (APFS). The two most used types of APFS membranes are classified as long side chain and short side chain membranes, with the Nafion and Aquivium membranes being used respectively, Figure 3.7 (Y. Wang et al., 2020).

The materials that make up the catalyst layers are essential for determining the performance and durability of fuel cells. The layers of conventional catalysts include nanometer-sized platinum particles dispersed on a larger surface carbon support. This platinum catalyst is mixed with an ion-conducting polymer and placed between a membrane of gas diffusion layers. On the anode side, the platinum catalyst allows hydrogen molecules to divide into protons and electrons. On the cathode side, the platinum catalyst allows the reduction of oxygen by reacting with the protons generated by the anode, thus producing water (Figure 3.7). Dependence on platinum for the development of this technology not only increases the price but affects its sustainability. Platinum is found in the form of chunks, but it is very scarce in the earth's crust, being included in the group of precious metals (European Precious Metals Federation aisbl, 2021). In addition to this, it also occurs in nature mixed with nickel and copper ores, as well as in several ores combined with arsenic. It has characteristics such as a high melting point (2 043.15 K) and a great resistance to corrosion (Y. Wang et al., 2020).

Gas diffusion layers (GDL) stay outside the catalyst layers and facilitate the transport of reagents through this layer, as well as the removal of water from the product. Each GDL is usually composed of a sheet of carbon paper on which the carbon fibers are partially coated with polytetrafluoroethylene (PTFE). The gases diffuse rapidly through the pores that are kept open by the hydrophobic PTFE, which prevents the excessive accumulation of water. In many cases, the inner surface of the GDL is coated with a thin layer of high surface area carbon mixed with PFTE, called a microporous layer. This layer can help to adjust the balance between the water retention required to maintain the conductivity of the membrane and the release of the water necessary to keep the pores open so that hydrogen and oxygen can be diffused into the electrodes (Y. Wang et al., 2020).

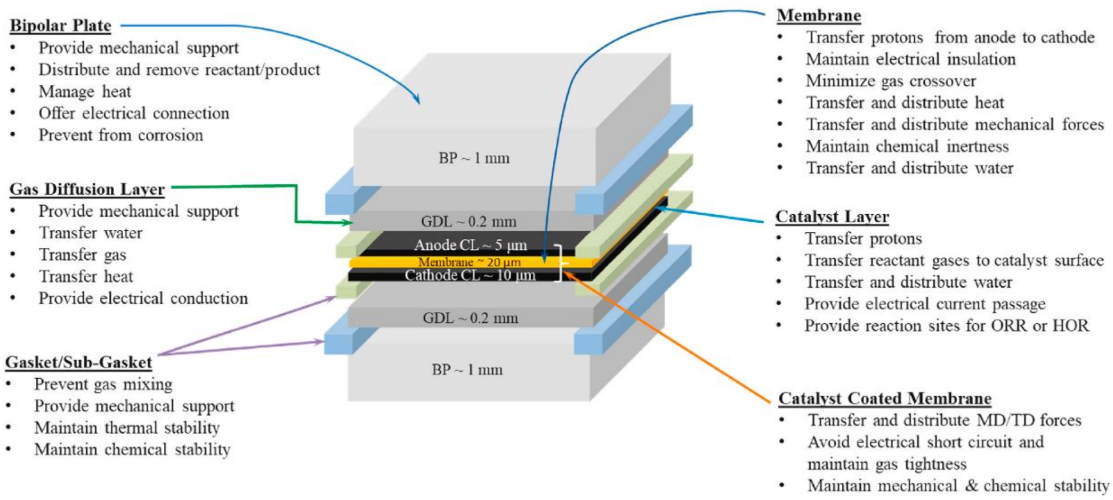


**Figure 3.7:** PEM components and their main functions (Yuan et al., 2021, p.4)

# Chapter 4

# Future of Hydrogen

Accordingly to Hydrogen Council (2020) hydrogen technologies may deliver competitive low-carbon solutions across a wide range of applications before 2030 and may even be competitive to conventional fuels in some fields. For that to become achievable there is a need to scale up production, transport, and investment in research and development of hydrogen technologies to become competitive, but there must be an increasing demand. There are a lot of potential users of hydrogen only within the European Union, as we may see in Figure 4.1.

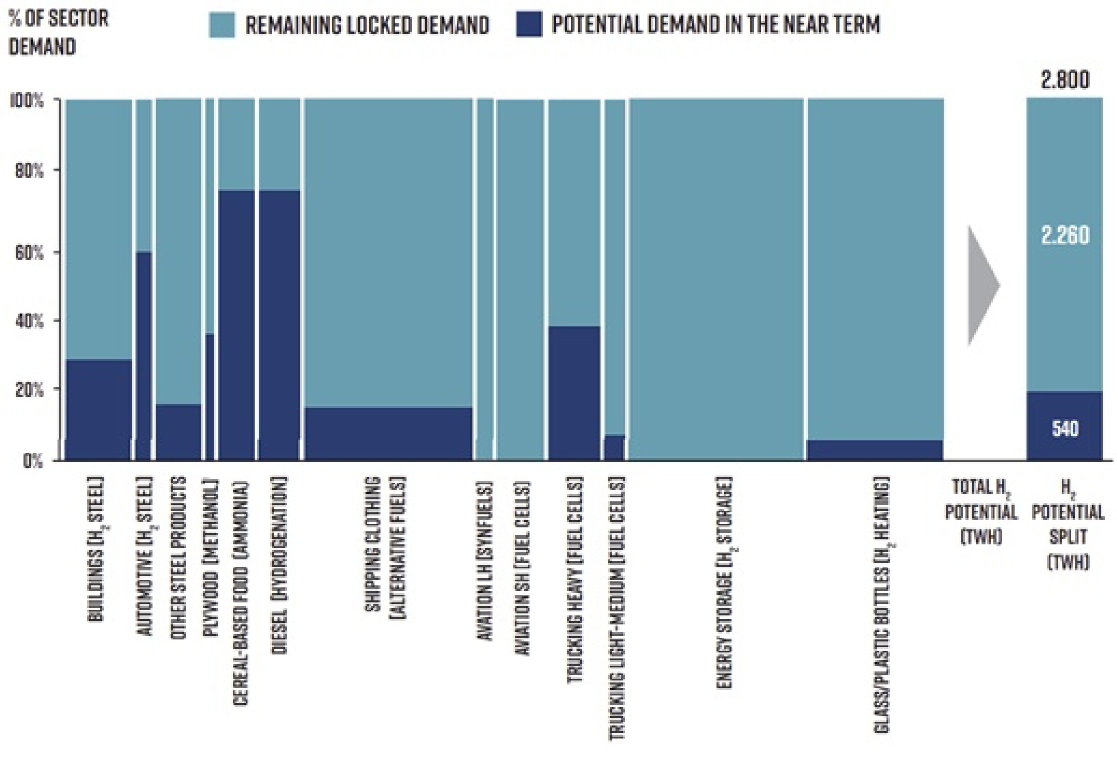


**Figure 4.1:** Potential demand for green hydrogen from end-use sectors in European Union (Enkvist et al., 2020, p.7)

## 4.1 Hydrogen Steel

Steel production represents an important sector to develop sustainable alternatives, traditional iron ore reduction utilizes a chemical reaction between iron oxide and carbon monoxide sourced from heating coke fuel in a blast furnace. Coke is a hard, porous, nearly pure carbon product made by heating coal in the absence of air (in coke ovens). Coke acts as both a fuel and reducing agent in the blast furnace, forming carbon monoxide when burned, and reacts with the iron oxide to produce molten pig iron and carbon dioxide. It is estimated that nowadays represents between 7% to 9% global CO2 emissions. The conventional method emitted 1,83 Tons CO2/ton crude steel cast in 2019 (World Steel Association, 2020).

Several companies of steel production are pursuing projects to make their process fully fossil free with the use of green hydrogen to replace coke for iron ore reduction with multi million investments. In figure 4.2 we can see the comparison of a traditional blast furnace method and a method used for tree Swedish companies (steel manufacturer SSAB, mining company LKAB, and energy company Vattenfall) in a alliance known as HYBRIT (Hydrogen Breakthrough Ironmaking Technology) to produce green steel.

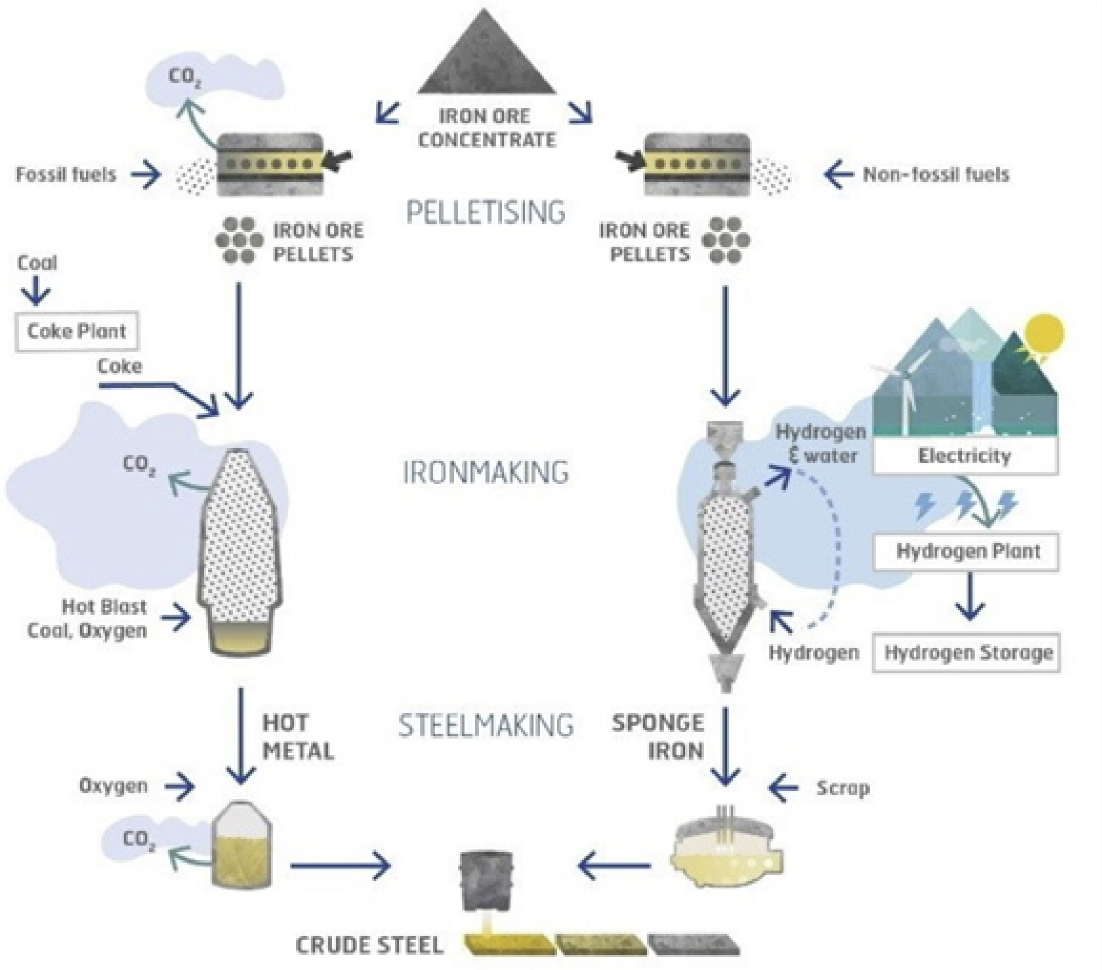


**Figure 4.2:** Traditional blast furnace and HYBRIT Methods of steel production (Homann, 2019, accessed on 22 october, 2021 from https://www.fchea.org)

The cost competitiveness of this method in comparison with a conventional blast furnace will depend greatly on the cost of hydrogen production and the cost of carbon emissions (€ ton/CO2).

Accordingly to Hydrogen Council (2020) and taking into account a cost of 41 €/ton $CO_2$ emitted and a cost of coke as 164 €/ton, hydrogen direct reduction iron can break even with conventional methods at about 1,3 €/kg hydrogen. Although the prices of carbon emissions are rising all over the world and it could be a competitive technology even with higher prices of hydrogen.

## 4.2 Methanol

Methanol ($CH_3OH$) is a volatile, flammable liquid poisonous for human consumption. Methanol has a fusion point of 155.15 K, and chemical properties which allow it to lower the freezing point water-based liquid and increase its boiling point. These attributes lead methanol to be used as an antifreeze in windshield washer fluid to keep the cleaning fluid from freezing. It is also injected in natural gas pipelines, where it lowers the freezing point of water during oil and gas transport.

Methanol is also used to create inks, resins, adhesives, and in the manufacture of pharmaceutical ingredients and products such as cholesterol, streptomycin, vitamins and hormones. Although, close to half of world methanol is used in energy-related applications, methanol can be used on its own as a vehicle fuel or blended directly into gasoline to produce efficient fuel with lower emissions than conventional gasoline. Methanol can be also used as cooking fuel and in thermal applications (e.g: industrial boilers and furnaces) (Methanex Corporation, 2021).

To produce Methanol, there are two key components, hydrogen and $CO_2$, today the hydrogen needed to produce methanol is obtained mostly from natural gas reforming or coal gasification, if we use green hydrogen there must be added an external source of $CO_2$. This external source may come from industrial plants, direct air capture of carbon, and biomass-based processes. These alternatives are currently costly, however, their viability will vary according to local conditions and regulations.

To achieve cost competitiveness of methanol production from green hydrogen, assuming no cost for carbon emissions, the cost of green hydrogen has to be between 0.65 €/kg Hydrogen to 1.25 €/kg Hydrogen, depending on the cost of natural gas. Even with cost per carbon emissions, these values may not differ much due to capture of $CO_2$ in the process of creating Methanol (Hydrogen Council, 2020).

## 4.3 Ammonia

Ammonia ($NH_3$) is a colorless gas, a building-block chemical and a key component in the manufacture of many daily use products (e.g; cleaning products, rubber, paper, plastics, explosives), can act as a cooling gas, be used in manufacture pesticides and many more. Although about 90% of ammonia produced worldwide is used fertilizers (Chemical Safety, 2021).

In comparison with the production of methanol, who is less sensitive to carbon costs, in regions with higher natural gas prices, such as Europe, to achieve cost competitiveness from grey hydrogen considering 44€/ton $CO_2$ hydrogen cost has to be between 1.20 €/kg Hydrogen to 1.35€/kg Hydrogen, suggesting that ammonia is initially more attractive for low-carbon hydrogen.

## 4.4 Hydrogen in transport

Transportation is one of the most important sectors to decarbonize. On today´s date we can see a world investment in electric vehicles, however in near-medium term fuel cell vehicles can become economic atractive and having short refueling times made possible by Hydrogen.

For example Toyota (2021) set the world Guinness record with Toyota Mirai for the longest distance by a hydrogen fuel cell electric vehicle without refueling with 1360 kilometers on a single, five-minute complete fill of 5.65 kg hydrogen.

Fuel cell passenger vehicles may be more competitive than battery electric vehicles in segments with heavier use and longer-range requirements (eg., taxi fleets, SUVs, large passenger cars) due to smaller battery and consequently lower cost of the vehicle, and less time to refuel (Hydrogen Council, 2020). On 12 of June 2021 more than 40 000 fuel cell, electric vehicles were on the road globally and more than 8000 were sold in the first half of 2021 (IEA, 2021a).

Fuel cell trucks may be the lowest cost way to decarbonize all the segments, electric fuel cell vehicles are less attractive due to the cost of batteries required, weight penalty, as well as long recharging times (Hydrogen Council, 2020). In the first half of 2021, only 5 fuel cell truck models were available, but 11 are expected in 2023 with joint ventures of Daimler Truck AG and Volvo Group and IVECO, OMV, and Shell collaborating on large-scale hydrogen truck deployment in Europe (IEA, 2021a).

Fuel cell buses may be the low-cost solution to long-range use, not being cheaper than battery-electric buses in urban use (Hydrogen Council, 2020).

In figure 4.3 is possible to analyze the evolution stock of fuel cell electric vehicles (FCEVs) in the most relevant regions and in the rest of the world (ROW) between 2017 and June 2021 as well as different segments.

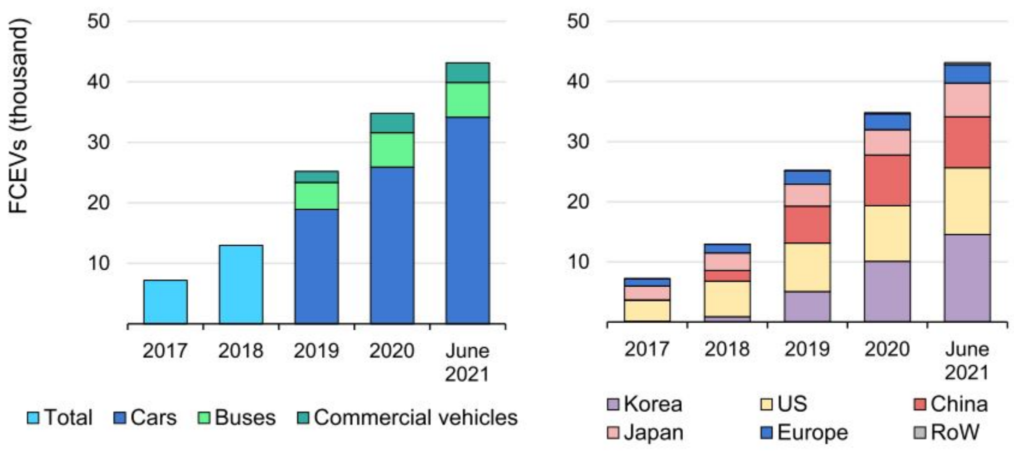


**Figure 4.3:** Fuel cell electric vehicle stock by segment and region (IEA, 2021a, p. 69)

Interest in hydrogen in aviation up to 1600 km and shipping has also been growing, although none are yet commercially available, however, the commercial operation of fuel cell ferries is expected to begin in 2021 in the United States and Norway (IEA, 2021a).

## 4.5 Energy Storage

One of the most important aspects of renewable energy is its intermittency and unpredictability. The energy consumption is not always the same but follows a pattern, there are peak hours at the end of the day and lower demand hours at dawn. This lack of consistency most of the time does not comes into accord between supply and demand from renewable energy sources. In Figure 4.4 we may see a representative day of the electrical energy consumption by the hour in Portugal (MW) on the day 10/01/2021. Having that into account it is essential to store energy to better manage the electric distribution network.

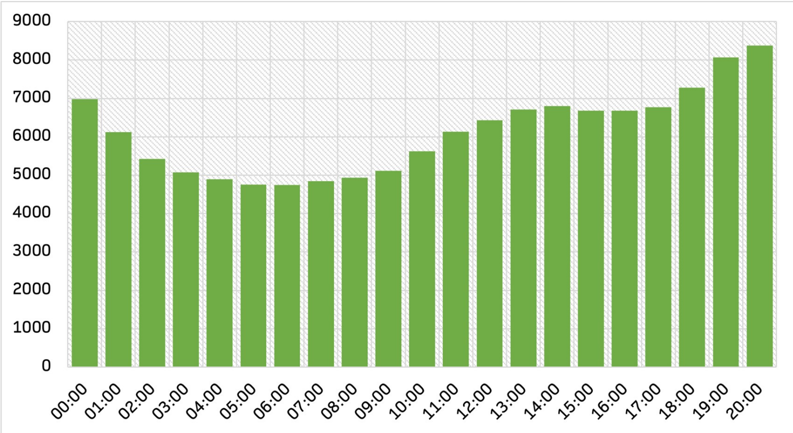


**Figure 4.4:** Electric energy consumption by the hour in Portugal 10/01/2021 [MW] (REN, 2021, accessed on 10 January, 2021 from https://www.ren.pt)

Energy storage systems have the advantage of managing energy supply in times of high demand and low production and vice versa. There are several electrical energy storage systems. In many cases, they involve the use of materials with a great environmental impact, which may not correspond to highly efficient systems. Hydrogen may be a way to store electricity producing and storing hydrogen through an electrolyzer and using hydrogen to produce electricity when needed using fuel cells.

Hydrogen storage require specific conditions. For liquid hydrogen, it is necessary for it to be kept at 20,38 K, which requires abundant energy expenditure to reach and maintain this temperature, which makes this process less efficient, however, in small spaces, it is possible to store a large amount of energy. The hazards associated with liquefied hydrogen are less than that of compressed hydrogen since in the event of leakage it will release into the atmosphere more slowly due to the low temperature.

### 4.5.1 Compressed hydrogen

Hydrogen in the form of compressed gas is currently used in the form of cylinders or tanks under pressure. These cylinders can take various sizes, serving for all types of applications, from industry to small equipment. These cylinders can be made of steel, aluminum, plastic, or carbon, the advantages of this method are simplicity and the absence of energy losses over time (Miguel et al., 2016).

Compressed hydrogen is the most used method for storing hydrogen, although it is not the cheapest option. Compressing gas increases its density, more precisely 42.9 g/L at 70 MPA and

298K, under these conditions 1 kg of hydrogen can be stored in 23L. Which requires special tanks to prevent metal embrittlement by the hydrogen molecules. Four types of high-pressure tanks are currently available. Type I and II are metal tanks, characteristic of their high weight, Type III tanks are made of composite materials with an inner lining of aluminum which makes them lighter than Type I and II but heavier than Type IV, which are the most widely used because is made of carbon fiber with a polymer inner lining preventing leakages which reduces the weight of the storage system and improves its performance. The cost of type IV tanks is approximately 14.75 USD/kWh considering the manufacturing of 500,000 tanks per year (Sdanghi et al., 2020).

### 4.5.2 Liquid hydrogen

The density of liquid hydrogen at atmospheric pressure is 70.8g/L, 40% higher than compressed hydrogen at 70 MPa, being possible to store 1 kg of hydrogen in 13.6 L. To store liquid hydrogen tanks with efficient thermal isolation are needed to minimize losses. They are made of an inner and outer lining empty layer with aluminum sheets alternated with glass fiber and losses are estimated to be 1% to 5% per day. To produce liquid hydrogen it is expected to be necessary 10 kWh/kg hydrogen, in addition to the high costs of industrial plants for liquefaction (Sdanghi et al., 2020).

### 4.5.3 Solid storage in Metal hydrides

The storage by absorption of metal hydrides involves the formation of chemical bonds between the hydrogen molecules and the spaces of the metal atoms. This is an expensive process and requires heating up to 573 K to cause hydrogen desorption, temperatures between 333 K and 393 K are demanded to consider this technology for commercialization (Sdanghi et al., 2020). It has the advantage of storage security and being a process fully reversible. The chemical equation for the reaction is as follows (Miguel et al., 2016):

$$M + H_2 = MH_2 \tag{4.1}$$

## 4.6 Injection of hydrogen into gas grid

Injection on the gas grid of hydrogen and other renewable gases may reduce the environmental impact of natural gas and importation costs in the meantime removing barriers to the entrance of hydrogen into the economy and avoiding the gas infrastructure to became obsolete in the future reusing it (DGEG - Direcção Geral de Energia e Geologia, 2020).

In Portugal, Galp Gás Natural Distribuição (GGND) is testing in real environment injection of green hydrogen in the distribution network up to 20%. The project will run for two years in Seixal. The final customers will be seventy residences, ten commercial and one industrial. The project aims to gather knowledge and information to develop infrastructure, legislation, and regulation.

*"Given its pioneering character, this project marks a position of leadership, innovation, and commitment to the decarbonization of gas distribution activities"* (Nuno Nacimento, 2020, p.6).

With current regulation and legislation it is not possible to inject hydrogen into the portuguese natural gas grid, however, natural gas transported in the national network must respect the maximum and minimum value of the Wobbe index, respectively, 57,66 $MJ/m^3$ maximum and 48,17 $MJ/m^3$ minimum. Based on these parameters, it is possible to determine the maximum calorific power of 13,51 $kWh/m^3$ and a minimum of 10,05 $kWh/m^3$ of natural gas (Entidade Reguladora dos Serviços Energéticos, 2021).

Considering a medium PCS of natural gas of 11,9 $KWh/m^3$ and 3 $kWh/m^3$ for hydrogen, the calorific power that circulates in the network will be reduced. It is possible to observe in Figure 4.5 that until 22% blend of hydrogen in the natural gas network calorific power of the gas balance between the boundaries of current regulamentation and legislation (DGEG - Direcção Geral de Energia e Geologia, 2020).

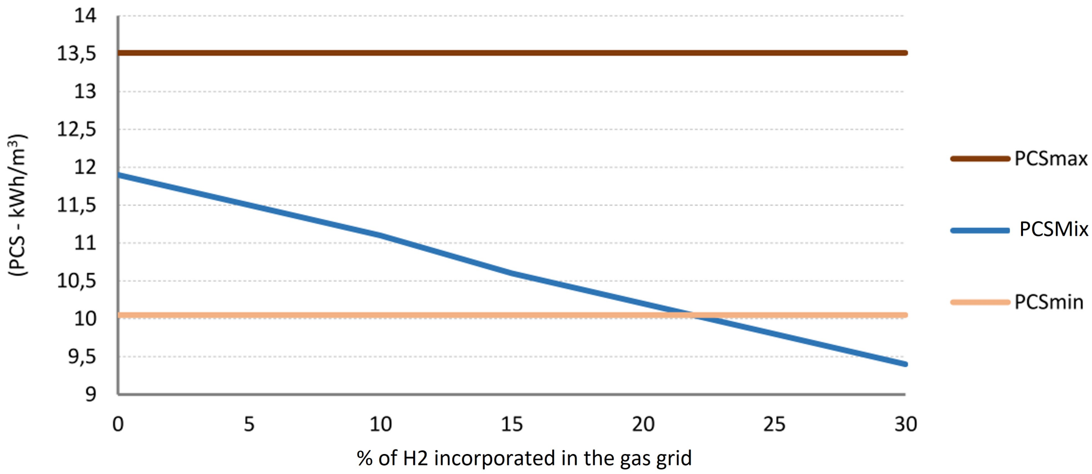


**Figure 4.5:** Representation of the evolution on PCS of Natural Gas with different percentages of incorporation with hydrogen (DGEG - Direcção Geral de Energia e Geologia, 2020, p.28)

In Table 4.1 we can see the annual impact of different percentages of grid injection in $Nm^3$, cost and CO2 emissions reduced, being the base case the year 2020.

| % H2 incorporated in the gas grid | 0 % | 5 % | 10% | 15% | 20% |
|---|---|---|---|---|---|
| Natural Gas consumption [$x10^6Nm^3$][1] | 2753,1 | 2615,4 | 2477,79 | 2340,1 | 2202,5 |
| Imports of natural gas [M€] [2] | 1020,30 | 967,71 | 916,78 | 865,85 | 814,92 |
| CO2 emissions reduced [ton/year] [3] | – | 304 | 607,9 | 911,92 | 1214,4 |

**Table 4.1:** Natural Gás in Portugal (Observatório Energia et al., 2021)

1 -Observatório Energia et al., (2021)
2 -Observatório Energia et al., (2021)
3 - Galp, (2021)

## 4.7 Barriers to overcome

Hydrogen may be an economical and environmental solution, however, there are still many barriers to overcome. In Figure 4.6, we can see a simulation by the Hydrogen Council (2020) of the difficulty of barriers to overcome in different end-use sectors in business as usual time and accelerated time with government financial support, regulation, and legislation in the European Union.

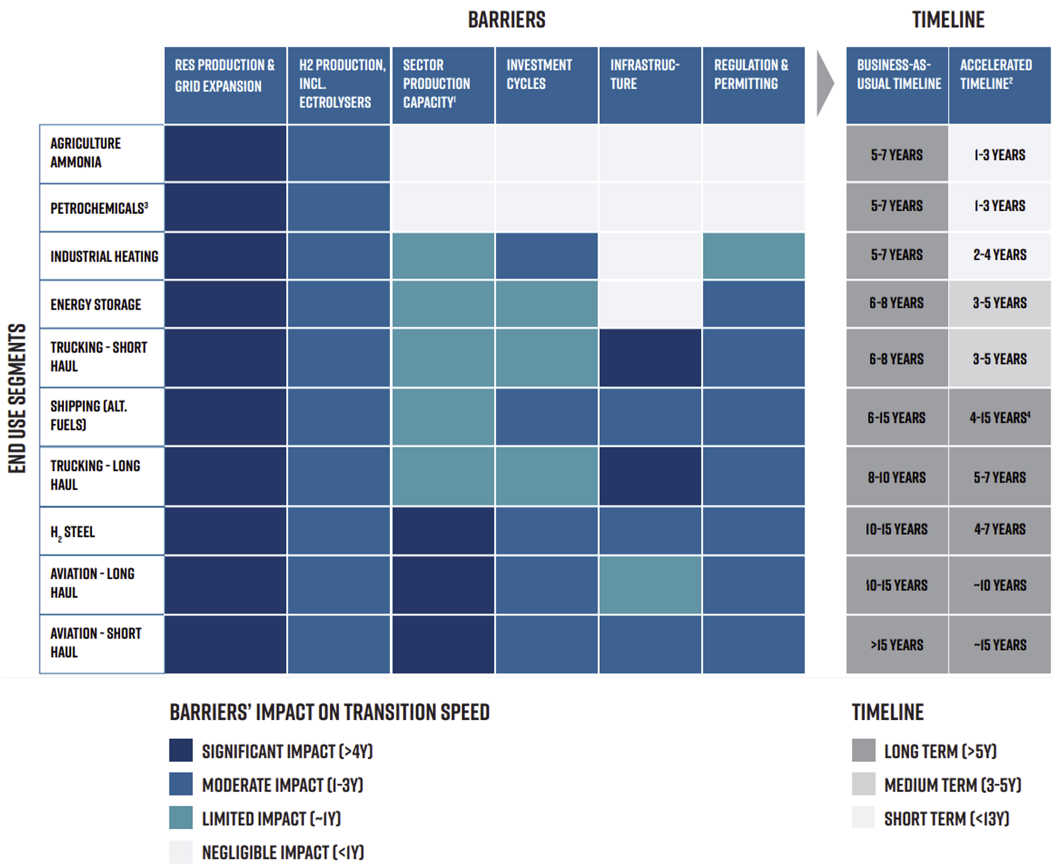


**Figure 4.6:** Barriers to overcome (Enkvist et al., 2020, p.9)

However, to reach this level of competitiveness there is a need for investment, policy alignment and demand creation. There is a need to invest approximately 58 billion euros worldwide for hydrogen to become competitive, in production, carbon capture and storage (CCS), transport (refuelling tanks and distribution network) and heating for buildings and industry (Hydrogen Council, 2020).

IEA (2021) made a simulation scenario where all national net-zero emissions commitments governments have announced until 2019 are realized on time. This simulation shows the potential contributions of different technologies to reach these pledges, including hydrogen. Hydrogen's relevance to reach these commitments may be reflected in its share in total final energy consumption, 2020 hydrogen and hydrogen-based fuels sum less than 0.1%, but it is expected that they meet 2% in 2030 and 10% in 2050 of total final energy consumption. To reach climate commitments low carbon hydrogen production must be increased. It is estimated that 90 Mt of hydrogen has been used in 2020, and about 80% was produced from fossil fuels which resulted in 900 Mt of CO2 emitted (IEA, 2021a). In this simulation, it is expected that production reach out 200 Mt of Hydrogen in 2030 with nearly 850 GW installed electrolysis capacity, and 500 Mt of hydrogen, with 3600 GW installed electrolysis capacity by 2050 (IEA, 2021a).

It is possible to analyze in Figure 4.7 the investments in research, design, and development [RD&D] on hydrogen and fuel cells in million euros of Japan, the United Kingdom, United States, and European Union on the timeline of 10 years until 2020, being Japan the biggest investor in this technology followed by the United States. Despite the growing investments, are growing there is a long way to reach the 58 billion euros mentioned by Hydrogen Council (2020) to hydrogen become competitive.

Besides investment, other government incentives are required to develop the hydrogen market, clarity of policy direction to support hydrogen´s adoption will accelerate the process as it approaches the threshold of competitiveness. Those incentives are justified by the medium long term of economic and environmental benefits that a hydrogen economy would bring. These incentives could be regulatory measures aimed to speeding up the production and use of hydrogen, or carbon emissions penalties which would favor cleaner sources of energy such as hydrogen (United Nations Environment Programme [UNEP], 2006).

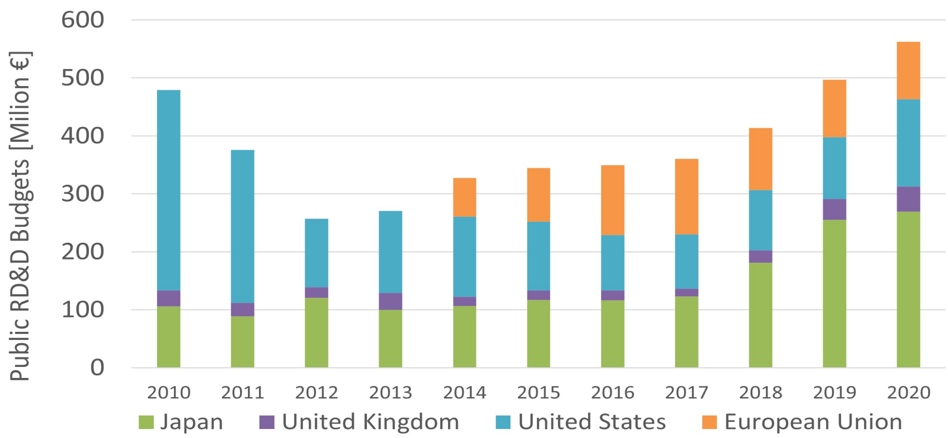


**Figure 4.7:** RD&D Hydrogen and fuel cells budget (IEA, 2021b)

Seven key aspects are necessary to scale up hydrogen (IEA, 2019):

1. Setting long-term energy strategies at a national and regional level. Companies should also have long-term goals in key sectors like chemicals, iron and steel, long-distance transport, power generation, and transport.

   To date, 18 governments, whose economies account for 70 percent of global gross domestic product, have developed detailed strategies for deploying hydrogen energy solutions (Hydrogen Council, 2020).

2. Through regulation, governments can develop international legislation to limit market specificities demand for clean hydrogen. Costs of green hydrogen remain higher as we may see in Figure 4.9. Policies and regulations that create sustainable markets for green hydrogen are needed to underpin investments by suppliers, distributors, and users.

3. Creation of long-term agreements to remove market risk from early installation projects, eg., tax breaks or subsidies, long-term agreements from installation projects to provide guarantees and help the private sector to invest, recurring demand.

4. Investments in RD&D are crucial to improve the performance of electrolyzers, fuel cells, and hydrogen-based fuels and consequently lower the costs. This investment may include public funds attracting capital for innovation.

5. Eliminate unnecessary regulatory barriers and permit implementing standards with clear requirements across sectors and countries, especially in equipment, pressure levels, and safety. Certifying emissions from different sources is also necessary taking into account the hydrogen complex supply chain.

6. International cooperation to track progress, sharing of good practices, and cross-border infrastructures where governments can choose to invest in the deployment of new infrastructure and re-use, where relevant, of existing networks (e.g., natural gas networks).

7. Explore existing industrial ports and turn them into low carbon hydrogen production centers (eg., Sines green hydrogen project) as well as establish commercial agreements and shipping routes to begin international hydrogen trade.

Low-cost hydrogen is one of the most important aspects in cost reductions for every hydrogen application and therefore a crucial point to create additional demand. Scaling applications and technologies create best cost improvement. Accordingly, to an analysis managed by the Hydrogen Council (2020) *"scaling fuel cell production from 10,000 to 200,000 units can reduce unit costs by as much as 45 per cent, irrespective of any major technological breakthroughs, and can impact multiple end-use cases. Scaling up to 70 GW of electrolysis will lead to electrolysers costs of less than USD 400 per kW"* (Hydrogen Council, 2020, p.vii).

Hydrogen solutions are already ramping up and considerable investments and policies are being made globally presenting not only solutions for decarbonization, but also numerous opportunities. Largest hydrogen programs are in European Union, China, and North America as we may see in Figure 4.8 accounting for nearly 85% of the production capacity of electrolysers for hydrogen production (IEA, 2020b).

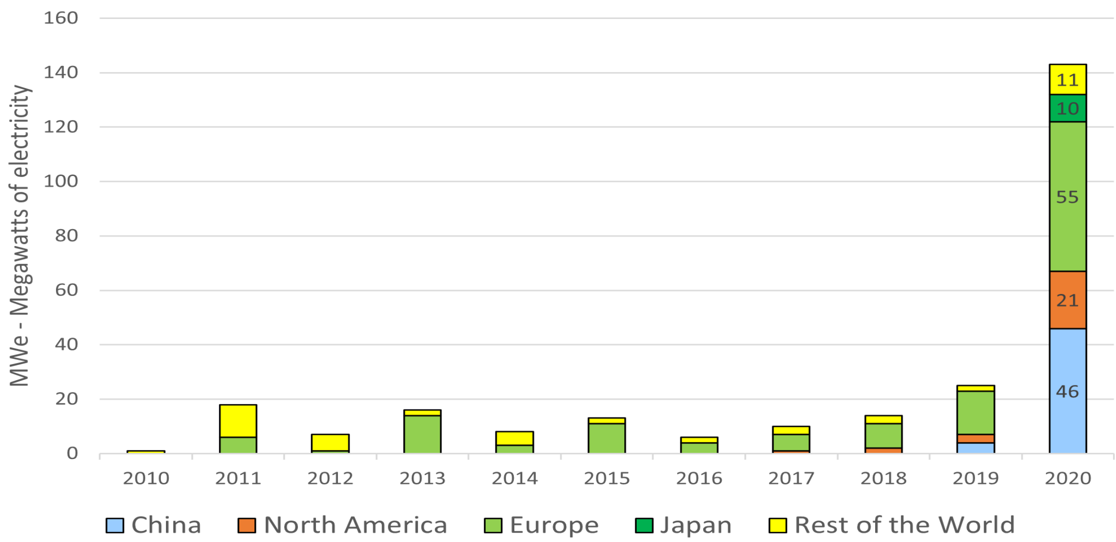


**Figure 4.8:** Capacity of electrolysers for hydrogen production by regions 2010-2020*(Announced) (IEA, 2020b, p.194)

Ramping up production also comes as a key cost driver of green hydrogen, for instance, the prices of green hydrogen became 60% cheaper as renewable electricity prices dropped. The cost of solar and wind power, the largest cost driver of green hydrogen production, has seen an 80% reduction over the past decade. This downward trajectory is expected to continue, and at the same time electrolysis capacity has also started to accelerate, which will contribute to a decrease in the cost of electrolyzers (Hydrogen Council, 2020).

However the production of green hydrogen still cannot compete in price against the other types of hydrogen production. It is possible to observe in Figure 4.9 that the price range of producing Hydrogen is still more expensive than Natural Gas and coal with carbon capture and storage (CCS) (IEA, 2020a).

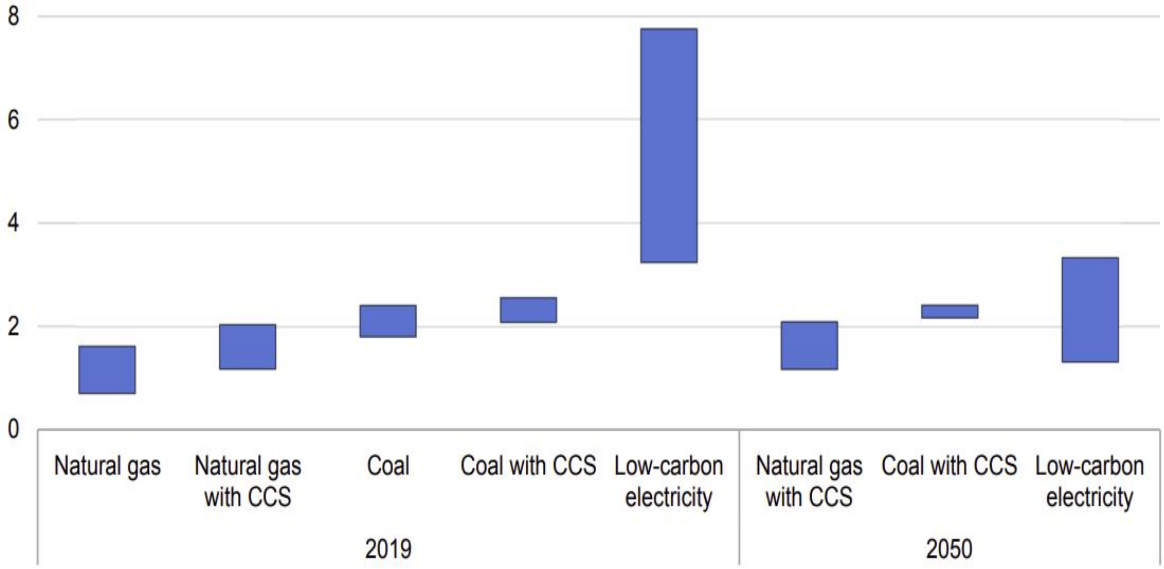


**Figure 4.9:** Global average levelised cost of hydrogen production by energy source and technology [USD/kg] (IEA, 2020a, p.74)

As mentioned before the key factor in developing a hydrogen economy is the cost of producing hydrogen and one of its most determinant aspect is the cost of (renewable) energy to produce green hydrogen.

Range prices of renewable energy sources are expected to decrease (Brändle et al., 2021). In Figure 4.10 is presented a study that shows cost ranges and mean levelized costs of hydrogen for the best 20 renewable energy sources available globally under baseline and optimistic assumptions of three different technologies, photovoltaic, onshore wind and offshore wind.

The cost range of equipment influence directly the Levelized cost of hydrogen presented in Figure 4.10. Offshore wind may vary significantly which makes it fluctuate the most, while photovoltaic is relatively narrow due to similar solar irradiation in the best areas.

Costs for all energy technologies can vary significantly by country and region and since an important share of the cost of producing hydrogen rely on prices of energy, there are places that undoubtedly the production of hydrogen will be cheaper as we can see in Figure 4.11.

Values presented in Figure 4.11 are the collected data of 24 countries that provide the data for the report, assuming the carbon emission costs of 25 €/Tonne of $CO_2$.

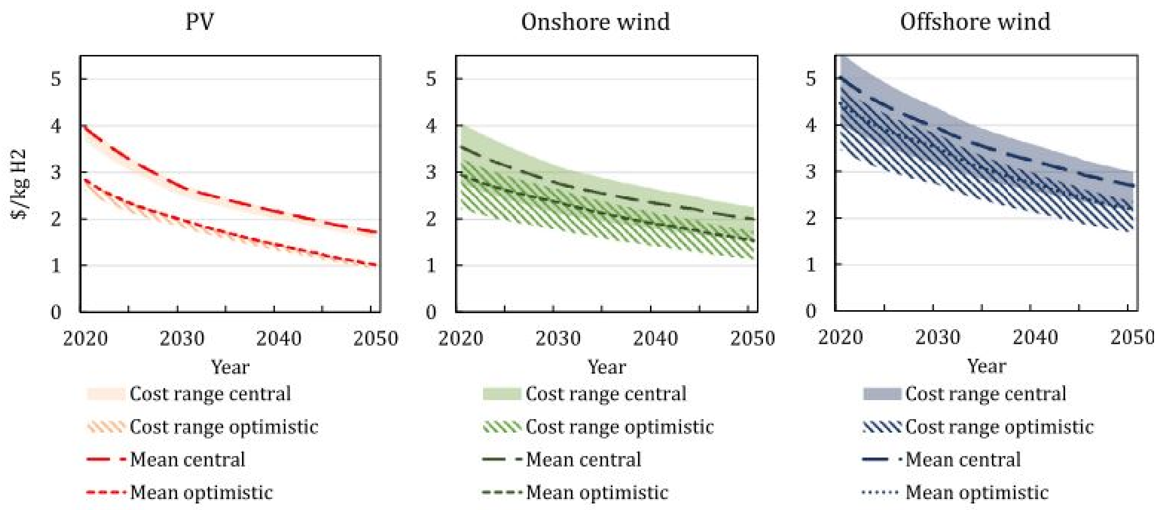


**Figure 4.10:** LCOH range and mean values of the 20 lowest-cost resources available for each renewable energy source-electrolyser combination, (Brändle et al., 2021, p.8)

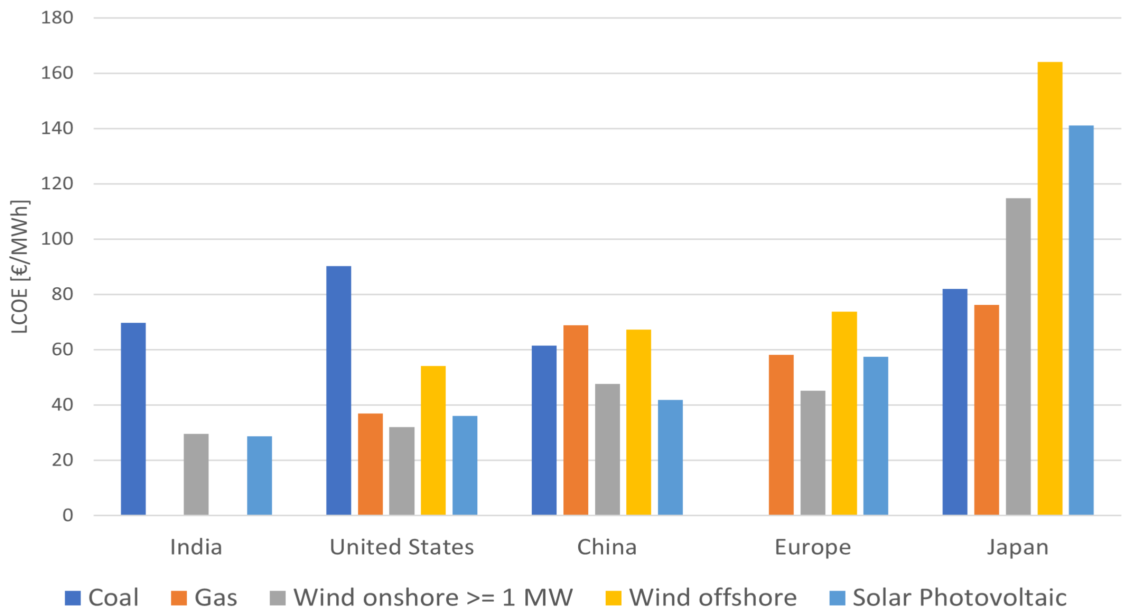


**Figure 4.11:** Levelized cost of energy, (adapted from IEA and NEA, 2020, p.47)

---

Countries like Japan and some parts of Europe have limited renewable resources and ambitious decarbonization policies that require hydrogen. If production costs due to high energy costs are too high to expect demand, they may become importers of hydrogen, (Figure 4.12).

Europe is an (early) leader on innovation. Analyzing the hydrogen startup landscape reveals that 50-60% of global startups are based in Europe. This startup ecosystem is crucial for ensuring Europe remains an innovation leader in hydrogen. Research, development, scale production, selling and maintaining all this equipment is a major industrial opportunity for

Europe (Enkvist et al., 2020).

Advances in technology will give to the European Union an advantage, however limited space available for renewable energy will be a constrain in comparison to other countries. Europe's long-term wind and solar electric energy potential is estimated to be approximately 110 Exajoule per year, compared with long term potential of 292 Exajoule and 275 Exajoule per year in Australia and the Middle East (e.g., Saudi Arabia), respectively, Figure 4.12. Both Australia and the Middle East are also looking to become green hydrogen export superpowers and have already announced multi-billion, multi-GW projects (Neom in Saudi Arabia, and the Asian Renewable Energy Hub in Australia). However, southern Europe (especially Spain and Portugal) comes close in solar radiation and may be competitive (Enkvist et al., 2020).

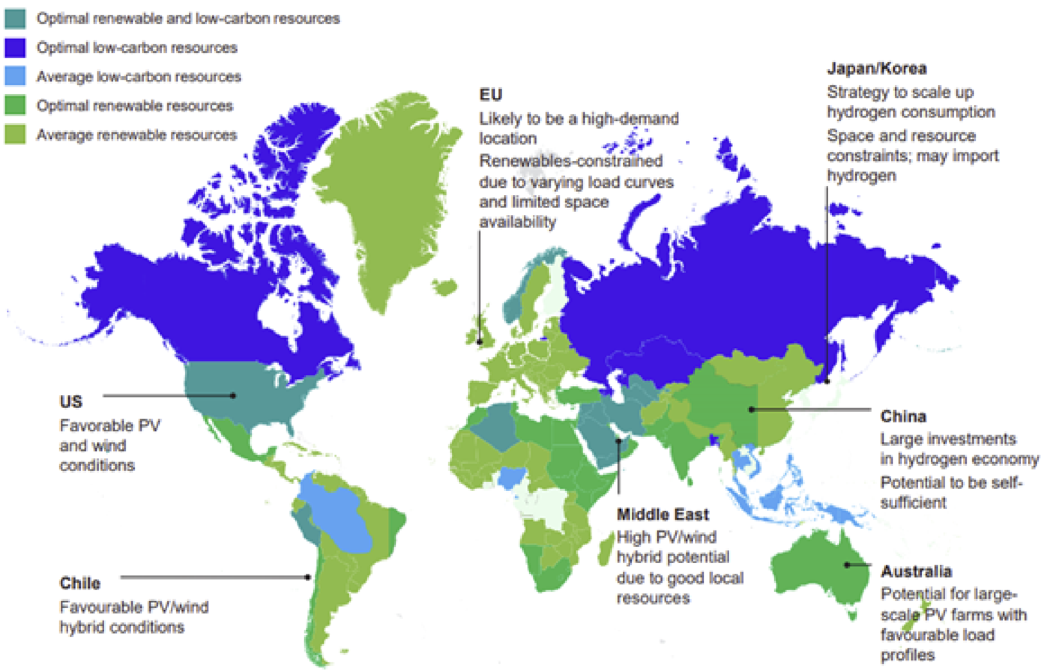


**Figure 4.12:** Sources of low carbon hydrogen per region (Hydrogen Council, 2020, p.22)

## 4.8 Cost indicators to transport hydrogen

Hydrogen production can be carried out on a large scale in specialized factories, or in small quantities where it is used.

Small-scale production has the advantage of reducing yield losses and reducing costs associated with storage and transportation, however, to produce the same amount of hydrogen compared to large-scale production, more equipment is needed, which considerably increases costs equipment and maintenance rising the capex electrolysers (€/kW) (Miguel et al., 2016). However, the price of energy will dictate a large share of the costs of Kg/Hydrogen, since the costs may differ considerably, countries with expected high demand of hydrogen and lack of suitable conditions to produce renewable energy, like Japan or Germany, may consider international trade in hydrogen. A global supply chain will likely consist of long-distance pipelines as well as shipping routes. The transport of hydrogen in a gaseous format can be made in ducts similar to the distribution of natural gas, even existing natural gas pipes can transport hydrogen with some updates. However due to the lower density of hydrogen it is necessary about 3 times more hydrogen to be able to obtain the same amount of energy. The lower density of hydrogen and the smaller size of its molecules can cause other problems, such as leakage through small openings or gaps in the welds. Another problem that can arise is the reaction of hydrogen with the metal walls, and to avoid this problem it is possible the mixture of hydrogen with other gases, the use of cement in the structure of the tubes, plastic, and the addition of reaction inhibitors in the tube itself (Hydrogen Council, 2020).

For distributions over shipping routes, there are several technology options, hydrogen is normally transported in liquid form ($LH_2$), ammonia ($NH_3$) and liquid organic energetic carriers (LOCCs).

$LH_2$ shipping delivers hydrogen in his pure state to the destiny location. However today shipping costs are high (e.g., for the route from Saudi Arabia to Japan about 13 € per kg in 2020), beneficiating of scale economies, they could fall to 1.40 € per kg in 2030 (Hydrogen Council, 2020).

$LH_2$ shipping are transport using refrigerated tanks and with good insulation in order to preserve its temperature, evaporating at the place of use. In order to decrease the shipping costs to 1.40 €/kg the dimension of the refrigeration tanks world require a scale up from 160 tons to 10,000 tons and liquefaction capacity from 10 to 50 tons per day to as much as 500 tons per day (Miguel et al., 2016).

Using ammonia as an energy carrier provides the possibility to use existing infrastructure for global distribution, and the processes of conversion from hydrogen to ammonia is an already established technology. However, this transportation is only preferred where the end-user is ammonia, due to its toxicity, and reconversion costs if the end-user is hydrogen, a process in an early stage of development. In addition, this reconversion requires the use of energy that dictates the overall cost of reconversion. If there is no access to low-cost energy, this may be the reason for importing hydrogen in the first place. It is estimated by the Hydrogen Council, (2020) that this reconversion could add 1 €/kg hydrogen to 2 €/kg hydrogen to production, conversion, and transportation costs.

LOHC shipping is based on a range of different chemical compounds such as *toluene* ($C_7H_8$) or *methylcyclohexane* ($C_7H_14$) and has the advantages and disadvantages like ammonia, has the benefit of leveraging existing shipping infrastructure and the challenge in reconversion that also requires significant energy input at the destination. This technology requires additional research and development to become economically viable.

Shipping technologies will depend on the end-use, required amount, and technology development. As mention above, if hydrogen is the end-use, $LH_2$ appears to be the closest to maturity across the value chain and the lowest-cost alternative by 2030, however, there is a need to scale up to achieve competitive prices.

Beyond long distance distribution there is a need to think in local distribution, most of the time it is not possible to produce hydrogen in the same place as the end user and the local distribution is a major cost driver, often responsible for more than 50% of total hydrogen cost, in accordance to Hydrogen Council, (2020).

Similar to shipping, transport local hydrogen can be made by trucking compressed or liquefied hydrogen or the use of pipelines. The distribution choice may differ considering distance from production to end user and demand of hydrogen. For shorter distances, compressed gaseous hydrogen ($GH_2$) offers the lowest cost. Liquid trucking is most economical for distances above 300 to 400 km because it is possible to storage more energy in less space and compensate energy spent in liquefaction. Pipelines are preferred for higher distances, although costs underlying construction of new distribution pipeline network requires significant investments that may compensate in a long-term depending on the volume of hydrogen transported. Blending Hydrogen with other gases to use existing natural gas pipelines is an option demanding to make adaptations on the existing grid to transport hydrogen as mentioned before when possible (Hydrogen Council, 2020).

# Chapter 5

# Portuguese context for hydrogen

In 2016, Portugal established the objective of becoming carbon neutral by 2050 and developed the roadmap for carbon neutrality, presented in 2018 anticipating the draft of the National Energy and Climate Plan 2021-2030 stated in 2019, a year marked by the intensification of the decarbonization commitment in Europe and Portugal (República Portuguesa, 2019).

The biggest improvement in that commitment is the inclusion of renewable gases with particular emphasis on hydrogen, integrating a central element in decarbonization strategies (República Portuguesa, 2019).

Portugal already demonstrated ambition to lead the energy transition and fight climate change, so defined ambitious targets for 2030, as we may see in Figure 5.1.

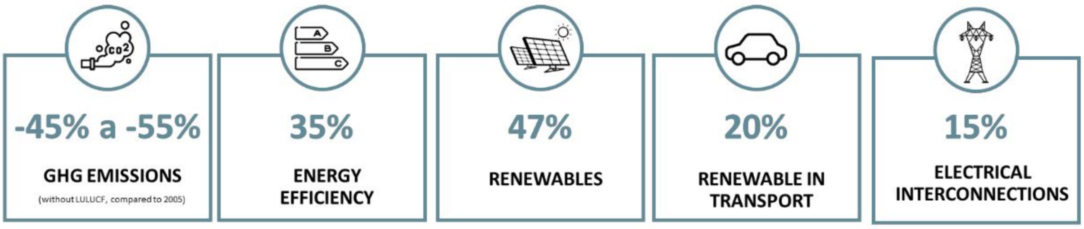


**Figure 5.1:** Portugal's energy and climate targets for the 2030 horizon (DGEG - Direcção Geral de Energia e Geologia, 2020, p.10)

Hydrogen plays a role in decarbonization in various sectors of the economy. To accelerate the utilization of this renewable gas and to promote an intense substitution of fossil fuels, Portugal must invest in the production and incorporation of green hydrogen infrastructures. With the objective of decarbonizing industry and promoting a new industrial sector with the potential to export, the government is promoting an industrial policy around hydrogen that mobilizes public and private investment in production, storage, transport, and utilization of this renewable gas (DGEG - Direcção Geral de Energia e Geologia, 2020).

The main objectives of hydrogen in the Portuguese national strategy are, complementing electrification strategy, storing electricity in overproduction periods and reinforce the security of supply, reduce greenhouse gas emissions replacing fossil fuels in sectors of the economy like refining, metallurgical, chemical, cement, mining, ceramics and glass industries, and promoting employment and economic growth through the development of new industries, and many other, as we may see in Figure 5.2.

This strategy contemplates an element of stability and incentive for the energy sector as a

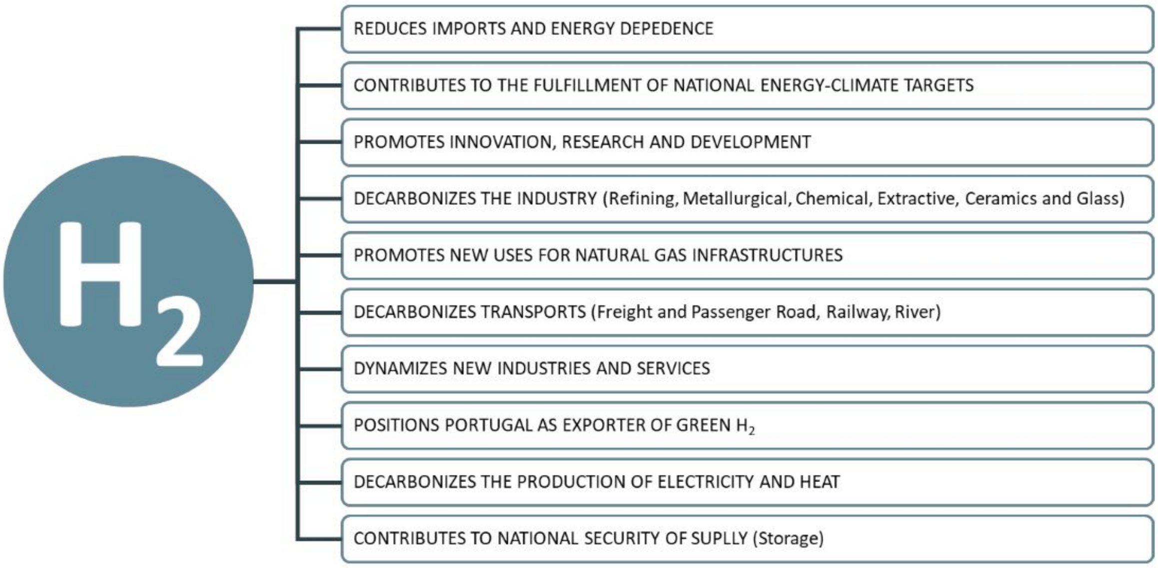


**Figure 5.2:** Hydrogen as a fundamental vector for decarbonizing Portuguese national economy towards carbon neutrality (DGEG - Direcção Geral de Energia e Geologia, 2020, p.11)

---

strategic opportunity for the country and implies the creation of necessary conditions to make this viable. Begins from financial resources and support mechanisms to regulation, guarantees of origin, security, and standards in transport and storage, regulation and injection in natural gas network.

The Portuguese government already has a set of actions ongoing (DGEG - Direcção Geral de Energia e Geologia, 2020):

1. Regulate the production of renewable gases;
2. Regulate the injection of renewable gases into the national natural gas network;
3. Design a support mechanism for hydrogen production;
4. Implement a system of guarantees of origin for renewable gases;
5. Ensure that the financial resources available in national and European funds allow support for the production of renewable gases;
6. Propose the setting of binding targets until 2030 for the incorporation of hydrogen in the natural gas network, in transport and in industry.

And goals for the horizon 2030 (DGEG - Direcção Geral de Energia e Geologia, 2020):

1. 5 % In final energy consumption
2. 5 % In consumption for road transport
3. 15 % Injection in natural gas Grid
4. 50-100 Filling Stations

5. 2 GW installed capacity in electrolyzers
6. 7000 M€ Investments in projects of hydrogen production
7. 300-600 M€ Reduction in importations of natural gas
8. 900 M€ Investment and production support

## 5.1 Energy dependence

Portugal does not produce coal, oil, or natural gas, which means that the supply of these fossil products is made exclusively by imports from other countries negatively penalizing the country's energy bill.

Energy imports have been decaying in the last years, where energy efficiency measures and renewable domestic electricity production are the main causes. However, with renewables, it is necessary to use natural gas to provide safety of power supply. One objective of investing in hydrogen is his ability to replace natural gas and consequently continue to diminish the energy dependency, we may see in Figure 5.3 evolution of Portugal external energy dependence.

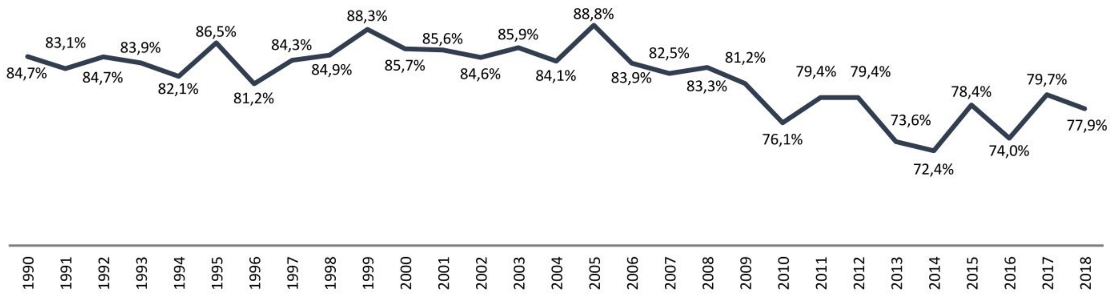


**Figure 5.3:** Evolution of Portugal's External Energy Dependence (DGEG - Direcção Geral de Energia e Geologia, 2020, p.23)

## 5.2 Availability of resources

Geographically, Portugal has the potential to develop a hydrogen economy. As mentioned before, the most relevant aspect for developing an hydrogen economy is the availability of renewable energy sources. In this matter, compared to other countries in Europe, Portugal has an advantage.

In Europe, Portugal and Spain are the countries that have more solar irradiation, namely in the South, between 1500 $kWh/m^2$ and 1900 $kWh/m^2$, as it is possible to observe in Figure 5.4.

Along with solar, Portugal has also wind potential, in different areas. Another crucial point is an extensive coast with the perspective of offshore wind energy becoming competitive in the next few years. We may see in Figure 5.5 the mean wind velocity at 50 meters height.

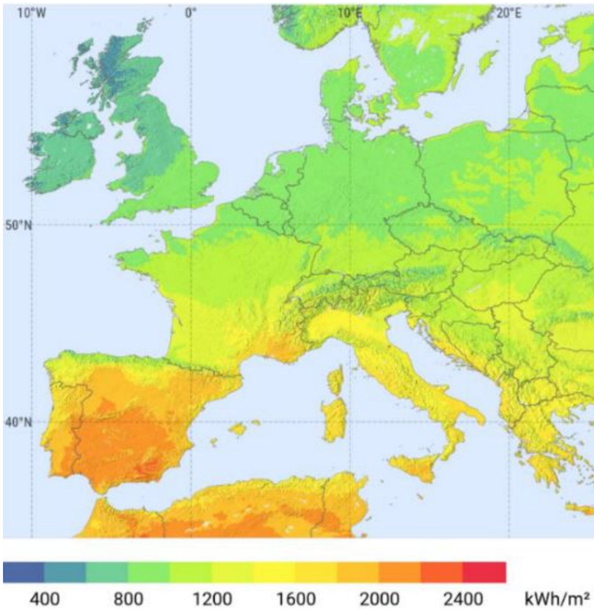


**Figure 5.4:** Normal direct irradiation in Europe (Solargris, 2017, accessed on 1 september, 2021 from https://solargis.com/)

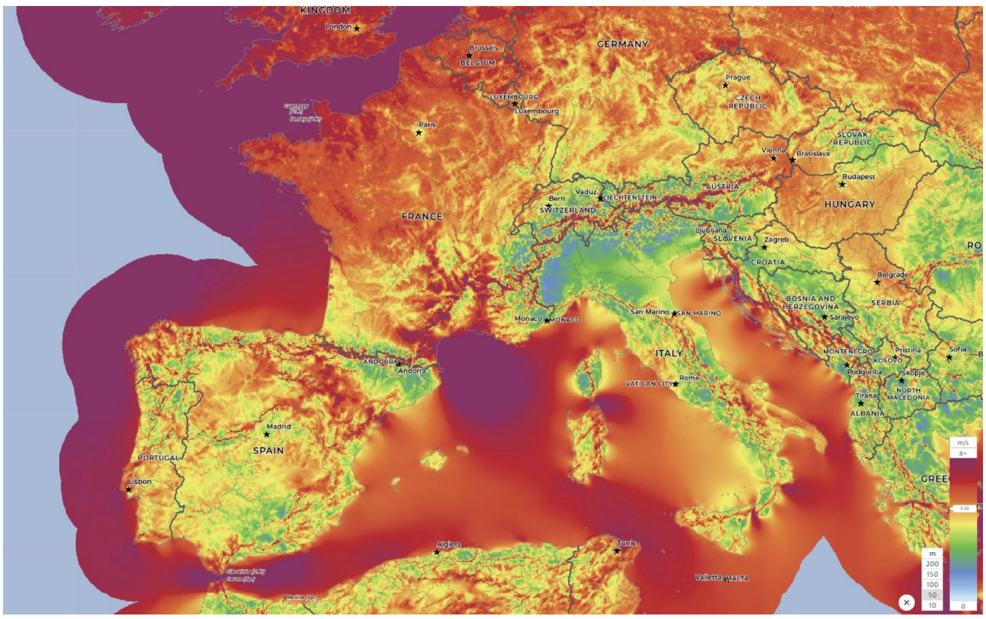


**Figure 5.5:** Mean wind speed Europe (EnergyData, 2021, accessed on 1 october, 2021 from https://globalwindatlas.info/)

## 5.3 Financial support mechanism for the production of green hydrogen

A very important aspect of the success of a project is the source of financing. For this type of project, Portugal and the European Union have several funding funds available for submission (Adene, 2021). A list of financial support mechanism in Portugal follows:

1. FUNDO DE APOIO À INOVAÇÃO (FAI)

   Fund directed to support innovation and technological development in areas of renewable energy and energy efficiency.

2. FUNDO DE INOVAÇÃO, TECNOLOGIA E ECONOMIA CIRCULAR (FITEC)

   FITEC is a fund directed to support scientific and technological knowledge and its transformation into innovation and more efficient use of resources, particularly through material and energy efficiency.

3. FUNDO AMBIENTAL

   Fund to support environmental policies to pursue sustainable development, achieve national and international goals, and commitments relatively to climate change, water resources, waste, and the conservation of nature and biodiversity.

The European strategy is also followed by the existence of funding opportunities for hydrogen projects (Adene, 2021):

1. EUROPEAN STRATEGIC ENERGY TECHNOLOGY PLAN (SET PLAN)

   An initiative that coordinates research and innovation activities in the EU Member States and other participating countries, helps to structure European and national research programs. Promotes search in current and upcoming funding opportunities for your research, as well as research partners, jobs, and fellowships in low-carbon technologies.

2. HORIZON 2020

   Horizon 2020 is a financial instrument that aims to ensure Europe's global competitiveness, remove barriers and make it easier for the public and private sectors to work together on innovation.

3. EUROPEAN REGIONAL DEVELOPMENT FUND (ERDF)

   It aims to strengthen economic and social cohesion in the European Union, correcting imbalances between regions. It concentrates investments in priority areas, including a low carbon economy.

4. EUROPEAN FUND FOR STRATEGIC INVESTMENTS (EFSI)

   Fund to address market gaps and mobilize private investment. Aid to strategic investments in key areas such as infrastructure, research, innovation, education, renewable energy, and energy efficiency, as well as risk finance for small and medium-sized businesses.

5. NER 300

   Funding program to innovation in low-carbon energy demonstration projects as carbon capture and storage technologies and renewable energy on a commercial scale within the European Union.

6. CONNECTING EUROPE FACILITY (CEF)

   Support for European networks and infrastructure in the transport, telecommunications, and energy sectors.

7. DEVELOPMENT COOPERATION

   It provides funding in the form of grants to support projects and organizations furthering their development goals.

8. INNOVFIN ENERGY DEMO PROJECTS

   Fund to finance commercial-scale demonstration projects in the areas of energy system transformation.

9. ELENA

   Elena provides grants for technical assistance focused on the implementation of energy efficiency, renewable energy, and urban transport projects and programs.

In the future, hydrogen produced may exceed the internal consumption necessity, and may compose an opportunity for Portugal to become a country exporter of energy seizing the advantage of its geographical potential to produce green hydrogen at competitive prices, ally to the need of northern Europe for large volumes of production, Portugal may have the opportunity to invert the role of energy importer and to become a reference producer, as it may be seen in Figure 5.6, where hydrogen strategy in Portugal is presented (DGEG - Direcção Geral de Energia e Geologia, 2020).

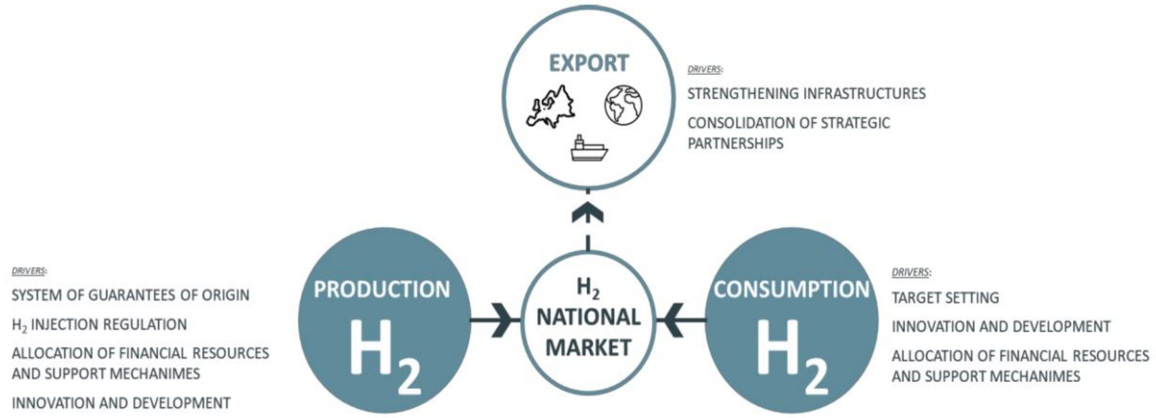


**Figure 5.6:** Hydrogen strategy in Portugal (DGEG - Direcção Geral de Energia e Geologia, 2020, p.12)

# Chapter 6

# Methodology and sensitivity analysis

## 6.1 Key components of the system: the choice

To determine if it is economically viable to produce and inject green hydrogen in the Portuguese natural gas grid, a selection of the key necessary components has been made.

To produce green hydrogen, the energy used needs to be entirely green. This analysis has explored the combination of sun and wind energy to produce hydrogen and oxygen not considering compression and storage. In each analysis will be included different percentages of energy by sun and wind. The base year is the year 2020, to improve the sensitivity analysis four distinct places in Portugal were chosen taking into account solar irradiation, wind velocity, and geographical location.

In Figure 6.1 we may see the system composition considered.

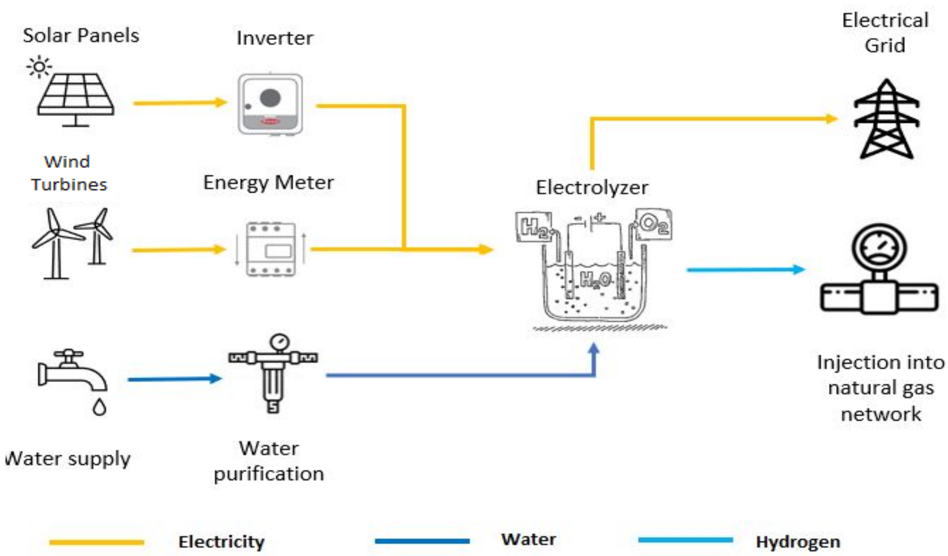


**Figure 6.1:** System composition

### 6.1.1 Solar energy

Electromagnetic radiation emitted by the sun is the fundamental source of energy on earth, known as solar irradiation. To quantify the solar irradiation on the land surface unit of measure $W/m^2$ is used. Solar irradiation depends on the distance between the sun and earth what differ throughout the year. Solar irradiation varies between $1.325W/m^2$ and $1.412W/m^2$, and his medium value is known as solar constant $1.367W/m^2$. Stepping into the atmosphere, solar irradiation is reduced through reflection, absorption by gases and particles, and only reaches the earth´s surface at noon, in good weather approximately $1.000W/m^2$ (GREENPRO, 2004).

Through PVSYST, 2021 it has been collected hourly data of global solar irradiation in different locations of a model year with $\beta = 20^{\text{o}}$ and Azimuth $0^{\text{o}}$, diffuse radiation was despised (Figure 6.2).

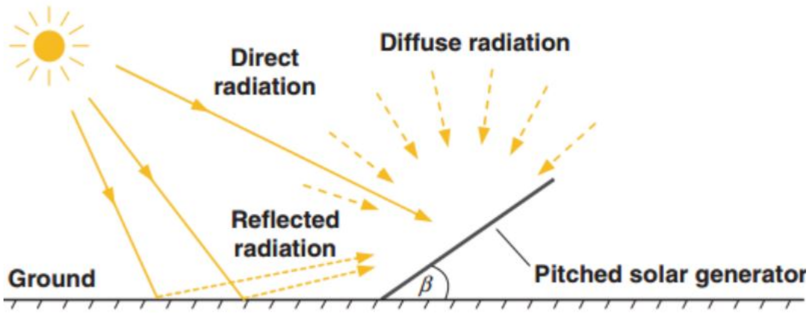


**Figure 6.2:** Solar Irradiaton (Mertens, 2018, p.41)

#### Photovoltaic panels

To transform the solar irradiation in energy a photovoltaic panel is necessary, for that, Eurenergroup, (2021) has been chosen with MEPV 320 monocrystalline silicon solar cells due to his cost efficiency, we may see in Figure 6.3 its technical features.

| Solar Panel | MEPV 320 |
|---|---|
| Nominal Power | $320W$ |
| Area of module | 1,62 $m^2$ |
| Module efficiency | 19,75 % |
| Price per unit | 155,12 € |
| Product warranty | 15 years |
| Performance warranty | 25 years |

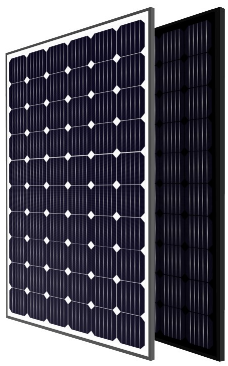

**Figure 6.3:** Photovoltaic Panel (Eurenergroup, 2021; FF Solar, 2021)

### Inverter

Connected to a photovoltaic module an inverter is necessary to convert the electricity generated from constant current to alternating current and adjust the electrical signal to appropriate network frequencies and voltages. The choice of the inverter is established by efficiency, price, and maximum input power, and the number of inverters is oversized by 10%. Inverter Sunny highpower peak3 has been chosen, we may see in Figure 6.4 its features.

| Inverter | Sunny highpower peak3 |
|---|---|
| Max input power | 11500 $W$ |
| Maximum efficiency | 99,1 % |
| Price per unit | 10.729 € |

**Figure 6.4:** Solar Inverter (SMA, 2020; FF Solar, 2021)

## 6.1.2 Wind energy

The kinetic energy created by moving air is used to generate electricity by a wind turbine. Wind causes the turbine's blades to revolve and turn the turbine connected to them changing kinetical energy to rotational energy by moving a shaft attached to a generator and this way producing electricity through electromagnetism (IRENA, 2021).

### Wind turbines

There are many types of turbines. This study is conducted between horizontal axis turbine, and vertical axis turbine. In Figure 6.5 and Figure 6.6 we can see the power curve of the two different turbines, Aeolia Windtech D2CF 200, and AtlasX TESUP.

Horizontal Axis turbines are larger, expensive, and may produce large amounts of energy with high wind velocities.

Vertical axis turbines are smaller turbines that produce less energy, however they produce electricity at lower wind speeds and their cost-efficiency may compensate depending on the final use.

For our study has been consider hourly wind velocities at 50 meters height in different locations of Portugal. Analyzing the power curve of both turbines it is possible to determine that AtlasX Tesup is better for lower wind speed and Aeolia with higher velocities, consider that average wind speed at 50 meters height in Portugal is 4.8 m/s (NASA, 2021). The viability study will consist on the use of AtlasX TSEUP.

AtlasX TESUP comes integrated with a charge controller, a battery, and an inverter, not being necessary additional equipment. It also demands less maintenance and unitary cost of this turbine is 1020 € (TESUP, 2021).

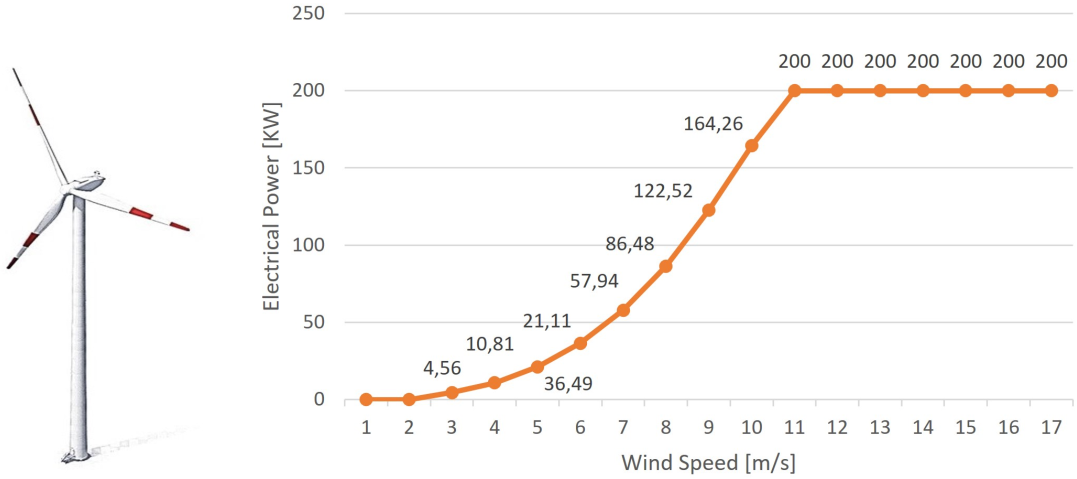


**Figure 6.5:** Aeolia Windtech D2CF 200 Power Curve (Wind Turbine Models, 2018, accessed on 14 october, 2021 from https://en.wind-turbine-models.com/turbines/1829-aeolia-windtech-d2cf-200))

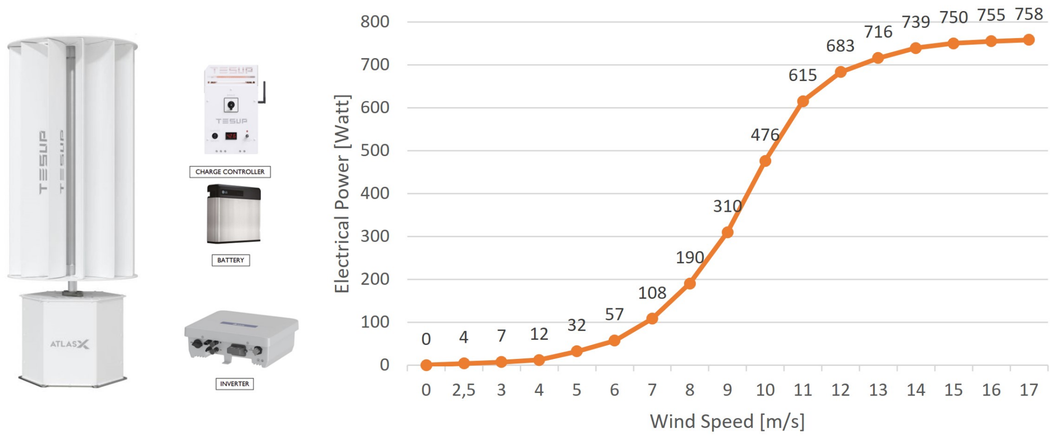


**Figure 6.6:** AtlasX Wind turbine Power curve (TESUP, 2021, p.12)

### 6.1.3 Electrolyzer

For the electrolyzer, PEM XZD-200/H-0.8 of nearly 1 MW has been chosen, with the specifications mentioned in Table 6.1:

**Table 6.1:** ZXD-200/H-0.8 specifications (ZXDH2, 2021)

| Electrolyzer | ZXD-200/H-0.8 |
|---|---|
| Hydrogen Production ($Nm^3/h$) | 200 |
| Oxygen Production ($Nm^3/h$) | 100 |
| Working Pressure (MPA) | 0.8 |
| Working Temperature (ºC) | 5-80 |
| Hydrogen Purity (V/V) % | $\geq$ 99.9 |
| Oxygen Purity (V/V) % | $\geq$ 99.2 |
| Working Current (A) | 5.300 |
| Working Voltage (V) | 180 |
| Weight (t) | 3.4 |
| Dimensions L x W x H (mm) | 2195x720x1500 |
| Price(€) | 1.051.280 |
| Life expetancy (years) | 10 |

#### Water Purifier

To use a PEM electrolyzer, a water purification system is required to redraw ions of the water, otherwise, the catalysts and membranes can be damaged during the process. His electrical resistance has to be $> 1 MegOhm/cm$ (Kinesis, 2021).

**Figure 6.7:** RO system water treatment, (Jiangmen Longning Water Purification Technology Co, 2021)

Choice of water purifier consists of its productivity, 500L/h to supply the electrolyzer without the need of water storage, easy operation, and maintenance, price, and versatility.

This system can also be used in wastewater after its treatment to produce hydrogen and oxygen, we may see the installation in Figure 6.7. The use of treated wastewater to produce hydrogen may provide an economically and environmentally sustainable alternative for this resource. Currently, in Portugal, exist 4.370 treatment facilities responsible for 602 million m3 of wastewater in 2018, and only 1.2% of that is available to reuse (DGEG - Direcção Geral de Energia e Geologia, 2020).

Price of this equipment is 1.471,15 €, (Jiangmen Longning Water Purification Technology Co, 2021).

## 6.2 Location choice

The choice of location of the project was based on different weather conditions to analyze the differences in productivity between places. The analysis will consist of 4 different zones identified in Figure 6.9.

1. Faro, is the region identified as having better solar irradiation zone in Portugal continental.
2. Leiria, due to the good wind potential.
3. Aveiro, as the reference location where the study is conducted.
4. Porto, as a reference for the north of the country.

Water cost, water supply fees, and land cost vary accordingly to location, this is shown in Figure 6.9.

To define the area needed for the correct functioning of solar park, shading between panels has been taking into account, through equation 5.1, we may see a schematic representation in Figure 6.8 (Dias, 2017).

Shading between panels reduces the production of energy and may cause anomalies on the panel affecting its life expectancy, shaded cells act as resistors opposing the passage of current and will heat the equipment affecting its components and efficiency (Dias, 2017).

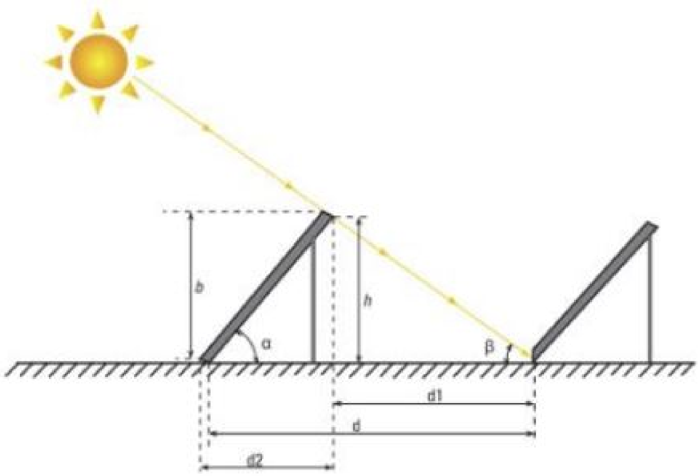


**Figure 6.8:** Minimum distance between panels, (adapted from Pereira, 2015, p.33)

$$d = b * (\cos\beta + \frac{\sin\alpha}{\tan\beta}) \tag{6.1}$$

Variable presented in Figure 6.8 where:

d = Minimal distance between panels

b = height of the panel 607mm

$\beta$ = The sun on the 21st of December 2020 was as low as possible in the sky over Lisbon and during its meridian reached a minimum height of 28°, (Observatório Astronómico de Lisboa, 2020).

$\alpha$ = Plane tilt [20º]

Obtained up the minimum distance between panels of 926 mm, however as the location in Lisbon has been consider for $\beta$, a minimum distance of 1 meter is assumed. The largest number of solar panels in the analysis is 9.200, so it is necessary a land with a surface of 20.000 $m^2$.

As the number of turbines necessary is less and the unitary space occupied by each is also smaller, the 20.000 $m^2$ is assumed to be enough.

| **Faro** | |
|---|---|
| Water cost [€/$m^3$][a] | 1,1586 |
| Water supply fee [€/30 days] a | 5,1426 |
| Land cost [€] [b] | 65.000 |
| **Leiria** | |
| Water cost [€/$m^3$] [c] | 1,5750 |
| Water supply fee [€/30 days] c | 4,95 |
| Land cost [€][d] | 55.000 |
| **Aveiro** | |
| Water cost [€/$m^3$] [e] | 1,8551 |
| Water supply fee [€/30 days] e | 6,52 |
| Land cost [€] [f] | 50.000 |
| **Porto** | |
| Water cost [€/$m^3$] [g] | 1,8036 |
| Water supply fee [€/30 days] g | 3,8152 |
| Land cost [€] [h] | 47.000 |

[a] Diário da república - FAGAR, 2020
[b] Idealista Faro, 2021
[c] Câmara Municipal Município Leiria, 2020
[d] Idealista Leiria, 2021
[e] Águas da Região de Aveiro, 2020
[f] Idealista Aveiro, 2021
[g] Águas do Porto, 2021
[h] Idealista Porto, 2021


**Figure 6.9:** Location and location variables

## 6.3 Methodology

Through NASA Langley Research Center (LaRC) (2021)has been withdrawn wind velocity by the hour in the year 2020, and though software PVSYST (2021), an hourly reference value of the solar irradiation [w/m2] was taken into account in the different locations of the study.

For wind speed in each hour of the year has been made an equation taking into consideration the power curve given by the manufacturer to obtain the kWh generated by the turbines.

For the solar irradiation has been made the calculation:

$$kWh = N * E * A^2 * I * \frac{\text{Solar irradiation } [W/m^2]}{1.000} \tag{6.2}$$

N = Number of solar panels

E [Module efficiency] = $19,14\%$

$A^2$ [Area of each module] = $1.62m^2$

I [Inverter efficiency] = 99.1%

## 6.4 Electricity surplus

Consider the nominal power of the electrolyzer of 954 kW, the electrolyzer could only work when the supplied power surpassed that value and in periods of higher production, sell the surplus to the grid (ZXDH2, 2021).

To sell the electricity surplus the company Simples Energia has been contacted and they offer three different plans for estimated case study production:

#### Option 1: Fixed Plan

$$R = E * FIT \tag{6.3}$$

R - The remuneration of electricity supplied in euros

E - Energy supplied, in kWh

FIT - Energy tariff to be applied 40 €/MWh

#### Option 2: Indexed Plan

$$R = \sum [E(h) * [OMIE(h) - k1] \tag{6.4}$$

R - The remuneration of electricity supplied in euros

E - Energy supplied, in kWh per hour

OMIE - Hourly price (€/MWh), which is fixed hourly on the market, OMIE, 2020

k1 - Fixed value corresponding to operating expenses (bank guarantees, deviation costs, etc.) – k1 = 6 €/MWh.

**Option 3: Solar Plan +**

$$R = E(m) * OMIE(m) - k2 \tag{6.5}$$

R - The remuneration of electricity supplied in euros
E(m) - Energy supplied in month 'm', in MWh
OMIE (m) - The resulting value of the monthly arithmetic average of month M, between 07:00h and 19:00h (OMIE, 2020)
k2 - Fixed amount corresponding to operating expenses (bank guarantees, deviation costs, etc.) – k2 = 7 €/MWh.

Consider these values it was concluded that in our case study for the year 2020, the fixed plan is the one giving the highest profit, therefore option 1 has been chosen.

## 6.5 Economic analysis

To determine the economic feasibility and to compare several investment alternatives, financial analysis was performed. A project is just considered viable if its payback is less than the lifetime of the electrolyzer, ten years, mentioned in Table 6.1.

To perform the financial analysis net present value of future cash flows has been determined considering different interest rates and then the payback.

### 6.5.1 Net Present Value

Net present value is an economic-financial formula to determine the present value of future payments discounted at an appropriate interest rate, making it possible to determine the profitability of a project or investment over a period of time, (Dias, 2017).

$$\text{updated cash flow} = \frac{CF_t}{(1+i)^t} \tag{6.6}$$

$CF_t$ = Cash flow generated by project in period t.
i = Interest rate
t = time period

### 6.5.2 Interest rate (i)

The interest rate is a necessary factor for analyzing the project NPV, and consequently in its evaluation. Allows discounting the benefits and costs generated during the study period of the project to make the values possible to be compared. Its determination depends on the capital source, whether the project is financed. By own capital the appropriate discount rate is the cost of equity or the cost of capital opportunity, or if it is financed by equity and debt, the appropriate discount rate is the weighted average cost of capital, whose value reflects the cost of funding sources both in terms of capital owned and that of others, (Rosário, 2014).

For this dissertation, simulations were made on equity and debt to obtain the necessary capital. The weighted average cost of capital was calculated for different debt rates, 0%, 50%, and 70%.

$$\text{WACC} = r * \frac{E}{E+D} + r_d * (1-t) * \frac{D}{E+D} \tag{6.7}$$

r = Equity cost [24,6%], (Banco de Portugal, 2019, Quadros do Setor - Fabricação de gases industriais).

E = Equity at market value

D = Liabilities, or debt amount at market values

$r_d$ = debt cost [25,9%], (Banco de Portugal, 2019, Quadros do Setor - Fabricação de gases industriais)

t = profit tax rate [21%] (Autoridade tributária e aduaneira, 2021)

The following values were obtained and used in calculations of the net present value.

WACC [50% financing] = 22.53%

WACC [70% financing] = 21.1%

### 6.5.3 Payback

Payback is the period of time necessary for the profits generated from the project to reach the value of the initial investment of the project (Rosário, 2014). It was calculated directly from the used formulas.

# Chapter 7

# Results

In this chapter, results obtained by this study in different scenarios are analyzed and compared. This study intends to determine the best composition of the system in analysis (solar and wind energy), accordingly to different locations, and the choice on the financing sources, with or without external funding. Different percentages of solar and wind energy are consider to analyze the cost-efficiency perspective in each geographical location, each system is dimensioned to produce between 4.600 MWh and 4.700 MWh per year, this value was defined as the common denominator between all cases.

Among sensitive analysis, variables common to all cases have been consider, they are represented in Table 7.1. Besides common variables, valuation of the oxygen product is also taken into account at 0.5 €/kg (Table 7.1).

To execute the financial analysis, a ten years period has been consider, and beyond prices mentioned organization and maintenance costs are assumed to increase 1% per year due to premature wear of equipment components. An increasing and decreasing profits by 2% over the period has been added in each simulation as a margin of error. Considering the installation efficiency depends on meteorological conditions that may vary significantly accordingly to year, month, or even week, being impossible to predict weather conditions between 2020-2030.

## 7.1 Faro

In Table 7.2 we may see represented the different scenarios, in case number 1 to produce 4.623 MWh/year there is a need for 8.000 photovoltaic panels and in case number 4, 3.800 wind turbines are necessary to produce 4.644 MWh/year, base case number 2 and 3 are different combinations of the systems, being characterized by the percentage of solar energy in the total annual energy production of the system. If the energy supplied in determining hour surpassed 954 kWh, the electrolyzer may function, more water will be spent adding costs, and only the electricity surplus will be sold to the grid, however, hydrogen and oxygen are produced. $CO_2$ savings consider that hydrogen produced is injected in natural gas grid avoiding the use of natural gas, we may see that the more hours the electrolyzer works, the greater the savings in $CO_2$.

In Faro the hypothesis where the production of hydrogen is higher are the ones with 100% of solar energy and 75%, however, the electricity surplus sales in the first case are the lowest, which is explained because the production of electricity through solar energy is over the irradiation period of the sun and the wind energy is over 24h, we may produce more

**Table 7.1:** Common variables taken into account for calculation

| | |
|---|---|
| **Electrolyzer** | |
| Nominal Power [kW] | 954 |
| Aquisition cost [€] | 1.053.268 |
| $H_2$ Production [$Nm^3$] | 200 |
| $O_2$ Production [$Nm^3$] | 100 |
| Water consumption [kg/h] | 150 |
| **Photovoltaic panels** | |
| Area of each panel [$m^2$] | 1.62 |
| Panel efficiency [%] | 19.14 |
| Aquisition cost of each panel [€] | 155,12 |
| **Inverter** | |
| Inverter capacity [kW] | 150 |
| Inverter efficiency [%] | 99,1 |
| Aquisition cost for unit [€] | 10.729 |
| **Wind Turbines** | |
| Unitary cost [€] | 1.020 |
| **Water purifier** | |
| Aquisition cost [€] | 1471.15 |
| **Comercialization prices** | |
| Hydrogen [€/kg][1] | 3 |
| Oxygen [€/kg]1 | 0.5 |
| Electricity sold to the grid [€/MWh] [2] | 40 |
| **Cost O&M**[3] | |
| Photovoltaic [€/kWh/year] | 15 |
| Wind turbines [€/kWh/year] | 80 |
| **Finance** [4] | |
| Return on equity[%] | 24.6 |
| Asset yield [%] | 25.9 |
| Income Tax [%] | 21 |
| WACC [70% financing] | 22.5 |
| WACC [50% financing] | 21.1 |

1 - Arbitrary price taking into account enunciated literature
2 - Simples Energia (2021)
3 - Government of Canada (2021)
4 - Banco de Portugal (2019)

energy, although not enough power to turn on the electrolyzer. Another crucial point in this analysis is the cost of the system, different hypotheses have a cost difference and a financial analysis is necessary to ascertain the economic feasibility of the project.

**Table 7.2:** Faro sensitivity analysis

| Base case nº | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Number of photovoltaic panels | 8000 | 6000 | 4000 | 0 |
| Number of wind turbines | 0 | 950 | 1900 | 3800 |
| Solar energy of the system [%] | 100 % | 75 % | 50 % | 0 % |
| Electrolyser functioning [h/year] | 2231 | 1942 | 1773 | 1732 |
| Electricity surplus sales [€/year] | 99 786 € | 110 977 € | 117 628 € | 119 557 € |
| Hydrogen produced [$Nm^3$/year] | 446 200 | 388 400 | 354 600 | 346 400 |
| Hydrogen produced [kg/year] | 39 782 | 34 629 | 31 616 | 30 884 |
| Oxygen produced [$Nm^3$/year] | 223 100 | 194 200 | 177 300 | 173 200 |
| Oxygen produced [kg/year] | 295 889 | 257 560 | 235 146 | 229 708 |
| Water cost [€/year] | 388 € | 338 € | 308 € | 301 € |
| Land cost [20.858 $m^2$] | 65 000 € | 65 000 € | 65 000 € | 65 000 € |
| Cost of the system [€] | 2 555 291 | 3 165 450 | 3 775 629 € | 4 996 040 € |
| O&M costs [€/year] | 37 024 € | 85 303 € | 133 582 € | 230 140 € |
| Revenues [€/year] | 367 077 € | 343 644 € | 330 047 € | 327 064 € |
| $CO_2$ Savings [kg/year] | 929 145 | 808 785 | 738 401 | 721 326 |
| Electricity Produced [kWh/year] | 4 623 015 | 4 628 473 | 4 633 931 | 4 644 847 |

In the financial analysis presented in Table 7.3, we may see that the project is only viable with 70% external funding. A net present value between 682 403€ and 476 640€ is expected in the ten years project. The payback of the project is also inferior to 5 years being possible to consider that under these conditions the project is economically and financially worth it. With a 50% funding and 2% increase in profits, it is expected that net present value in ten years would be 102 322€, however, if the sales decrease due to meteorological conditions or other external factors, net present value in ten years would be -89 964€, not mentioned as a good investment.

**Table 7.3:** Faro base case number 1

| Capital | 70 % Financed | | 50% Financed | | 0% Financed | |
|---|---|---|---|---|---|---|
| Profit variation | 2% | -2% | 2% | -2% | 2% | -2% |
| NPV 10 years | 682 403 € | 476 640 € | 102 322 € | -89 964 € | -1 264 826 € | -1 439 909 € |
| Payback | 3 Years<br>4 Monts | 3 Years<br>10 Months | 8 Years<br>2 Months | — | — | — |

In the financial analysis presented in Table 7.4, base case number 2, we may see that the project is only viable with 70% external funding, being the net present value between 195 938€ to 9 007€ expected while answering a ten years project. Although project payback is inferior to 10 years net present value is considered low in the option of decreasing profits jeopardizing the project's viability.

In Table 7.5, base case number 3 and Table 7.6, base case number 4 we may see that

**Table 7.4:** Faro base case number 2

| Capital | 70 % Financed | | 50% Financed | | 0% Financed | |
|---|---|---|---|---|---|---|
| Profit variation | 2% | -2% | 2% | -2% | 2% | -2% |
| NPV 10 years | 195 938 € | 9 007 € | -491 880 € | -666 568 € | -2 145 561 € | -2 304 621 € |
| Payback | 6 Years 8 Months | 9 Years 11 Months | —– | —– | —– | —– |

none of the options for the project is feasible, mostly due to low wind speeds in Faro and higher equipment and maintenance costs of wind turbines. Whenever the net present value is negative, no payback can be computed.

**Table 7.5:** Faro base case number 3

| Capital | 70 % Financed | | 50% Financed | | 0% Financed | |
|---|---|---|---|---|---|---|
| Profit variation | 2% | -2% | 2% | -2% | 2% | -2% |
| NPV 10 years | -247 574 € | -423 527 € | -1 045 178 € | -1 209 608 € | -2 988 052 € | -3 137 771 € |
| Payback | —- | —- | —- | —– | —– | —– |

**Table 7.6:** Faro base case number 4

| Capital | 70 % Financed | | 50% Financed | | 0% Financed | |
|---|---|---|---|---|---|---|
| Profit variation | 2% | -2% | 2% | -2% | 2% | -2% |
| NPV 10 years | -1 028 873 € | -1 202 265 € | -2 051 088 € | -2 213 124 € | -4 578 896 € | -4 726 436 € |
| Payback | —- | —- | —- | —– | —– | —– |

In Faro due to solar irradiance available it is possible to consider the installation of the project considering previous results, due to unitary price and maintenance wind energy is not economically and financially worth it.

## 7.2 Leiria

In Table 7.7 we may see represented the different scenarios, in case number 1 to produce 4.646 MWh/year there is a need for 9.200 photovoltaic panels and in case number 4, 7.650 wind turbines are necessary to produce 4.607 MWh/year, base case number 2 and 3 are different combinations of the systems, characterized by the percentage of solar energy in the total annual energy production of the system. To produce the same amount of energy due to poor weather conditions more equipment is necessary (eg., 1200 Solar panels in base case number 1 and more than 3850 wind turbines in base case number 4), thus resulting in higher organization and maintenance costs, surpassing revenues in base case number 4. In this case, no financial analysis is presented because no payback can be achieved.

In Leiria as in Faro, as we may see in Table 7.7 the hypothesis where production of hydrogen is higher are the ones with 100% and 75% of solar energy, nonetheless, the electricity surplus sales in the first case are the lowest.

**Table 7.7:** Leiria sensitivity analysis

| Base case nº | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Number of photovoltaic panels | 9200 | 6800 | 4600 | 0 |
| Number of wind turbines | 0 | 1950 | 3800 | 7650 |
| Solar energy of the system [%] | 100 % | 75 % | 50 % | 0 % |
| Electrolyser functioning [h/year] | 2289 | 2000 | 1629 | 1245 |
| Electricity surplus sales [€/year] | 98 509 € | 107 943 € | 122 180 € | 136 522 € |
| Hydrogen produced [$Nm^3$/year] | 457 800 | 400 000 | 325 800 | 249 000 |
| Hydrogen produced [kg/year] | 40 817 | 35 663 | 29 048 | 22 200 |
| Oxygen produced [$Nm^3$/year] | 228 900 | 200 000 | 162 900 | 124 500 |
| Oxygen produced [kg/year] | 303 581 | 265 252 | 216 048 | 165 119 |
| Water cost [€/year] | 541 € | 473 € | 385 € | 294 € |
| Land cost [20.858 $m^2$] | 55 000 € | 55 000 € | 55 000 € | 55 000 € |
| Cost of the system [€] | 2 756 137 | 4 315 715 | 5 809 053 € | 8 913 033 € |
| O&M costs [€/year] | 41 705 € | 146 195 € | 245 676 € | 452 605 € |
| Revenues [€/year] | 372 749 € | 347 559 € | 317 347 € | 285 683 € |
| $CO_2$ Savings [kg/year] | 953 300 | 832 940 | 678 430 | 518 505 |
| Electricity Produced [kWh/year] | 4 646 428 | 4 608 822 | 4 611 995 | 4 607 677 |

In the financial analysis presented in Table 7.8, we may see that likewise, the project in Faro only with 70% external funding, generates a positive net present value between 627 429€ and 417 573€ for the ten years project. The payback of the project is also inferior to 5 years. Then it is possible to consider that under these conditions the project is economically and financially worth it. With a 50% funding and 2% increase in profits, it is expected that net present value in ten years would be 6 916€. However, if the profits decrease, net present value in ten years would be negative, more precisely -189 196€, not being considered a good investment.

**Table 7.8:** Leiria base case number 1

| Capital | 70 % Funding | | 50% Funding | | 0% Funding | |
|---|---|---|---|---|---|---|
| Profit variation | 2% | -2% | 2% | -2% | 2% | -2% |
| NPV 10 years | 627 429 € | 417 573 € | 6 916 € | -189 196 € | -1 460 997 € | -1 639 564 € |
| Payback | 3 Years 8 Months | 4 Years 2 Months | 10 Years | — | — | — |

In Table 7.9, base case number 2 and Table 7.10, base case number 3 we may see that none of the options for the project is feasible, mostly due to low wind speeds and higher equipment and maintenance costs of wind turbines.

**Table 7.9:** Leiria base case number 2

| Capital | 70 % Funding | | 50% Funding | | 0% Funding | |
|---|---|---|---|---|---|---|
| Profit variation | 2% | -2% | 2% | -2% | 2% | -2% |
| NPV 10 years | -385 647 € | -576 102 € | -1292443,2 | -1 470 424 € | -3 506 881 € | -3 668 939 € |
| Payback | — | — | — | — | — | — |

**Table 7.10:** Leiria base case number 3

| Capital | 70 % Funding | | 50% Funding | | 0% Funding | |
|---|---|---|---|---|---|---|
| Profit variation | 2% | -2% | 2% | -2% | 2% | -2% |
| NPV 10 years | -1 379 916 € | -1 546 154 € | -2559682,3 | -2 715 033 € | -5 487 442 € | -5 628 894 € |
| Payback | —— | —— | —- | —— | —— | —— |

In Leiria, due to lower solar irradiance than Faro, more system components are needed, although it is possible to consider the installation of the project 100% solar and 70% funding. The investment on the projects with wind energy is even more expensive and due to unitary price and maintenance wind energy is not economically and financially worth it.

## 7.3 Aveiro

In Table 7.11 we may see represented the different scenarios, in case number 1 to produce 4.646 MWh/year there is a need for 8.600 photovoltaic panels and in case number 4, 12.000 wind turbines are necessary to produce 4.629 MWh/year, base case number 2 and 3 are different combinations of the systems, characterized by the percentage of solar energy in the total annual energy production of the system. The number of wind turbines necessary to produce the same amount of energy is nearly three times Faro, being reflected in costs of the system and organization and maintenance costs in case numbers 2,3, and 4 jeopardizing project viability.

As in previous cases, in Aveiro the hypothesis where production of hydrogen is higher are the ones with 100% and 75% of solar energy, and, the electricity surplus sales in the first case are the lowest as we may see in Table 7.11. In base case number 3 and number 4 organization and maintenance also surpass revenues. In this cases, no financial analysis is presented because no payback can be achieved.

In the financial analysis presented in Table 7.12, we may see that the project is only viable with 70% external funding, where a net present value between 281 402€ and 79 972€ is expected in a ten-year project, much less than in previous cases. The payback of the project is between 5 to 10 years being possible to consider that under these conditions the project is feasible, although not very interesting.

In base case number 2, Table 7.13, the net present value in a 10 years perspective is still negative, consequently, its payback is not attended, not being considered economically and financially worth it.

In Aveiro, due to lower wind velocities, more wind turbines are needed, jeopardizing any installation of this type of renewable energy, although it is possible to consider the installation of the project 100% solar and 70% funding.

**Table 7.11:** Aveiro sensitivity analysis for the base case

| Base case nº | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Number of photovoltaic panels | 8800 | 6500 | 4400 | 0 |
| Number of wind turbines | 0 | 3050 | 6000 | 12000 |
| Solar energy of the system [%] | 100 % | 75 % | 50 % | 0 % |
| Electrolyser functioning [h/year] | 2160 | 1970 | 1554 | 1153 |
| Electricity surplus sales [€/year] | 103 443 € | 109 043 € | 125 991 € | 140 717 € |
| Hydrogen produced [$Nm^3$/year] | 432 000 | 394 000 | 310 800 | 230 600 |
| Hydrogen produced [kg/year] | 38 516 | 35 128 | 27 710 | 20 560 |
| Oxygen produced [$Nm^3$/year] | 216 000 | 197 000 | 155 400 | 115 300 |
| Oxygen produced [kg/year] | 286 472 | 261 273 | 206 101 | 152 918 |
| Water cost [€/year] | 375 € | 342 € | 270 € | 200 € |
| Land cost [20.858 $m^2$] | 65 000 € | 65 000 € | 65 000 € | 65 000 € |
| Total system cost [€] | 3 797 213 | 6 208 484 | 8 578 559 € | 13 359 940 € |
| O&M costs [€/year] | 38 764 € | 208 107 € | 372 446 € | 706 128 € |
| Revenues [€/year] | 362 228 € | 345 065 € | 312 173 € | 278 855 € |
| $CO_2$ Savings [kg/year] | 899 575 | 820 446 | 647 195 | 480 190 |
| Electricity Produced [kWh/year] | 4 646 705 | 4 608 783 | 4 637 892 | 4 629 080 |

**Table 7.12:** Aveiro base case number 1

| Capital | 70 % Funding | | 50% Funding | | 0% Funding | |
|---|---|---|---|---|---|---|
| Profit variation | 2% | -2% | 2% | -2% | 2% | -2% |
| NPV 10 years | 281 402 € | 79 972 € | -545 715 € | -733 953 € | -2 532 077 € | -2 703 475 € |
| Payback | 6 Years 4 Months | 8 Years 2 Months | —— | —— | —— | —— |

**Table 7.13:** Aveiro base case number 2

| Capital | 70 % Funding | | 50% Funding | | 0% Funding | |
|---|---|---|---|---|---|---|
| Profit variation | 2% | -2% | 2% | -2% | 2% | -2% |
| NPV 10 years | -1 222 224 € | -1 410 704 € | -2 494 968 € | -2 671 104 € | -5 639 431 € | -5 799 808 € |
| Payback | —— | —— | —— | —— | —— | —— |

## 7.4 Porto

In Table 7.14 we may see represented the different scenarios, in case number 1 to produce 4.608 MWh/year there is a need for 9.000 photovoltaic panels and in case number 4, 9.500 wind turbines are necessary to produce 4.609 MWh/year, base case number 2 and 3 are different combinations of the systems, characterized by the percentage of solar energy in the total annual energy production of the system. The number of wind turbines necessary to produce the same amount of energy is 5700 more, reflecting costs of the system and organization and maintenance costs in case numbers 2,3, and 4 jeopardizing project viability as in Leiria and Aveiro.

The last case in Porto didn't differ much from the others. The hypothesis where production of hydrogen is higher is the same, 100% and 75% of solar energy with less electricity surplus sales as we may see in Table 7.14. In base case number 4 organization and maintenance costs surpass the revenues, so no financial analysis is presented because no payback can be achieved.

**Table 7.14:** Porto sensitivity analysis for the base case

| Base case nº | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Number of photovoltaic panels | 9000 | 6800 | 4500 | 0 |
| Number of wind turbines | 0 | 2400 | 4800 | 9500 |
| Solar energy of the system [%] | 100 % | 75 % | 50 % | 0 % |
| Electrolyser functioning [h/year] | 2202 | 2000 | 1641 | 1186 |
| Electricity surplus sales [€/year] | 100 298 € | 109 421 € | 122 526 € | 138 774 € |
| Hydrogen produced [$Nm^3$/year] | 440 400 | 400 000 | 328 200 | 237 200 |
| Hydrogen produced [kg/year] | 39 265 | 35 663 | 29 262 | 21 148 |
| Oxygen produced [$Nm^3$/year] | 220 200 | 200 000 | 164 100 | 118 600 |
| Oxygen produced [kg/year] | 292 042 | 265 252 | 217 639 | 157 294 |
| Water cost [€/year] | 383 € | 348 € | 285 € | 206 € |
| Land cost [20.858 $m^2$] | 65 000 € | 65 000 € | 65 000 € | 65 000 € |
| Total system cost [€] | 2 726 566 | 4 781 844 | 6 819 246 € | 10 809 945 € |
| O&M costs [€/year] | 40 105 € | 174 417 € | 308 283 € | 570 456 € |
| Revenues [€/year] | 364 115 € | 349 037 € | 319 131 € | 280 866 € |
| $CO_2$ Savings [kg/year] | 917 067 | 832 940 | 683 427 | 493 934 |
| Electricity Produced [kWh/year] | 4 608 151 | 4 646 195 | 4 633 038 | 4 609 404 |

In the financial analysis presented in Table 7.15, we may see that the project is only viable with 70% external funding, where a net present value between 281 485 940€ and 307 596€ is expected in a ten-year project. The payback of the project is between 5 to 10 years being possible to consider that under these conditions the project is economically and financially worth it.

In base case number 2 and number 3, Table 7.16 and 7.17 respectively, the net present value in 10 years perspective is still negative, consequently, its payback is not attended, not being considered feasible.

**Table 7.15:** Porto base case number 1

| Capital | 70 % Funding | | 50% Funding | | 0% Funding | |
|---|---|---|---|---|---|---|
| Profit variation | 2% | -2% | 2% | -2% | 2% | -2% |
| NPV 10 years | 485 940 € | 307 596 € | -83 235 € | -249 898 € | -1 434 492 € | -1 586 244 € |
| Payback | 4 Years 1 Month | 4 Years 5 Months | — | — | — | — |

**Table 7.16:** Porto base case number 2

| Capital | 70 % Funding | | 50% Funding | | 0% Funding | |
|---|---|---|---|---|---|---|
| Profit variation | 2% | -2% | 2% | -2% | 2% | -2% |
| NPV 10 years | -636 569 € | -827 503 € | -1 631 388 € | -1 809 817 € | -4 072 138 € | -4 234 604 € |
| Payback | — | — | — | — | — | — |

**Table 7.17:** Porto base case number 3

| Capital | 70 % Funding | | 50% Funding | | 0% Funding | |
|---|---|---|---|---|---|---|
| Profit variation | 2% | -2% | 2% | -2% | 2% | -2% |
| NPV 10 years | -1 935 933 € | -2 103 216 € | -3 305 885 € | -3 462 212 € | -6 723 357 € | -6 865 699 € |
| Payback | — | — | — | — | — | — |

# Chapter 8

# Conclusion

This study had as an objective to analyze the economic and financial feasibility of an installation to produce green hydrogen in four different locations in Portugal. Within the scope of the study different proportions of solar and wind energy were taken into account as well as different amounts of external funding.

The study performed concluded that the renewable energy source which gives the best option for this type of project is solar energy because to turn on the equipment selected to produce hydrogen is necessary nearly 1MW of nominal power, although solar energy equipment produces less energy over one year. The amount of time that nominal power is enough to turn the equipment is more than it is with wind turbines that produce larger amounts of energy but in 24 hour period. Wind velocities at 50 meters height in Portugal, more expensive costs of equipment, and maintenance are some reasons why the wind turbines seem not to be economically viable in this application. Other external factors may have an impact on the viability of the project, considering the energy used comes from renewable energy sources and that energy sources depend on meteorological conditions. A 2% margin for profits was consider, but meteorologic conditions could vary more than that. Maintenance costs could also vary, 1% increment is also assumed, but due to unpredictable situations that may vary (eg., storms and inefficient installation).

Under these conditions, any project was viable in 10 years without external funding being the best case scenario the higher solar energy provided in all the different locations. Hydrogen has a great potential to help decarbonize the global economy in a variety of sectors, however, it is not yet economically viable to produce. Thus improvements in electrolyzer cost and efficiency as well as in solar panels are necessary. Storage, transport, and utilization are also essential for the development and they are still in the early stage of development.

The best scenario obtained was the production of hydrogen in Faro with 100% solar energy and 70% external funding, having been obtained values of net present value in a ten year period of 682 403 € to 476 640 € to which corresponds a payback between 3 and 4 years.

The simulation of the entire value chain, including production, storage, and dispenser, was necessary to improve this study, however, it was not possible due to difficulty acquiring budgets and additional information from companies.

Would be necessary to have more reliable and realistic results in the measurement of wind velocity over the course of a period with an anemometer in key locations to determine if the results were the same if a study to determine the specific location of the wind turbines were conducted. Therefore, these difficulties could originate relevant future research directions.

# Bibliography


Adene. (2021). Portugal Energia. Retrieved October 22, 2021, from https://www.portugalenergia.pt/financiamento/

Aguiar, R., Martins, P., Borges, R., & Partidário, P. (2020). Energy Scenarios in support of the Portuguese Strategy for Hydrogen. *DGEG (2020)*, *DEIR Studi*(Directorate-General for Energy and Geology, Divison of Research and Renewables, Lisbon, Portugal.). https://www.dgeg.gov.pt/pt/areas-setoriais/energia/energias-renovaveis-e-sustentabilidade

Autoridade tributária e aduaneira. (2021). CIRC. Retrieved October 19, 2021, from https://info.portaldasfinancas.gov.pt/

Banco de Portugal. (2019). Quadros do Setor - Fabricação de gases industriais. Retrieved October 19, 2021, from https://www.bportugal.pt/QS/qsweb/Dashboards

BP. (2020). Statistical Review of World Energy globally consistent data on world energy markets . and authoritative publications in the field of energy The Statistical Review world of World Energy and data on world energy markets from is The Review has been providing, 66. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf

Bp. (2021). Statistical Review of World Energy. Retrieved October 27, 2021, from https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

Brändle, G., Schönfisch, M., & Schulte, S. (2021). Estimating long-term global supply costs for low-carbon hydrogen. *Applied Energy*, *302*(March), 117481. https://doi.org/10.1016/j.apenergy.2021.117481

Câmara Municipal Município Leiria. (2020). *Tarifário de abastecimento de água e saneamento de águas residuais e tarifário de serviços auxiliares para 2020* (tech. rep. No. 1). https://www.ersar.pt/pt/consumidor/tarifas-dos-servicos/encargos-tarifarios/pesquisa-por-concelho

Chemical Safety. (2021). Ammonia. Retrieved June 7, 2021, from ChemicalSafetyFacts.org

de Souza, A. C. C., & Silveira, J. L. (2004). *Ensinando os princípios básicos da reforma a vapor para a produção de hidrogênio* (tech. rep.).

DGEG - Direcção Geral de Energia e Geologia. (2020). *EN-H2: Estratégia Nacional para o Hidrogénio* (tech. rep.).

Diário da república - FAGAR. (2020). *FAGAR — Faro, gestão de águas e resíduos, E. M.* (tech. rep.). https://www.ersar.pt/pt/consumidor/tarifas-dos-servicos/encargos-tarifarios/pesquisa-por-concelho

Dias, J. (2017). *Análise económico-financeira de um projeto de energia fotovoltaica numa grande superfície* (Doctoral dissertation). Universidade de Aveiro.

Dosio, A., Mentaschi, L., Fischer, E. M., & Wyser, K. (2018). Extreme heat waves under 1.5 °c and 2 °c global warming. *Environmental Research Letters*, *13*(5). https://doi.org/10.1088/1748-9326/aab827

E4tech. (2021). *The Fuel Cell Industry Review 2020* (tech. rep.). http://www.fuelcellindustryreview.com/FCIRarchive.html

Energy, & climate inteligence unit. (2021). United Nations. Retrieved June 1, 2021, from https://www.un.org/en/climatechange/net-zero-coalition

EnergyData. (2021). Global Wind Atlas. Retrieved October 1, 2021, from https://globalwindatlas.info/

Enkvist, P.-A., Westerdahl, R., & Elmqvist, A. (2020). Mainstreaming Green hydrogen in Europe. *Material economics* (pp. 83–98). John Wiley & Sons, Ltd.

Entidade Reguladora dos Serviços Energéticos. (2021). Entidade Reguladora dos Serviços Energéticos. Retrieved October 1, 2021, from https://www.erse.pt/inicio/

Escobar-Yonoff, R., Maestre-Cambronel, D., Charry, S., Rincón-Montenegro, A., & Portnoy, I. (2021). Performance assessment and economic perspectives of integrated PEM fuel cell and PEM electrolyzer for electric power generation. *Heliyon*, *7*(3). https://doi.org/10.1016/j.heliyon.2021.e06506

Eurenergroup. (2021). *MEPV 300 - 320W* (tech. rep.). Eurener. https://www.ffsolar.com/products

European Commission. (2020). Update of the NDC of the European Union and its Member States. (December), 1–19.

European Environment Agency. (2020). *The European environment-state and outlook 2020. Knowledge for transition to a sustainable Europe* (Vol. 60). https://doi.org/10.15196/TS600305

European Precious Metals Federation aisbl. (2021). European Precious Metals Federation. Retrieved October 23, 2021, from https://www.epmf.be/

Federal Ministry for Economic Affairs and Energy. (2020). *National Hydrogen Strategy Germany* (tech. rep.). www.bmwi.de

FF Solar. (2021). *Public Prices List 2021* (tech. rep.).

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Sitch, S., Le Quéré, C., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S., Aragão, L. E., Arneth, A., Arora, V., Bates, N. R., . . . Zaehle, S. (2020). Global Carbon Budget 2020. *Earth System Science Data*, *12*(4), 3269–3340. https://doi.org/10.5194/essd-12-3269-2020

Friedrich, J., Ge, M., & Pickens, A. (2020). World Resources Intitute. Retrieved June 1, 2021, from https://www.wri.org/insights/interactive-chart-shows-changes-worlds-top-10-emitters

Galp. (2021). Método utilizado para efeitos de cálculo das emissões de CO2. Retrieved September 29, 2021, from https://www.galp.com/pt/pt/empresas/eletricidade-e-gas/Apoio-ao-Cliente/Centro-de-Informacao/Eletricidade-e-Gas-Natural-da-Galp

Government of Canada. (2021). RETScreen Expert. https://www.nrcan.gc.ca/maps-tools-and-publications/tools/modelling-tools/retscreen/7465

GREENPRO. (2004). *Energia Fotovoltaica manual sobre tecnologias, projetos e instalação* (tech. rep.).

Harrington, L. J., & Otto, F. E. (2018). Changing population dynamics and uneven temperature emergence combine to exacerbate regional exposure to heat extremes under 1.5 $\circ$C and 2 ∘C of warming. *Environmental Research Letters*, *13*(3). https://doi.org/10.1088/1748-9326/aaaa99

Homann, Q. (2019). Hydrogen as a Clean Alternative in the Iron and Steel Industry. Retrieved July 2, 2021, from https://www.fchea.org/in-transition/2019/11/25/hydrogen-in-the-iron-and-steel-industry

Hydrogen Council. (2020). *Path to hydrogen competitiveness: a cost perspective* (tech. rep. January). www.hydrogencouncil.com.

Idealista Aveiro. (2021). Terreno em Aveiro. Retrieved October 7, 2021, from https://www.idealista.pt/imovel/31385368/

Idealista Faro. (2021). Terreno em Faro. Retrieved October 7, 2021, from https://www.idealista.pt/imovel/29790674/

Idealista Leiria. (2021). Terreno em Leiria. Retrieved October 7, 2021, from https://www.idealista.pt/imovel/30015212/

Idealista Porto. (2021). Terreno no Porto. Retrieved October 7, 2021, from https://www.idealista.pt/imovel/30862180/

IEA. (2019). *The Future of Hydrogen: Seizing today's opportunities* (tech. rep. June).

IEA. (2020a). *Energy Technologies Perspectives 2020* (tech. rep.). International Energy Agency. https://doi.org/10.1787/208b66f4-en

IEA. (2020b). *World Energy Investment 2020* (tech. rep.).

IEA. (2021a). *Global Hydrogen Review* (tech. rep.). International Energy Agency. www.iea.org

IEA. (2021b). World Energy Balances. Retrieved October 21, 2021, from https://www.iea.org/data-and-statistics/data-product/world-energy-balances%7B%5C#%7Denergy-balances

IEA, & NEA. (2020). *Projected Costs of Generating Electricity* (tech. rep. January). https://ncdc.gov.ng/themes/common/docs/protocols

IRENA. (2021). International Renewable Energy Agency. Retrieved October 14, 2021, from https://www.irena.org/wind

Jiangmen Longning Water Purification Technology Co, L. (2021). Spirit RO pure water system 500L small RO system water treatment plant price. Retrieved October 14, 2021, from https://www.alibaba.com/product-detail/Pure-Water-System-Spirit-RO-Pure%7B%5C_%7D1600329664428.html?spm=a2700.galleryofferlist.normal%7B%5C_%7Doffer.d%7B%5C_%7Dtitle.5d895c95hjtjNm%7B%5C&%7Ds=p

Kinesis. (2021). Kinesis scientific experiments. Retrieved October 14, 2021, from https://kinesis-usa.com/

Liu, C., Li, F., Lai-Peng, M., & Cheng, H. M. (2010). Advanced materials for energy storage. *Advanced materials* (pp. 28–62). https://doi.org/10.1002/adma.200903328

Mertens, K. (2018). *Photovoltaic: Fundamentals, Technology and Practice*. https://books.google.pt

Methanex Corporation. (2021). Methanex. Retrieved June 7, 2021, from https://www.methanex.com/about-methanol/how-methanol-used

Miguel, F., Mamede, S., Santos, D. O. S., António, F., Mamede, C., & Santos, D. O. S. (2016). Combustível "hidrogénio". *Millenium*, *0*(31), 252–270.

NASA. (2021). NASA Prediction Of Worldwide Energy Resources. Retrieved October 7, 2021, from https://power.larc.nasa.gov/

NASA Langley Research Center (LaRC). (2021). Prediction of Worldwide Energy Resources (POWER). Retrieved October 1, 2021, from https://power.larc.nasa.gov/data-access-viewer/

National Development and Reform Comission of China. (2016). *Enhanced actions on climate change: China´s intended nationally determined contributions* (tech. rep.).
Nuno Nacimento, G. G. N. D. (2020). *Green Pipeline Project* (tech. rep.).
Observatório Astronómico de Lisboa. (2020). Solstício de Inverno 2020. Retrieved October 14, 2021, from https://oal.ul.pt/solsticio-de-inverno-2020/
Observatório Energia, DGEG, & ADENE. (2021). *Energia em números - Edição 2021* (tech. rep. EDIÇÃO).
OMIE. (2020). Preço horário do mercado diário. Retrieved October 19, 2021, from https://www.omie.es/pt/market-results/daily/daily-market/daily-hourly-price
Pasieka, A. (2017). Physicsworld. Retrieved October 20, 2021, from https://physicsworld.com/a/an-unelementary-affair-150-years-of-the-periodic-table/
Pereira, P. F. M. (2015). *A produção fotovoltaica em portugal análise da legislação em vigor e do custo/benefício* (tech. rep.).
Pretis, F., Schwarz, M., Tang, K., Haustein, K., & Allen, M. R. (2018). Uncertain impacts on economic growth when stabilizing global temperatures at 1.5°C or 2°C warming. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *376*(2119). https://doi.org/10.1098/rsta.2016.0460
PVSYST. (2021). PVSYST. https://www.pvsyst.com/
REN. (2021). Redes Energéticas Nacionais. Retrieved January 10, 2021, from https://www.ren.pt
República Portuguesa. (2019). *PNEC 2030 - Plano Nacional Energia-Clima* (tech. rep.).
Robinson, A., Calov, R., & Ganopolski, A. (2012). Multistability and critical thresholds of the Greenland ice sheet. *Nature Climate Change*, *2*(6), 429–432. https://doi.org/10.1038/nclimate1449
Rosário, L. (2014). *Análise da viabilidade económica e financeira de projetos de investimento em cabo verde* (Doctoral dissertation). Instituto superior de ciências económicas e empresariais.
Schmidt, O., Gambhir, A., Staffell, I., Hawkes, A., Nelson, J., & Few, S. (2017). Future cost and performance of water electrolysis: An expert elicitation study. *International Journal of Hydrogen Energy*, *42*(52), 30470–30492. https://doi.org/10.1016/j.ijhydene.2017.10.045
Sdanghi, G., Maranzana, G., Celzard, A., & Fierro, V. (2020). Towards non-mechanical hybrid hydrogen compression for decentralized hydrogen facilities. *Energies*, *13*(12). https://doi.org/10.3390/en13123145
Seneviratne, S. I., Donat, M. G., Pitman, A. J., Knutti, R., & Wilby, R. L. ((2016)). Allowable CO2 emissions based on regional and impact-related climate targets. *Nature*, *529*(7587), 477–483. https://doi.org/10.1038/nature16542
Silva, E., Vieira, R., Martinez, J., Haikal, M., Rocha, M., & VilasBoas, C. (2012). Gaseificação e pirólise para conversão da biomassa em eletricidade e biocombustíveis. *Biocombustíveis - Volume 1*, (January), 1200.
Simples Energia. (2021). *Proposta de compra da energia excedente* (tech. rep.).
SMA. (2020). *Sunny highpower peak3* (tech. rep.). www.SMA-Solar.com
Solargris. (2017). Normal direct irradiation in Europe. Retrieved September 1, 2021, from https://solargis.com/
TESUP. (2021). *ATLASX Vertical Wind Turbine* (tech. rep. Turbina Eólica de ATLASX). https://www.tesup.pt/product-page/turbina-eolica-de-atlasx-para-casas
Toyota. (2021). *Toyota newsroom*. https://pressroom.toyota.com/toyota-mirai-sets-guinness-world-records-title-with-845-mile-zero-emission-journey/

United Nations Environment Programme [UNEP]. (2006). *The Hydrogen Economy*. UNEP.
United States of America, N. D. C. (2021). United States NDC April 21 2021. *The Small Firm: An International Survey*, 7–45. https://doi.org/10.4337/9781781006122.00009
Wang, Carriveau, R., Ting, D. S., Xiong, W., & Wang, Z. (2019). A review of marine renewable energy storage. *International Journal of Energy Research*, *43*(12), 6108–6150. https://doi.org/10.1002/er.4444
Wang, Y., Seo, B., Wang, B., Zamel, N., Jiao, K., & Adroher, X. C. (2020). *Fundamentals, materials, and machine learning of polymer electrolyte membrane fuel cell technology* (tech. rep.). Elsevier Ltd. https://doi.org/10.1016/j.egyai.2020.100014
Warren, R., Price, J., Graham, E., Forstenhaeusler, N., & VanDerWal, J. (2018). *The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5°C rather than 2°C* (tech. rep. No. 6390). https://doi.org/10.1126/science.aar3646
Wender, I. (1996). Reactions of synthesis gas. *Fuel Processing Technology*, *48*(3), 189–297. https://doi.org/10.1016/S0378-3820(96)01048-X
Wind Turbine Models. (2018). Aeolia Windtech D2CF 200. Retrieved October 14, 2021, from https://en.wind-turbine-models.com/turbines/1829-aeolia-windtech-d2cf-200
World Steel Association. (2020). *Sustainable steel* (tech. rep.).
Yuan, X. Z., Nayoze-Coynel, C., Shaigan, N., Fisher, D., Zhao, N., Zamel, N., Gazdzicki, P., Ulsh, M., Friedrich, K. A., Girard, F., & Groos, U. (2021). A review of functions, attributes, properties and measurements for the quality control of proton exchange membrane fuel cell components. *Journal of Power Sources*, *491*(February), 229540. https://doi.org/10.1016/j.jpowsour.2021.229540
ZXDH2. (2021). *ZXD200H0.8 specifications.pdf* (tech. rep.). https://www.zxdh2.com/