

Optimization model for the installation of a green hydrogen power plant

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Abstract

Green hydrogen is a promising alternative for the decarbonization of the energy, industrial and transportation sectors. Green hydrogen is produced from renewable energy, so no CO₂ particles are emitted during its production.

The objective of this dissertation is to develop an optimization model that determines the best combination of wind and solar photovoltaic energy to be installed for a green hydrogen production plant, maximizing the profit obtained from the sale of the electricity generated and the hydrogen produced. For this purpose, the model is implemented using the PuLP library in Python, so that a mixed integer programming approach will be used to solve the problem. Another objective of the dissertation is to apply the model in four locations in the Iberian Peninsula, two in Portugal and two in Spain so that the results obtained contribute to a better understanding of the installation of green hydrogen production plants and to analyze the potential of Portugal and Spain in becoming the main producers of green hydrogen in Europe. Also, different scenarios involving cost reduction and different parameters for hydrogen production will be conducted.

Some of the most relevant results obtained are, for instance, the higher efficiency of wind energy, in comparison with solar photovoltaic energy, for hydrogen production, where the renewable resource that most influences the results obtained is wind energy in comparison with solar photovoltaic. Another relevant result is that, at present, the production of green hydrogen is not as profitable as the sale of the electricity generated by the renewable park, but the results obtained also indicate that in the near future, with the development of water electrolyzer technology, the production of green hydrogen could be as profitable as the sale of the electricity generated.

Resumo

O hidrogénio verde é uma alternativa promissora para a descarbonização dos sectores da energia, da indústria e dos transportes. O hidrogénio verde é produzido a partir de energia renovável, pelo que não são emitidas partículas de CO_2 durante a sua produção.

O objetivo desta dissertação é desenvolver um modelo de otimização que determine a melhor combinação de energia eólica e solar fotovoltaica a instalar para uma central de produção de hidrogénio verde, maximizando o lucro obtido com a venda da eletricidade gerada e do hidrogénio produzido. Para este efeito, o modelo programação inteira mista é implementado utilizando a biblioteca PuLP em Python, de modo a que seja utilizada uma abordagem de programação linear para resolver o problema. Outro objetivo da dissertação é aplicar o modelo em quatro localizações na Península Ibérica, duas em Portugal e duas em Espanha, para que os resultados obtidos contribuam para uma melhor compreensão da instalação de centrais de produção de hidrogénio verde e para analisar o potencial de Portugal e Espanha em se tornarem os principais produtores de hidrogénio verde na Europa. Serão ainda realizados diferentes cenários envolvendo a redução de custos e diferentes parâmetros para a produção de hidrogénio.

Alguns dos resultados mais relevantes obtidos são, por exemplo, a maior eficiência da energia eólica, em comparação com a energia solar fotovoltaica, para a produção de hidrogénio, sendo o recurso renovável que mais influencia os resultados obtidos é a energia eólica em comparação com a energia solar fotovoltaica. Outro resultado relevante é que, atualmente, a produção de hidrogénio verde não é tão rentável como a venda da eletricidade gerada pelo parque renovável, mas os resultados obtidos indicam também que num futuro próximo, com o desenvolvimento da tecnologia do eletrolisador de água, a produção de hidrogénio verde poderá ser tão rentável como a venda da eletricidade gerada.

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"Queda prohibido no sonreír ante los problemas, no luchar por lo que quieres, abandonarlo todo por miedo, no convertir en realidad tus sueños."

Alfredo Cuervo Barrero

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Acronyms and Symbols

AEM	Anion Exchange Membrane
CARB	Coal Gasification
CCS	Carbon Capture and Storage
CO ₂	Carbon dioxide
e ⁻	electrons
H ₂	Hydrogen
H ⁺	Hydrogen ions
H ₂ O	Water
HC	Hydrogen Council
HRES	Hybrid Renewable Energy System
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
JRC	European Commission's Joint Research Centre
LCOWE	Levelized Cost Of Wind-Generation Electricity
LCOSE	Levelized Cost Of Solar-Generation Electricity
LCOWHP	Levelized Cost Of Wind Hydrogen Production
LCOSHP	Levelized Cost Of Solar Hydrogen Production
OH ⁻	Hydroxide ions
PEM	Polymer Electrolyte Membrane
PL	Piecewise Linearization
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
SMR	Steam Methane Reforming
WEC	World Energy Council

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Chapter 1

Introduction

In the following chapter, a brief introduction to green hydrogen will be presented, together with the motivation and objectives of the present dissertation. The methodology followed to create the optimization model and the dissertation structure will be presented as well.

1.1 Project background and motivation

In recent years, the transition to a more sustainable future has become a priority for many countries. As a result, the need to transition to renewable energy sources is becoming increasingly urgent. In this context, green hydrogen has emerged as a promising alternative for the decarbonization of key sectors such as transport and industry.

Green hydrogen is produced from the electrolysis of water, where renewable energy sources are used to separate water molecules into hydrogen and oxygen. By producing hydrogen in this way, no CO₂ particles are being emitted into the atmosphere, making it a more environmentally friendly alternative.

1.2 Objectives of the project

The present dissertation is aiming to develop an optimization model for the installation of a green hydrogen power plant with a hybrid renewable energy system, solar photovoltaic and wind energy. The optimization model will determine the most optimal combination of wind turbines and solar photovoltaic panels to be installed, with the objective of maximizing the profits obtained from the sale of the electricity generated and the hydrogen produced.

Another objective of this dissertation is to test the model in different scenarios to verify that the model works correctly, and to provide an analysis of the results obtained for each scenario in order to help understand how the various factors that influence the design of green hydrogen production plants affect the production of green hydrogen.

1.3 Method followed in the project

The PuLp library will be explored using the Python programming language to create the optimization model. This will be a model with a mixed integer/mathematical optimization approach, which will take into account several factors, including the meteorological data and the renewable resource for each location where the installation is intended, the investment, operation and maintenance costs, the main focus of hydrogen production, either to store surplus renewable energy or to meet the demand for hydrogen from industry or transportation, among others.

Then, the model will be applied in different locations in the Iberian Peninsula to obtain results that will be helpful for understanding the installation of green hydrogen plants.

1.4 Dissertation structure

The structure of this dissertation is divided into several chapters:

- **Theoretical background:** a theoretical study of the current hydrogen situation, the types of hydrogen that exist and their uses will be presented. Then, the importance that green hydrogen can have in the decarbonization of the energy, industrial and transport sectors will be presented. Also, it will be explained how green hydrogen is produced, and what kind of technologies exist. Finally, some information about the green hydrogen market will be provided.
- **Description of the green hydrogen production problem:** this chapter will present the problem of green hydrogen production in the dissertation, along with an explanation of the various formulas and parameters that will be used to create and solve the optimization model. Also, the different scenarios to be studied are presented.
- **Optimization Model:** the optimization model will be presented, explaining the different decision variables, the objective function and the different constraints. Also, it will be explained how some parameters must be linearized, using piecewise linearization.
- **Results:** the optimization model is used in a set of hydrogen production scenarios in order to understand better the green hydrogen production.
- **Conclusions and future work:** a summary of the dissertation will be presented, with the main results, limitations and with suggestions for future work.

Chapter 2

Theoretical Background

During this chapter, the theoretical foundation of hydrogen in general and especially green hydrogen will be presented, addressing different topics such as its importance in achieving the objectives of Net Zero emissions, its production methods and other characteristics such as transportation or costs. Lastly, the market for green hydrogen is also described.

2.1 Hydrogen Types

Hydrogen can be produced following different technologies and processes. The energy industry uses a color code to differentiate and classify the various types of hydrogen. Table 2.1 shows the different color spectra of hydrogen according to the production technologies used along with the various main characteristics of each type of hydrogen. Note that hydrogen is a colorless gas, and the following color assignment is purely used for differentiation of the hydrogen production method.

Both green and pink hydrogen are produced by electrolysis, applying electrical energy, from renewable or nuclear sources respectively, to split water into hydrogen and oxygen. It is therefore a CO₂ emission-free process, although for pink hydrogen the waste generated at the nuclear power plant is taken into account to measure its environmental impact.

On the other hand, gray and blue hydrogen are produced from natural gas or coal, in both processes CO₂ emissions are produced, with the difference that blue hydrogen is used as a method of capturing and storing part of the emissions generated at the end of the process. Finally, turquoise hydrogen is obtained by methane pyrolysis.

It should be noted that there are other colors for the classification of hydrogen such as black and brown hydrogen, produced by the gasification of black or brown coal (lignite) respectively, this production method generates high CO₂ emissions.

Table 2.1 shows that the relationship between environmental impact and economic performance is inverse, where the costs of production methods with lower environmental impact are higher. However, it is expected that by the year 2030, the costs of green and blue hydrogen will be reduced, improving economic performance (IRENA, 2020a).

Table 2.1: Hydrogen Color Spectrum and Characteristics. Sources: (NationalGrid, 2023), (Fernández et al., 2023), (Hermesmann & Müller, 2022)

Hydrogen Color	Green	Grey	Blue	Turquoise	Pink
Technology	Electrolysis	Steam Methane Reforming (SMR), Coal Gasification (CARB)	SMR, CARB with Carbon Capture and Storage (CCS)	Methane Pyrolysis	Electrolysis
Primary Feedstock	Water + Renewable Electricity	Natural Gas, Coal	Natural Gas, Coal	Natural Gas	Water + Nuclear Electricity
Output	H ₂ + Oxygen	H ₂ + CO ₂	H ₂ + CO ₂	H ₂ + Solid Carbon	H ₂ + Oxygen
Environmental Impact	Low (CO ₂ -free emissions)	High-CO ₂ emissions	Medium/Low CO ₂ emissions	Medium/Low (CO ₂ -free emissions)	Medium (CO ₂ -free emissions, Nuclear Residues)
Economic Performance	Medium/Low	High	Medium/Low	Low	Low
Technology Maturity	Commercial	Commercial	Commercial	Early-stage	Early-stage

2.2 Hydrogen End Use

It should be noted that hydrogen is considered an energy carrier (Sazali, 2020), in the same way as electricity. In other words, hydrogen is not a primary energy source, since it is not naturally available, and another energy source must be used for its production.

Hydrogen can have a variety of uses and applications in different sectors:

- **Industrial processes:** energy source for various industries such as petrochemical refinery, ammonia production for fertilizers, methanol production for chemicals and in the steel and iron industry (HydrogenCouncil, 2020).
- **Energy sector flexibility:** hydrogen can be used as a form of energy storage during renewable generation peaks when available energy is greater than electricity demand. This hydrogen can then be used for electricity generation in a flexible or off-grid power supply (Maestre et al., 2021).

- **Fuel and Transportation:** production of ammonia and synthetic fuels that can be used as fuel in the marine and aviation sectors. It can also be used directly in fuel-cell electric vehicles (Maestre et al., 2021).
- **Heat production in buildings:** hydrogen can be used for industrial, residential or commercial heating.

2.3 Green Hydrogen

2.3.1 Impact on energy development

Nowadays, a large part of global energy comes from fossil fuels. As a result, the global temperature of the planet and pollution levels in the atmosphere have increased significantly since the beginning of the industrial revolution. In 2022, global CO₂ emissions reached an all-time peak with a total of 36.8 Gt (IEA, 2023).

To reverse this situation, a large coalition of more than 70 countries, including China, the United States and the European Union, has set a net-zero emissions target. The goal is to prevent global temperature not to increase more than 1.5° C, as outlined in the Paris Agreement, so emissions must be reduced by 45% by 2030 and reach a total of zero emissions by 2050 (United Nations, 2023). It is expected that 90% of global emissions can be reduced with the use of renewable energy and improved energy efficiency to achieve the targets set for 2050 (IRENA, 2018).

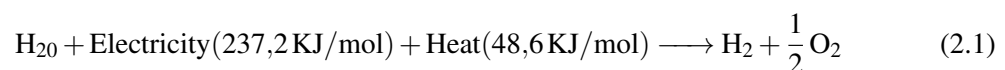
In the net-zero emissions scenario, hydrogen is set to play a key role in the decarbonization of the energy system, since its combustion does not emit pollutant emissions, especially green hydrogen, the production of which also has zero emissions due to the use of renewable energy. It offers great potential for replacing fossil fuels in the sectors that are most difficult to electrify, i.e. the sectors where renewables have the least impact (IRENA, 2021).

2.3.2 Green Hydrogen Production

2.3.2.1 Water Electrolysis

Green hydrogen is produced by the electrolysis of water, an electrochemical water-splitting technique powered by electrical energy from renewable sources: solar, wind or geothermal energy. This is the most sustainable production method because no emissions are emitted during the entire process.

Equation 2.1 (Shiva Kumar & Lim, 2022) shows the water electrolysis reaction:



There are four types of water electrolysis technology, these are:

1. Alkaline Water Electrolysis:

Electrochemical process in which an alkaline solution (KOH or NaOH) is used as an electrolyte to increase electrical conductivity. Applying an electric current to the alkaline water solution causes a chemical reaction that breaks down the water into hydrogen (H_2) and oxygen (O_2). At the cathode of the electrolyzer, the alkaline solution is reduced to form hydrogen (H_2) and hydroxide ions (OH^-). The hydrogen (H_2) produced is removed from the electrolyzer and the hydroxide ions (OH^-) are conducted through a separator, made of nickel or asbestos, to the anode, where the hydroxide ions (OH^-) are discharged producing oxygen (O_2) and water (H_2O). Operation temperatures of the process are low ($70 - 90^\circ C$). Figure 2.1 shows the operation of the alkaline electrolyzer.

Alkaline water electrolysis is an established technology for the production of green hydrogen, with a high level of commercialization and applications in industry. Some of the advantages of alkaline water electrolysis are relatively low cost and high operating stability. However, the purity of the gases produced is low compared to other hydrogen production technologies (99.9%) (IRENA, 2020b), (Shiva Kumar & Lim, 2022), (Kuckshinrichs et al., 2017), (Zoulias et al., 2004).

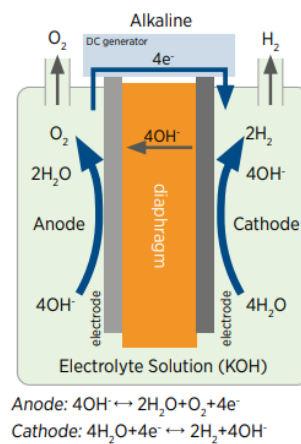


Figure 2.1: Operation of the alkaline electrolyzer. Source: (IRENA, 2020b)

2. Polymer Electrolyte Membrane (PEM) water electrolysis:

Through this process, water is separated into hydrogen (H_2) and oxygen (O_2). In the case of PEM water electrolysis, a polymer sulfate membrane is used as an electrolyte instead of a liquid solution. This polymeric material allows hydrogen ions (H^+) to pass through it. On the anode side of the electrolyzer, when an electric current is applied, water molecules (H_2O) are broken down to generate oxygen (O_2), hydrogen ions (H^+) and electrons (e^-). The hydrogen ions (H^+) travel across the membrane to the cathode side, where together with the electrons (e^-), which are also conducted to the cathode by the external circuit, they

recombine to produce hydrogen in the form of gas (H_2). Operation temperatures of the process are low (50 - 80°C). Figure 2.2 shows the operation of the PEM electrolyzer.

PEM water electrolysis is also a commercialized technology and is used for large-scale applications in industry. Some of the advantages over alkaline electrolysis are that it produces a higher gas purity (99.999%), the production process is faster and safer, and it also has high operating stability. However, the major disadvantage of PEM water electrolysis is the high cost of the components required for the electrolyzer (IRENA, 2020b), (Shiva Kumar & Lim, 2022), (Carmo et al., 2013), (Zoulias et al., 2004).

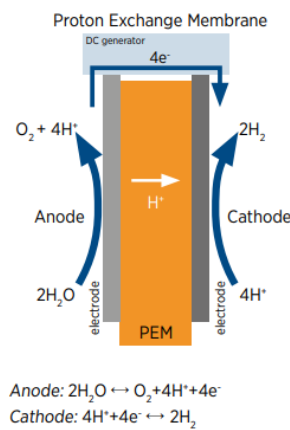


Figure 2.2: Operation of the PEM electrolyzer. Source: (IRENA, 2020b)

3. Anion exchange membrane (AEM) water electrolysis:

An electrochemical process in which an anion exchange membrane and electricity are used to produce hydrogen (H_2). On the cathode side of the electrolyzer, when an electrical current is applied, water molecules (H_2O) are reduced to form hydrogen (H_2) and hydroxide ions (OH^-). The hydrogen (H_2) generated is captured and the hydroxide ions (OH^-) are attracted to the anode side of the electrolyzer through the anion exchange membrane. Once there, the hydroxide ions (OH^-) recombine into water (H_2O) and oxygen (O_2). Operation temperatures of the process are low (40 - 60°C). Figure 2.3 shows the operation of the AEM electrolyzer.

AEM water electrolysis is a technology currently under development. Some of the advantages of this type of electrolysis are its low cost of the necessary electrolyzer components and its high performance. However, its operating stability levels are still too low to have an impact at the industrial level (IRENA, 2020b), (Shiva Kumar & Lim, 2022), (Zoulias et al., 2004).

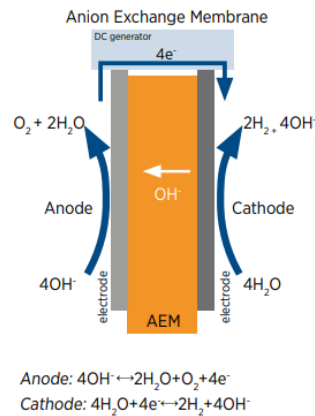


Figure 2.3: Operation of the AEM electrolyzer. Source: (IRENA, 2020b)

4. Solid oxide water electrolysis:

A process in which water (H_2O) is decomposed by applying electric current to produce hydrogen (H_2). However, unlike in the previous cases, the solid oxide water electrolysis process works at higher temperatures; and in this case, the water (H_2O) is in a gaseous state. Initially, at the cathode of the electrolyzer, the water molecules (H_2O) are reduced to hydrogen (H_2) and oxide ions (O^{2-}) when the electric current is applied. The hydrogen (H_2) generated is captured, and the oxide ions (O^{2-}) are transported through a ceramic electrolyte, capable of conducting these ions, to the anode side. Once at the anode, the oxide ions (O^{2-}) are reduced to generate oxygen (O_2) and electrons (e^-), which are transported back to the cathode by the electrical circuit. Figure 2.4 shows the operation of the Solid oxide water electrolysis electrolyzer.

In the electrolysis of solid oxide water, as it works at high temperatures ($700 - 850^\circ\text{C}$), the energy required for water separation is lower. Therefore, energy efficiency is higher than with other technologies, thus reducing operating costs. However, it has low operating stability, so it is still a developing technology (IRENA, 2020b), (Shiva Kumar & Lim, 2022).

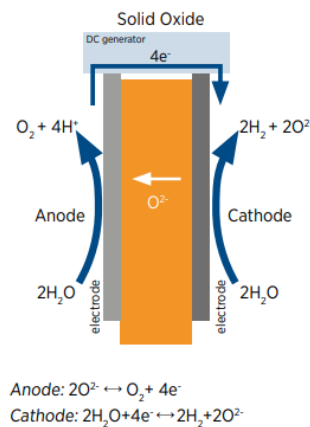


Figure 2.4: Operation of the solid oxide electrolyzer. Source: (IRENA, 2020b)

2.3.2.2 Electricity generation - Hybrid renewable energy system

In order to conduct the water electrolysis, the electrolyzer needs to receive electricity, in the case of green hydrogen must be renewable production. The two most promising types of renewable energy for green hydrogen production are solar photovoltaics and wind power.

First, solar photovoltaic electricity generation is one of the cleanest ways of generating hydrogen, but some of the negative points are its high installation costs and lower efficiency compared to gray hydrogen production (Olabi et al., 2021).

Although solar energy is an abundant and clean resource, the power output of solar photovoltaic panels is around 20-30% (Kontrosh et al., 2021). Therefore, solar photovoltaic energy has difficulty supplying the electrical demand required for hydrogen production. Another drawback is the fact that it is only capable of generating electricity during the day and when weather conditions are favorable.

On the other hand, wind energy is the most efficient, cheapest and cleanest way to produce green hydrogen compared to other renewable energy sources (Olabi et al., 2021). In addition, unlike solar photovoltaics, wind energy can operate both at night and during the day. However, wind energy is also very volatile and difficult to predict, so there can be complications in securing the electricity supply for hydrogen production.

To cope with this volatility of renewable energies, a promising solution has recently started to appear. This is the hybrid renewable energy system (HRES) (Sarker et al., 2023). The benefit of installing an HRES for hydrogen production is that by combining several renewable sources, usually solar and wind, an uninterrupted and constant supply can be guaranteed. So, for instance, when weather conditions do not satisfy one of the installed energies, the other can be producing since the conditions for this second source may be favorable.

2.4 Market

Due to the important role hydrogen may play in the future, the market and demand for hydrogen are expected to increase considerably in the coming years. Several studies have been consulted regarding demand forecasts for the hydrogen market. According to the World Energy Council, global demand for hydrogen currently stands at 90 Mt and is forecasted to increase to 110 Mt by 2030 (World Energy Council et al., 2021). For green hydrogen, the International Renewable Energy Agency (IRENA) forecasts a demand of 3 EJ (15 Mt) in 2030 and 19 EJ (95 Mt) in 2050 (IRENA, 2020a). It should be noted that, according to the same study, an overall hydrogen demand of 29 EJ (145 Mt) is forecasted for 2050. Therefore, two-thirds of the total hydrogen demand will be covered by green hydrogen. Finally, according to the Hydrogen Council, in a study described as ambitious but realistic, it forecasts that overall hydrogen demand will be 140 Mt in 2030, of which 20-30 Mt will be green hydrogen, and 660 Mt in 2050 (Hydrogen Council & McKinsey and Company, 2021).

It is important to note that the development of the hydrogen market depends on the installed renewable energy, i.e., without an exponential growth of renewable energy it will not be possible to guarantee the production of green hydrogen needed to achieve the Net-zero emissions targets. On the other hand, another decisive actor in the future of the hydrogen market are the countries with the actions and policies they elaborate to promote the development of hydrogen and its technology.

Several countries have developed roadmaps for hydrogen development. One of the biggest promoters of green hydrogen is the European Union, with the creation of the Hydrogen Strategy in July 2020 (European Commission & Directorate-General for Energy, 2020), whose objectives are to reach an installed water electrolysis capacity of at least 6 GW by 2024, and 40 GW by 2030. In addition, it intends to support neighboring countries to install an additional 40 GW by 2030, in order to export green hydrogen to Europe, thus becoming one of the largest markets for green hydrogen. Currently, the European Clean Hydrogen Alliance has approved more than 840 projects related to the production, distribution and applications of clean hydrogen (European Clean Hydrogen Alliance, 2022). Some of the countries within the EU with the greatest focus on green hydrogen development are Germany, which plans to install 6 GW of water electrolysis capacity in 2030 and 10 GW in 2040 (Federal Ministry for Economic Affairs and Energy (Germany), 2020); Italy, with the installation of 5 GW in 2030 (Ministry for Business and Made in Italy, 2020); Spain, with the installation of 4 GW in 2030 (Ministerio para la Transición Ecológica y el Reto Demográfico (MITERD), 2020); Portugal, with the installation of 2 - 2.5 GW in 2030 (Republica Portuguesa, 2020); and the Netherlands, that in 2020, in the Government Strategy on Hydrogen (Government of the Netherlands, 2020), stated the intention to install 4 GW for the year 2030. However, a new plan was presented in November 2022 to extend this target to 6.8 GW in 2030 (NautaDutihl, n.d.).

Outside Europe, other major powers are also developing hydrogen roadmaps. China, the world's largest hydrogen user and producer, is developing more than 30 green hydrogen projects (IRENA, 2022a). The United States of America, the second largest consumer and producer of hydrogen, has invested \$9.5 billion in green hydrogen technology development (Menezes et al., 2020). Japan, which was the first country to adopt a national hydrogen strategy, has invested about \$670 million in hydrogen technologies (Trade and Industry Ministry of Economy, 2017).

Other countries have a high potential to become major exporters of green hydrogen. This is the case of Chile, with a high renewable energy potential, which aims to install 5 GW of water electrolysis capacity by 2025 and reach 25 GW by 2030 (Correa et al., 2022). India aims to become a world center for the production and export of green hydrogen (National Portal of India, 2021). Finally, Morocco, in its national plan, mentions green hydrogen as a key sector to develop, due to its high renewable energy potential, and aims to become a major exporter of green hydrogen (Morocco Ministry of energy transition and sustainable development, 2021).

2.4.1 Hydrogen Transportation

Currently, 85% of hydrogen is produced and directly consumed on-site (IEA, 2019). Even when it is sold, it is not usually transported long distances due to logistical difficulties and costs.

However, over time, hydrogen may become a common form of international trade, as it can be used for energy transportation, for instance, a country with a surplus of renewable energy can use it to produce hydrogen, which can be transported to another country.

There are two methods of transporting hydrogen: by ship or by pipeline. New hydrogen pipelines can be built to transport hydrogen over medium/short distances (1500 - 4000 km), or existing natural gas pipelines can be retrofitted to transport hydrogen (8000 km). For long-distance transport, the best option is to transport hydrogen by ship. The hydrogen must be converted to liquid form because this gives a better energy density per volume. However, the most viable option is to produce ammonia by mixing hydrogen with nitrogen, since the energy density of nitrogen is higher than that of liquid hydrogen (IRENA, 2022a).

2.4.2 Hydrogen Costs

Currently, the production costs of green hydrogen are higher than those of conventional hydrogen. However, with the development and technological advances in electrolyzers, it is expected that costs will be reduced in the near future. On the other hand, most of the production costs of green hydrogen are directly related to the cost of electricity, therefore, advances in renewable energy can lower the cost of electricity, then, reducing the cost of hydrogen production (IRENA, 2020a), (World Energy Council et al., 2021).

Figure 2.5 shows a comparison of expected green hydrogen production costs according to (IRENA, 2020a) and the World Energy Council (WEC) (World Energy Council et al., 2021), compared to the expected price of blue hydrogen for the years 2030 and 2050. For both years, two scenarios are presented: the expected price best scenario in countries with high renewable energy potential, and the average price in countries with lower renewable energy capacity, average scenario, are shown. It is observed that in the year 2030, the price of hydrogen will be quite close to that of blue hydrogen in the countries with the highest renewable energy potential. By 2050, green hydrogen production is expected to be cheaper than blue hydrogen production in both scenarios.

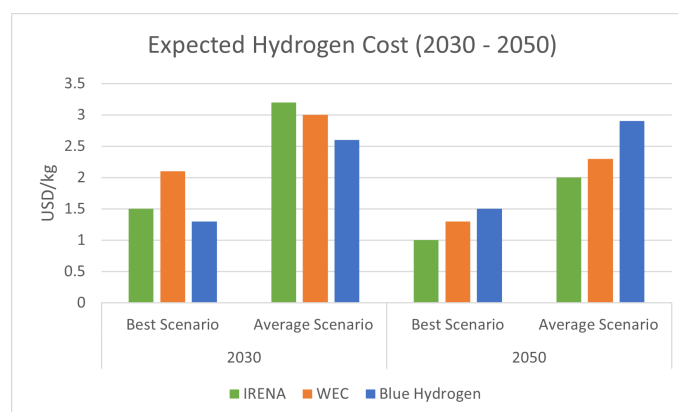


Figure 2.5: Comparison of expected green hydrogen production costs. Source: (IRENA, 2020a; World Energy Council et al., 2021)

Chapter 3

Description of the green hydrogen production problem

As already mentioned, green hydrogen can be a key factor in the decarbonization of the energy and industrial sector, helping to reduce dependence on fossil fuels, and contributing to achieving the goals set out in the Paris Agreement.

On the one hand, renewable energies, especially solar photovoltaic and wind energy, offer numerous advantages for the development of a more sustainable world. However, one of the major disadvantages is the fact that the production of renewable energy is subject to environmental factors so a constant supply of energy cannot be guaranteed. It is therefore important to develop systems to store this energy, such as batteries or in this case, green hydrogen, which can be produced by electrolysis of water, using surplus renewable energy during peak renewable production hours.

On the other hand, most of the industrial sector's hydrogen is produced from natural gas or coal, gray hydrogen and blue hydrogen. Therefore, the use of renewable energy for the production of green hydrogen will help reduce greenhouse gas emissions compared to the production of hydrogen from fossil fuels.

In the following chapter, the problem of green hydrogen will be presented, as well as the calculation required in order to solve the optimization model. At last, the different scenarios that will be tested will be presented with their respective values assumed for the resolution of the model.

3.1 Problem description

The primary purpose of this dissertation is to develop an optimization model for the installation of a hybrid renewable power generation plant or HRES, in this case, using wind and solar photovoltaic energy, with hydrogen production. The optimization model, from an initial given budget, shall determine the best combination of the number of wind turbines and the number of photovoltaic solar panels to install in order to maximize the profits from the hydrogen and electricity

sales. For it, the model shall take into account different cost and production parameters for both renewable energy and hydrogen, which will be explained in the next section.

Figure 3.1 shows a diagram of the complete system. In the first place, from the initial budget, the model will determine the number of wind turbines and the number of solar panels to install. With the initial inputs, which in this case are meteorological factors, like wind velocity and solar irradiance, and, installation and production costs, the model should consider, depending on the number of wind turbines and solar panels, the electricity that may be produced by the renewable generation park and the hydrogen that also may be produced by the electrolyzer. Finally, with the electricity and hydrogen selling prices, the model should maximize the profit obtained depending on the number of wind turbines and solar panels to install.

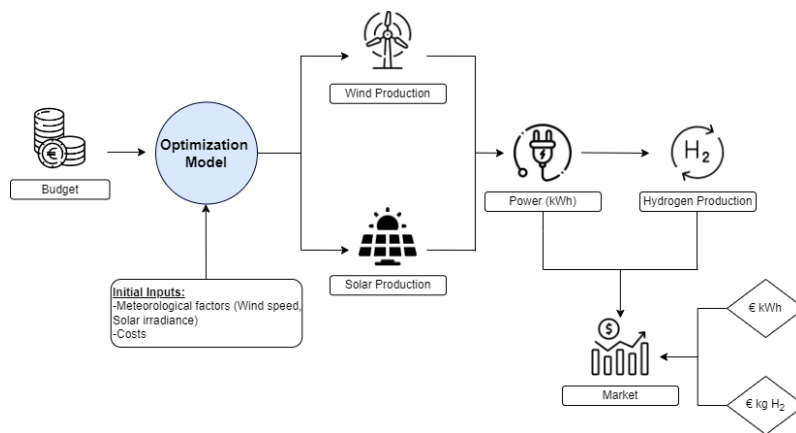


Figure 3.1: System diagram

Another objective of the dissertation is to utilize the model in order to study and analyze the results obtained in different scenarios and sensitivity analysis. It is important to note that the model will be tested in different regions of the Iberian Peninsula, Portugal and Spain, but it can be applied anywhere in the world by introducing the corresponding data on renewable resources and costs. Some of the questions to be explored are:

- What influence do the location of the park and the meteorological factors of the area/region have?
- What will be the best approach to hydrogen production: is it better to use it as a storage system for surplus renewable energy, or is it better to focus on the use of electricity mostly for hydrogen production in the industry?
- How will the evolution of the costs impact green hydrogen production in the following years?
- Can green hydrogen become a real alternative to other forms of energy such as fossil fuels in the future?
- Can the Iberian Peninsula become one of the largest suppliers of green hydrogen for the European market?

3.2 Energy and Hydrogen Production Calculation

In order to model green hydrogen production, there is a need to understand the calculation behind the cost and energy obtained by a wind, solar, and hydrogen plant. So, the following section will explain all the calculations needed to solve the optimization problem.

3.2.1 Wind power

First, the Levelized Cost Of Wind-Generation Electricity (*LCOWE*) is calculated in Equation 3.1 (Rezaei et al., 2021), which is the average cost to generate 1 KWh of electricity by the wind turbines:

$$LCOWE = \frac{\sum_{i=1}^n \frac{CI+OM+REP-ENV}{(1+f)^i}}{\sum_{i=1}^n \frac{Ew_{prod,i}}{(1+d)^i}} \quad (3.1)$$

Where *CI* is the capital investment required for the installation of the wind plant, *OM* is the operation and maintenance cost, *REP* is the replacement cost and *ENV* is the environmental cost. Note that *ENV* is introduced in a negative way since with wind energy no CO₂ particles are emitted, which means saving with respect to pollution costs. Continuing, *f* is the difference between the interest and inflation ratio, *d* is the degradation factor of the wind plant, *n* is the life of the project in years, *i* represents the individual number of years and *Ew_i* is the total electricity obtained in one year (KWh/year) by the wind plant. Equation 3.2 (Rezaei et al., 2021) shows the calculation of *Ew_{prod,i}*.

$$Ew_i = N_T \cdot C_R \cdot C_F \cdot 8760 \quad (3.2)$$

Where *N_T* is the total number of turbines installed, *C_R* is the turbine nominal capacity, *C_F* represents the turbine capacity factor and 8760 is the total hours in a year.

Equation 3.3 (Rezaei et al., 2021) shows how *C_F* is calculated:

$$C_F = \frac{e^{-(v_i/c)^k} - e^{-(v_r/c)^k}}{(v_r/c)^k - (v_i/c)^k} - e^{-(v_o/k)^k} \quad (3.3)$$

Where *v_i*, *v_o* and *v_r* are the cut-in, the cut-out, and the rated wind velocity respectively, which are turbine specifications; *k* is the parameter of shape and *c* is the parameter of scale. Equations 3.4 and 3.5 (Rezaei et al., 2021) show how *k* and *c* are calculated respectively, in which *v_m* is the mean wind speed and Γ represents the Gamma function.

$$k = 0.83 \cdot v_m^{0.5} \quad (3.4)$$

$$c = \frac{v_m}{\Gamma \cdot (1 + \frac{1}{k})} \quad (3.5)$$

3.2.2 Solar power

Following the same procedure as for the wind generation calculations, the Levelized Cost Of Solar-Generation Electricity (*LCOSE*) will be calculated for the solar generation, as shown in Equation 3.6:

$$LCOSE = \frac{\sum_{i=0}^n \frac{CI+OM+REP-ENV}{(1+f)^i}}{\sum_{i=1}^n \frac{ES_{prod,i}}{(1+d)^i}} \quad (3.6)$$

Where $ES_{prod,i}$ is the total electricity obtained in one year (KWh/year) by the solar plant. Equation 3.7 (Al-Sharafi et al., 2017) shows the calculation of ES_i .

$$ES_i = N_{PV} \cdot V_{PV} \cdot i_{PV} \cdot 8760 \cdot Pr \cdot Cl \quad (3.7)$$

N_{PV} is the number of PV modules installed, Pr is the performance ratio ($=0.75$), Cl is the additional capacity loss ($=0.21$), V_{PV} and i_{PV} are the voltage and the current of the PV module respectively, which should be calculated at their optimum operating point as shown in Equations 3.8 and 3.9 (Al-Sharafi et al., 2017):

$$V_{PV} = V_{mp} \cdot [1 + 0.0539 \cdot \log(\frac{I_t}{I_{st}})] + \beta_o \cdot \Delta T \quad (3.8)$$

$$i_{PV} = i_{SC} \cdot (1 - C_1 \cdot [e^{(\frac{V_{PV}-\Delta V}{C_2 \cdot V_{oc}})} - 1]) + \Delta i \quad (3.9)$$

Where Equations 3.10, 3.11, 3.12, 3.13, 3.14 and 3.15 (Al-Sharafi et al., 2017) show the formulas to calculate all the remaining factors:

$$C_1 = (1 - \frac{i_{mp}}{i_{SC}}) \cdot e^{(-\frac{V_{mp}}{C_2 \cdot V_{oc}})} \quad (3.10)$$

$$C_2 = \frac{\frac{V_{mp}}{V_{oc}-1}}{\ln(\frac{1-i_{mp}}{i_{SC}})} \quad (3.11)$$

$$\Delta V = V_{PV} - V_{mp} \quad (3.12)$$

$$\Delta i = \alpha_o \cdot (\frac{I_T}{I_{st}}) \cdot \Delta T + (\frac{I_T}{I_{st}} - 1) \cdot i_{SC} \quad (3.13)$$

$$\Delta T = T_{cell} - T_{st} \quad (3.14)$$

$$T_{cell} = T_A + 0.02 I_T \quad (3.15)$$

In which i_{SC} is the short-circuit current, V_{mp} is the maximum power voltage, V_{oc} is the open-circuit voltage, i_{mp} is the maximum power current, α_o is the temperature coefficient and β_o is the

voltage temperature coefficient; all of them are specifications of the PV module. I_T is the total solar radiation that the panel receives, I_{st} is the standard solar radiation (equal to 1000 W/m^2), and T_A is the ambient temperature.

3.2.3 Hydrogen production

Similarly to the previous calculations, for hydrogen production, the Levelized Cost Of Wind and Solar Hydrogen Production ($LCOWHP$ and $LCOSHHP$ respectively) is calculated, as 3.16 and 3.20 (Rezaei et al., 2021) shows. $LCOWHP$ and $LCOSHHP$ represent the cost of producing 1 kg of hydrogen by using wind and solar electricity respectively.

Where $C_{electrolyzer}$ and $C_{electricity}$ represent the costs of the electrolyzer and the electricity respectively, presented in 3.17 and 3.21 and 3.18 and 3.22 (Rezaei et al., 2021), and M_{H2} is the amount of hydrogen produced, presented in 3.19 and 3.23.

In which CI_h is the unit cost of the electrolyzer, E_e is the electric power required for the water electrolysis, η_e is the electrolyzer efficiency and t is the lifetime of the electrolyzer.

LCOWHP

$$LCOWHP = \frac{C_{electrolyzer} + C_{electricity}}{\sum_{i=1}^t M_{H2}} \quad (3.16)$$

$$C_{electrolyzer} = CI_h \cdot \frac{\sum_{i=1}^t M_{H2}^w \cdot E_e}{t \cdot 8760 \cdot CF^w \cdot \eta_e} \quad (3.17)$$

$$C_{electricity} = LCOWE \cdot \frac{\sum_{i=1}^n Ew_{prod,i}}{n} \quad (3.18)$$

$$MH2_w = \frac{Ew_{prod,i}}{E_e} \cdot \eta_e \quad (3.19)$$

LCOSHHP

$$LCOSHHP = \frac{C_{electrolyzer} + C_{electricity}}{\sum_{i=1}^t M_{H2}} \quad (3.20)$$

$$C_{electrolyzer} = CI_e \cdot \frac{\sum_{i=1}^t M_{H2}^s \cdot E_e}{t \cdot 8760 \cdot CF^s \cdot \eta_e} \quad (3.21)$$

$$C_{electricity} = LCOSE \cdot \frac{\sum_{i=1}^n Es_{prod,i}}{n} \quad (3.22)$$

$$MH2_w = \frac{Es_{prod,i}}{E_e} \cdot \eta_e \quad (3.23)$$

3.3 Scenarios

To obtain answers to the questions previously raised, the model will be tested in different locations and scenarios. This will serve as a way to validate that the model is working correctly and, at the same time, to conduct a deep analysis of which conditions are more favorable for green hydrogen production.

First of all, regarding the data required in order to model the optimization problem for wind, photovoltaic and hydrogen production the following sources were consulted:

- For wind data, **Global Wind Atlas** is an online platform that provides access to high-resolution wind resource data and tools for analyzing and visualizing wind energy potential at a global scale (Global Wind Atlas, 2023). Global Wind Atlas allows exploring wind data in interactive maps around different regions in the world, helping to identify suitable locations for wind farms.
- For solar data, **PVGIS (Photovoltaic Geographical Information System) Online Tool** is an interactive web-based platform developed by the European Commission's Joint Research Centre (JRC) (European Commission's Joint Research Centre, 2023). It provides valuable information and data for assessing the solar energy potential of specific locations worldwide. It also allows exploring solar data in interactive maps helping to identify the best locations for solar farms.
- For solar and wind costs, data was gathered from the IRENA report: **RENEWABLE POWER GENERATION COSTS IN 2021** (IRENA, 2022b). The report provides cost data for different renewable energy sources, including wind and solar photovoltaic. Allowing to consult costs for turbines, solar panels, fixed costs, installation costs, and maintenance costs.
- For electricity prices, the designated electricity market operator, known as OMIE was consulted, which is in charge of managing the daily and intraday electricity market in the Iberian Peninsula (Operador de Mercado Eléctrico Designado, 2023).
- For electrolyzer data, an IRENA report was also consulted: **GREEN HYDROGEN COST REDUCTION** (IRENA, 2020b). This report provides relevant data about electrolyzers including costs and performance. Additionally, the following master thesis from Politecnico Di Torino was consulted: Technical and economic analysis of state-of-the-art electrolytic systems for hydrogen production (Bosio, 2021), providing performance data about electrolyzers technologies.

Table 3.2 summarizes the different scenarios to be tested in the optimization model, these scenarios will be explained hereunder.

The two main factors to be studied are, firstly, the location of the plant, which will determine the amount of energy to be produced depending on the meteorological factors of wind and sun. The location will also have a direct impact on costs, where depending on the region or country the costs

may be higher or lower. Secondly, the role that hydrogen production will play, as hydrogen can be produced as a way to take advantage of surplus renewable electricity production, or, on the other hand, the majority of renewable energy production can be used for hydrogen production to meet the demand of some of the industries where hydrogen is required. In the first case (scenarios 1, 3 and 5), where hydrogen will be used as a storage system for the surplus of renewable generation, it will be considered that an 80% of the electricity generated will be sold in order to meet the electrical demand, while, the remaining 20%, that corresponds to surplus in renewable generation, will be used for hydrogen production. In the second case (scenarios 2, 4 and 6), in which the electricity produced for hydrogen production will be used to cover the hydrogen demand for the industry, it will be considered that 100% of the electricity generated by the renewable park will be used for hydrogen production.

By last, as the technology is expected to keep improving and becoming more efficient and cheaper, a sensitivity analysis will be conducted in order to study how the reduction in costs, both in renewable energy generation and in electrolyzers, will impact green hydrogen production around the world. It is expected that renewable generation costs will be reduced by around 20-35% by 2030 (IRENA, 2022b). So, two different scenarios will be tested for cost reduction, one less optimistic with a reduction in renewable costs of 20% (scenarios 3 and 4), and a second one, more optimistic, with a 35% of cost reduction (scenarios 5 and 6). On the other hand, water electrolyzers have a huge potential in terms of cost reduction, based on historical trends it is expected a cost reduction of around 40-80% by 2030. For the less optimistic scenario (scenarios 3 and 4), a 40% of cost reduction in hydrogen production will be considered and in the most optimistic scenario (scenarios 5 and 6), an 80% cost reduction will be considered. By last, regarding electrolyzer capacity for each scenario, different capacities will be tested depending on the potential of hydrogen production. For instance, for scenarios with less hydrogen potential (scenarios 1, 3 and 5) the electrolyzer capacity will be lower than for scenarios 2, 4 and 6, respectively, where when using all the electricity for hydrogen production, the hydrogen output is expected to be much higher so, a bigger electrolyzer will be needed.

Table 3.1 shows the prices for wind turbines, solar panels, and the electrolyzer.

Table 3.1: Cost of Renewable Energy and Electrolyzer. Source: (IRENA, 2022b)

Equipment	Cost (€/unit)
Wind Turbines	712.57 (€/kW)
Solar Panels	0.38 (€/W)
Electrolyzer	800 (€/kW)

Table 3.2: Scenario Comparison

Scenario	Electricity Use	Cost Reduction	Electrolyzer Capacity	Electricity and Hydrogen Price
1	80% Sale of electricity 20% Hydrogen production	None	1 MW	$Pe = 0.36/kWh$, $Ph = 6/kg$
2	100% Hydrogen Production	None	5 MW	$Ph = 6/kg$
3	80% Sale of electricity 20% Hydrogen production	20% Renewable generation 40% Hydrogen production	3 MW	$Pe = 0.3/kWh$, $Ph = 6/kg$
4	100% Hydrogen Production	20% Renewable generation 40% Hydrogen production	10 MW	$Ph = 6/kg$
5	80% Sale of electricity 20% Hydrogen production	35% Renewable generation 80% Hydrogen production	5 MW	$Pe = 0.27/kWh$, $Ph = 6/kg$
6	100% Hydrogen Production	35% Renewable generation 80% Hydrogen production	15 MW	$Ph = 6/kg$

Regarding wind turbines and photovoltaic panels, Table 3.3 and 3.4 show the specifications for the turbines and panels selected in the model respectively. Regarding the electrolyzer it should be noted that an AEM electrolyzer is selected for the calculations and resolution of the model. The rest of the parameters needed to solve the model are presented in Table 3.5:

Table 3.3: Wind turbine specifications

Model	Wind speed	Cr (kW)	vi (m/s)	vo (m/s)	vr (m/s)	Rotor diameter (m)	Hub height (m)
Vestas V110-2MW	6 - 7.5	2000	3	21	12	110	100
Vestas V100-2MW	7.5 - 8.5	2000	3	22	12	100	90
Vestas V117-3.45MW	8.5 - 10	3450	3	25	11.5	117	100

Table 3.4: Solar panel specifications

Model	Pmp (W)	Vmp (V)	Imp (A)	Voc (V)	Isc (A)	A (m ²)	α	β
TrinaSolar Vertex TSM	670	38.2	17.55	46.1	18.62	3,106,352	0.04%	-0.25%

Table 3.5: Terms and assumed values

Term	Description	Value
Budget	Budget Available for the installation of the plant	25 M€
CI	Capital Investment (Initial Investment) for the wind/solar plant: a) + b)	
a) Fixed part	Purchase of land, electrical inverters, labor, materials, etc.	Different value depending on the country (source)
b) Variable part	Cost purchase wind turbines/solar panels	See Table 3.1
OM	Operation and Maintenance Cost	$0.06 \cdot CI$ (Rezaei et al., 2021)
REP	Replacement cost (assumed no need of replacement for the lifetime of the plant)	0
ENV	Emissions CO ₂ prevented by using renewable production	0.277 kg CO ₂ /kWh (Rezaei et al., 2021)
f	Difference between interest and inflation rate - assumed 0.05	
d	Degradation factor wind turbines/solar panels - assumed 0.5	
Ee	Specific energy required by the electrolyzer in order to produce 1 kg of H ₂	47 kWh/kg (Bosio, 2021)
n	Solar and wind park lifetime	25 years for both
t	Electrolyzer lifetime	10 years

In the following section, the different locations to be studied will be presented.

3.3.1 Portugal

The first country where the model will be tested is Portugal. Portugal is one of the countries in Europe with more renewable energy generation potential, with a high level of solar irradiation and wind patterns. And despite the fact that Portugal does not have the cheapest costs for renewable energy production in Europe, according to (IRENA, 2022b), it is considered that Portugal can become one of Europe's major hydrogen producers due to this vast potential for renewable power generation. In addition, another advantage in favor of Portugal for the production of green hydrogen is its strategic position with respect to the maritime transport of green hydrogen due to its Atlantic coast, with important ports such as the port of Lisbon, Leixões, Sines and Aveiro. Thus, it can transport large quantities of hydrogen by sea to other European countries with less renewable potential for the production of green hydrogen.

Two locations will be tested for the Portugal scenario, one in the northern region of the country, Penafiel, and one in the south, Monchique. Figure 3.2 shows the locations chosen on the map of Portugal, together with the maps of solar irradiance and average wind speeds.

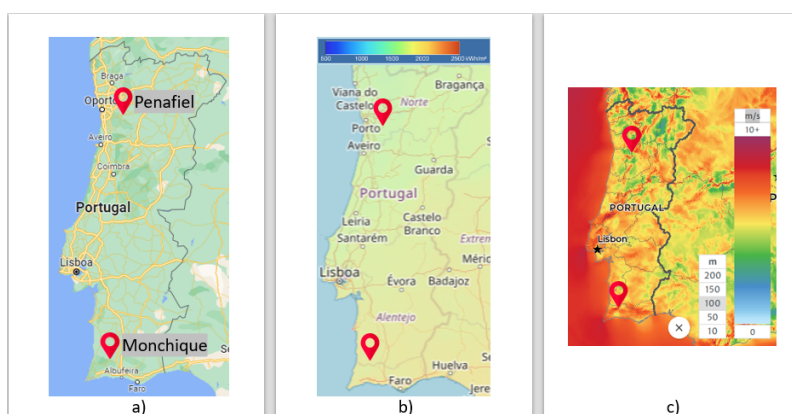


Figure 3.2: Portugal Locations. Sources: a) Google Maps, b) PVGIS, c) Global Wind Atlas

3.3.1.1 Penafiel, north of Portugal

The location selected for the northern region of the country will be Penafiel. This location is close to the metropolitan area of Porto, which is a region with one of the larger populations and industrial sectors in the country. Also, Penafiel is located less than 50 kilometers from Leixões port.

In this first location, both, wind and solar resources are not too high, with an average wind speed of 7.15 m/s (Global Wind Atlas, 2023) and with a solar irradiance of 1837.79 kWh/m² (European Commission's Joint Research Centre, 2023), compared to other regions with more renewable resources in the country. But, this will help to have a notion of profitability in places where the renewable resource is not so high.

Table 3.6 shows the values considered for Penafiel scenario calculations.

3.3.1.2 Monchique, south of Portugal

Monchique is a small town located in southern Portugal, in the Algarve region. This region has high solar and wind resource so it can be an ideal place for hydrogen production. The average wind speed is 8.29 m/s (Global Wind Atlas, 2023) and the solar irradiance is 2043.73 kWh/m² (European Commission's Joint Research Centre, 2023), being one of the regions with more potential for renewable generation and green hydrogen production. In addition, it is located less than 100 kilometers from the port of Sines, one of the biggest ports in the country, through which large quantities of liquefied natural gas are moved.

Table 3.6 shows the values considered for Monchique scenario calculations.

Table 3.6: Penafiel and Monchique Scenarios

Parameter	Penafiel	Monchique
Average Wind Speed (100m height)	7.15 m/s	8.29 m/s (Global Wind Atlas)
Solar Irradiance	1837.79 kWh/m ²	2043.73 kWh/m ² (PVGIS)
Available Area	40,000 m ²	40,000 m ²
Fixed Costs	4 M€	4 M€ (IRENA 2022)
Turbine Model	Vestas V110-2MW	Vestas V100-2MW
Solar Panel Model	TrinaSolar Vertex TSM	TrinaSolar Vertex TSM

3.3.2 Spain

Spain, as well as Portugal, is one of the European Union countries with the greatest potential for renewable energy generation. The two countries of the Iberian Peninsula could therefore position themselves as major producers of green hydrogen, helping to supply the demand for hydrogen in the rest of Europe. One of the advantages that Spain has over Portugal is that renewable energy installation costs are 9.33% cheaper than in Portugal, according to (IRENA, 2022b). In the case of Spain the model will also be tested for two different locations, and the results obtained will be analyzed.

It is decided to study first a location with high solar irradiance, but little wind resource, in this case, in the town of Llerena, located in the province of Badajoz. A second location will be explored, located in the province of Cadiz, in the town of El Almarchal, where both wind and solar resources are considerably high.

Figure 3.3 shows the locations chosen on the map of Spain, together with the maps of solar irradiance and average wind speeds.



Figure 3.3: Spain Locations. Sources: a) Google Maps, b) PVGIS, c) Global Wind Atlas

3.3.2.1 Llerena, Badajoz

Llerena is a small town located in the province of Badajoz in Extremadura. In this first location, the aim is to study how it will affect the model and its results when the solar irradiance is elevated, but the wind resource is not so high. In this case, the average wind speed at the location of the plant is 5.94 m/s and the solar irradiance is 2116.97 kWh/m²

Table 3.7 shows the values considered for Llerena scenario calculations.

3.3.2.2 El Almarchal, Cádiz

For the second location in Spain scenarios, the location El Almarchal was chosen, in the region of Cádiz, Andalusia. This region was selected due to its renewable resources for both wind and solar energy. The average wind speed in the region selected is 9.18 m/s. For this range of wind velocity a bigger turbine in terms of nominal capacity must be selected, so for this case, the wind turbine selected is the "Vestas V117-3.45MW" with a nominal capacity of 3.45 MW, in comparison with the turbines selected in the previous scenarios with 2 MW. Therefore, the El Almarchal scenario will provide additional analysis in order to understand how different technologies can impact green hydrogen production. On the other hand, the solar irradiation is 2136.73 kWh/m².

Also, as the renewable resource is elevated, it will be tested how a reduction in the sale price of electricity will affect it with respect to the previous scenarios. The selling prices are assumed as $Pe = 0.3/kWh$ for scenario 1, $Pe = 0.25/kWh$ for scenario 3 and $Pe = 0.2/kWh$ for scenario 5. Hydrogen selling price is assumed to be equal to the other scenarios, that is because green hydrogen demand is expected to keep growing as stated in chapter 2. So, in this way, it is possible to study if in the future can be more profitable to produce green hydrogen as the green hydrogen demand keeps growing.

Table 3.7: Llerena and El Almarchal Scenarios

Parameter	Llerena	El Almarchal
Average Wind Speed (100m height)	5.94 m/s	9.18 m/s (Global Wind Atlas)
Solar Irradiance	2116.97 kWh/m ²	2136.73 kWh/m ² (PVGIS)
Available Area	40,000 m ²	40,000 m ²
Fixed Costs	3.6268 M€	3.6268 M€ (IRENA 2022)
Turbine Model	Vestas V110-2MW	Vestas V117-3.45MW
Solar Panel Model	TrinaSolar Vertex TSM	TrinaSolar Vertex TSM

Chapter 4

Optimization Model

As described in Chapter 3, the objective of the optimization model is to determine the best configuration for the installation of a renewable energy park, including solar and wind energy, with green hydrogen production. For this purpose, the model will take into account different costs and production parameters of renewable energy and hydrogen production, including the land area available for renewable park development, the potential power generation capacity of wind turbines and solar panels, the efficiency of hydrogen production, electricity and hydrogen market prices, as well as operational and maintenance costs. Given an initial budget, the model will determine the optimal number of wind turbines and solar photovoltaic panels to be installed, aiming to maximize the profit, considering the interplay between selling renewable electricity and hydrogen production.

To solve the problem, a mixed integer programming model was developed, that was implemented with Python language, using the PuLP library, a flexible and efficient tool for formulating and solving optimization problems. Some of the benefits of using the PuLP library are:

1. User-Friendly Interface: PuLP allows to easily define and formulate the optimization model, simplifying the formulation of the decision variables, objective function and constraints.
2. Integration with Python ecosystem: PuLP library, being a Python library allows to integration of other Python capabilities like input-data manipulation, visualization, and analysis of the optimal results obtained using other Python libraries.

In the following Chapter, the optimization model will be described, explaining all the decision variables, constraints, linearization of parameters, and any relevant information needed in order to find the best solution.

4.1 Notation

As stated before, the goal of the model is to determine the number of photovoltaic solar panels and the number of wind turbines to install given an initial budget. Therefore, the model has two main binary decision variables. The decision variables $X_{T,j}$ and X_S represent whether j and p units of

wind turbines and PV panels are installed respectively. These decision variables determine the size or capacity of the wind and solar power generation systems. And, by manipulating these values it can be obtained the best combination that maximizes the profit from the plant. Then, $y_{S,p}$ will be introduced as a decision variable that will be needed for the Piecewise Linearization (PL) of the auxiliary decision variables *LCOSE* and *LCOSHP*.

Table 4.1 shows the notation and definition of the variables and parameters of the model.

Table 4.1: Notation Optimization Model

Indexes	
j	Turbine Units $j = [1, 2, \dots, J]$
p	PV panel intervals form PL $p = [1, 2, \dots, P]$ for <i>LCOSE</i> and <i>LCOSHP</i>
Decision Variables	
$x_{T,j}$	(= 1) if j wind turbines are installed
x_S	number of PV panels to install
$y_{S,p}$	(= 1) if the number of PV panels is within interval p from the PL of <i>LCOSE</i> and <i>LCOSHP</i>
Auxiliar Decision Variables	
<i>LCOSE</i>	Levelized Cost Of Solar-Generation Electricity
<i>LCOSHP</i>	Levelized Cost Of Solar Hydrogen Production
Parameters	
$W_{(sell)}$	Percentage of wind electricity to sell
$W_{(h)}$	Percentage of wind electricity for hydrogen production
$S_{(sell)}$	Percentage of Solar electricity to sell
$S_{(h)}$	Percentage of Solar electricity for hydrogen production
P_e	Electricity price
P_h	Hydrogen price
$LCOWE_j$	Levelized Cost Of Wind-Generation Electricity for j turbines
$LCOWHP_j$	Levelized Cost Of Wind Hydrogen Production for j turbines
$LCOSE_{a,p}$	Derivative PL function of the <i>LCOSE</i> PL function
$LCOSE_{b,p}$	Coordinate at the origin of the <i>LCOSE</i> PL function
$LCOSHP_{a,p}$	Derivative of the <i>LCOSHP</i> PL function
$LCOSHP_{b,p}$	Coordinate at the origin of the <i>LCOSHP</i> PL function
CI_j^w	Capital Investment for j turbines
OM_j^w	Operation and Maintenance cost for j turbines
REP_j^w	Replacement cost for j turbines
ENV_j^w	Environmental cost for j turbines
CI_p^s	Capital Investment for p PV panels
OM_p^s	Operation and Maintenance cost for p PV panels
REP_p^s	Replacement cost for p PV panels
ENV_p^s	Environmental cost for p PV panels
CI^h	Capital Investment for Hydrogen Electrolyzer
<i>Budget</i>	Available project budget
A_{turb}	Area occupied by a single turbine
A_{panel}	Area occupied by a single PV panel
$A_{available}$	Area available for the installation of turbines and panels
EW_u	Energy produced by a single turbine
ES_u	Energy produced by a single PV panel
J	Maximum number of turbine units
P	Number of intervals resulting from the PL of <i>LCOSE</i>
min_{x_p}	minimum of PV panels for interval p resulting for the PL of <i>LCOSE</i>
max_{x_p}	maximum of PV panels for interval p resulting for the PL of <i>LCOSE</i>

4.2 Parameter Linearization

In order to ensure a linear model, some parameters need to be linearized. Most of the parameters used in the model are constants calculated from the specifications of the solar panels or turbines and are linear. However, the calculation of the levelized costs ($LCOSE$, $LCOWE_j$, $LCOWHP_j$ and $LCOSHP$), by looking at their respective equations shows that the values as a function of the number of turbines/solar panels are not linear. To verify this, the value of these parameters have been calculated for different numbers of turbines/panels.

4.2.1 LCOWE

Figure 4.1 shows the value of $LCOWE_j$ for different numbers of turbines, ranging from 1 to 30 turbines. Indeed, it can be seen that the $LCOWE_j$ function follows an exponential relationship, so it should be linearized.

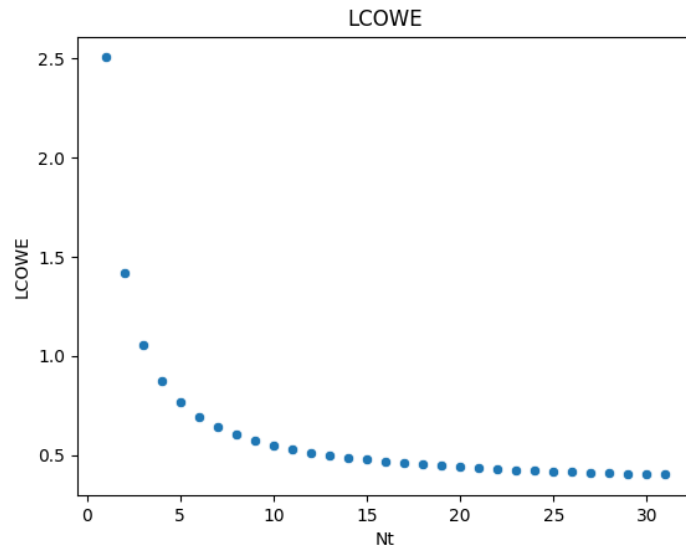


Figure 4.1: LCOWE function

As the range of the number of turbines is not very high, due to the high unit cost of each turbine, it has been decided to discretize the parameter, that is, for each number of turbines, the respective value of $LCOWE_j$, is used for that group these values were grouped in a table so that for each given number of turbines, $LCOWE_j$ will have a constant value.

4.2.2 LCOSE

Figure 4.2 shows the value of $LCOSE$ for different numbers of solar panels. In the case of solar energy, the range of solar panels is larger, because the unit cost of each solar panel is much lower than that of a wind turbine.

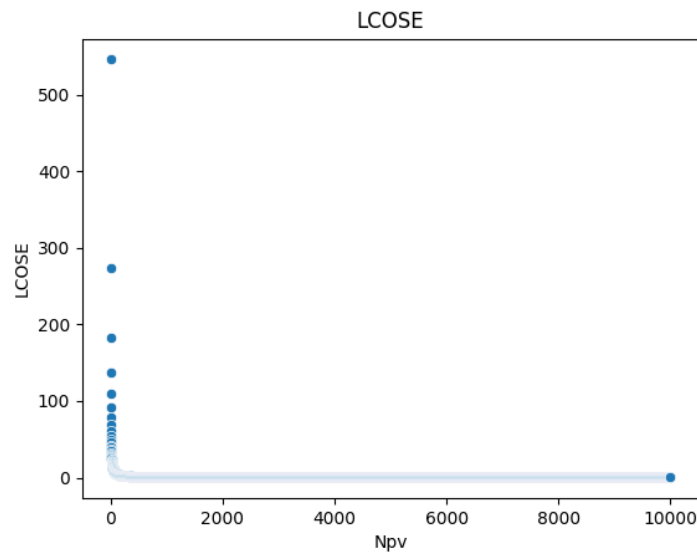


Figure 4.2: LCOSE function

It can be seen that the function follows a non-linear relationship, but that after a certain number of panels, the value of *LCOSE* starts to tend towards a constant value. Therefore, the method chosen in this case for the linearization is piecewise linearization, where the function is separated into different intervals. In this way, for each interval, a linear function is obtained, and the main function ends up being formed by *X* number of linear intervals. Figure 4.3 shows the piecewise linearization for the *LCOSE* function.

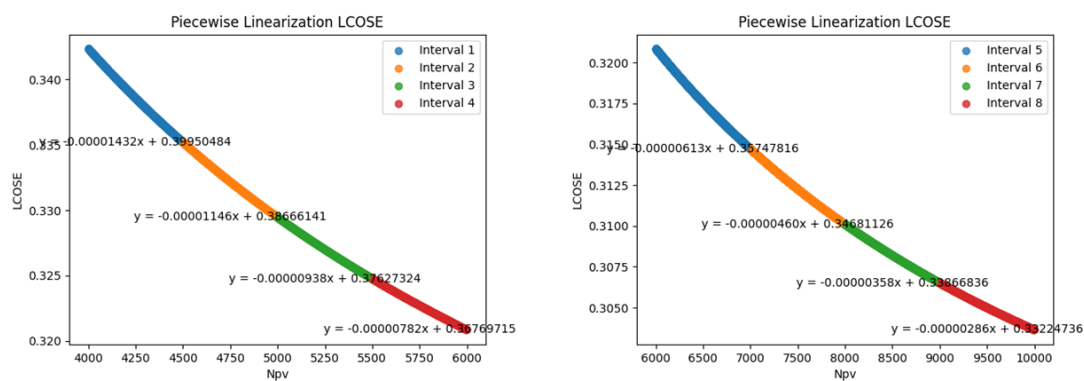


Figure 4.3: Picewise Linearization LCOSE

4.2.3 LCOWHP and LCOSHP

For the levelized cost of hydrogen production, a similar procedure will be followed. First, Figure 4.4 and Figure 4.5 show the behavior of the curves for the values of $LCOWHP_j$ and $LCOSHP$ respectively.

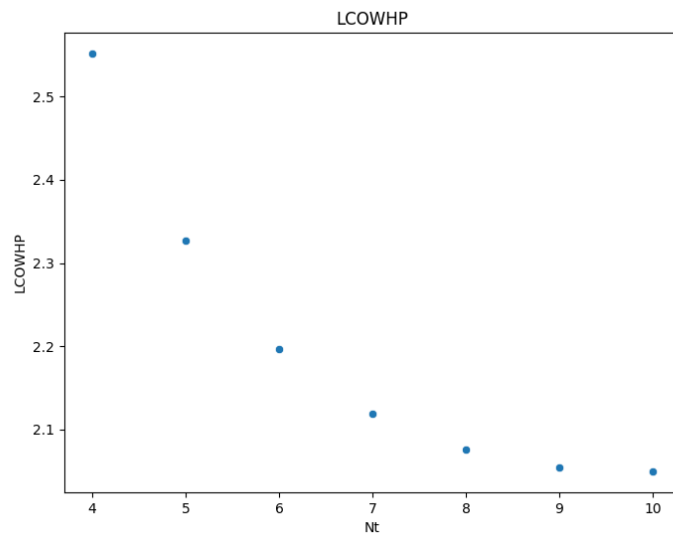


Figure 4.4: LCOWHP function

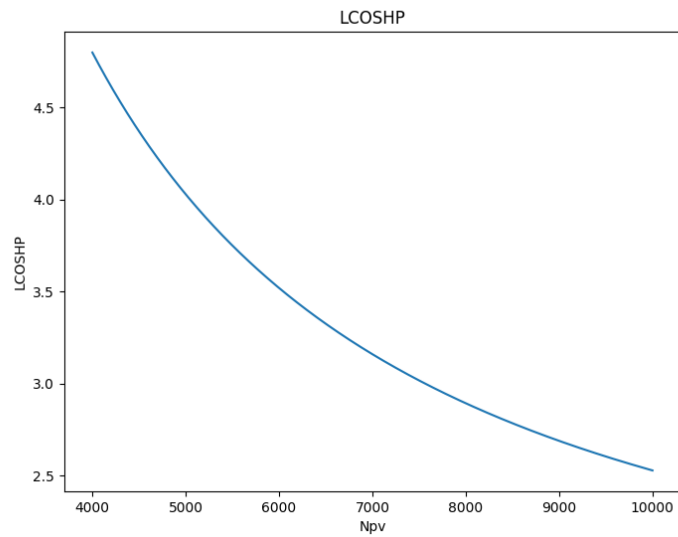


Figure 4.5: LCOSHP function

As in the previous cases, for the function of $LCOWHP_j$ the same procedure as $LCOWE_j$ will be applied, having a constant value for each value of x_T . On the other hand, for the function $LCOSHP$, a piecewise linearization will be applied in the same way as in the linearization of $LCOSE$, splitting the function into the same intervals and calculating their linear expression. Figure 4.6 shows the piecewise linearization for $LCPSHP$.

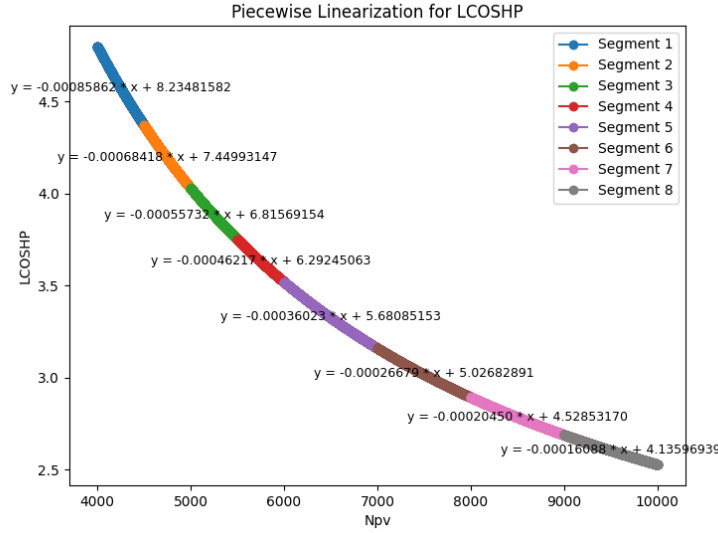


Figure 4.6: LCOSHP Piecewise Linearization

4.3 Mathematical Model

Objective Function:

Equation 4.1 shows the objective function of the optimization problem, where the goal is to maximize profit from the sale of electricity and hydrogen as a function of the configuration to be installed.

$$\begin{aligned}
 \text{Max} : & W_{(sell)} \cdot E_{w,u} \sum_{j=1}^J x_{T,j} \cdot (P_e - LCOWE_j) + S_{(sell)} \cdot E_{S,u} \cdot x_S \cdot (P_e - LCOSE) \\
 & W(h) \cdot \frac{E_{w,u}}{47} \sum_{j=1}^J x_{T,j} \cdot (P_h - LCOWHP_j) + S(h) \cdot \frac{E_{S,u}}{47} \cdot x_S \cdot (P_h - LCOSHP)
 \end{aligned} \tag{4.1}$$

Where, in the first part of the equation the profit of the sale of electricity from both wind and solar energy, $E_{w_{sold}}$ and $E_{s_{sold}}$ respectively, is calculated, by multiplying by the selling price of electricity, P_e , and then the corresponding generation costs are subtracted using the levelized cost of generating this electricity, $LCOWE_j$ and $LCOSE$. Then, in the second part, the same procedure is followed, where the electricity available for hydrogen production, $E_{w(h)}$ and $E_{s(h)}$, is divided by the conversion rate of the electrolyzer, where for producing a kg of hydrogen is required 47 kWh of electricity. And, the hydrogen produced by solar and wind energy is multiplied by the difference between the selling price of hydrogen Ph minus the levelized costs of producing 1kg of hydrogen by wind and solar energy $LCOWHP_j$ and $LCOSHP$ respectively.

Constraints:

The following constraints must be met in the model.

The sum of the initial and maintenance costs must be less than or equal to the total project budget, Equation 4.2:

$$\sum_{j=1}^J (x_{T,j}(CI_j^w + OM_j^w + REP_j^w + ENV_j^w)) + \sum_{p=1}^P y_{s,p}(CI_p^s + OM_p^s + REP_p^s + ENV_p^s) + CI^h \leq Budget \quad (4.2)$$

Where CI_j^w Capital Investment for j turbines, OM_j^w is the Operation and Maintenance cost for j turbines, REP_j^w is the Replacement cost for j turbines, ENV_j^w is the Environmental cost for j turbines, CI_p^s is Capital Investment for p PV panels, OM_p^s is the Operation and Maintenance cost for p PV panels, REP_p^s is the Replacement cost for p PV panels, ENV_p^s is the Environmental cost for p PV panels, CI^h is the Capital Investment for Hydrogen Electrolyzer and $Budget$ is the Available project budget

To ensure that the area occupied by the turbines and solar panels needs to be less than or equal to the total area available, Equations 4.3 and 4.4. One of the benefits of using an HRES is that turbines and solar panels can be installed together in the same area, so the area occupied by wind turbines can be less than or equal to the total available area, and the area occupied by solar panels can be less than or equal to the total of the available area

$$\sum_{j=1}^J x_{T,j} \cdot A_{turb} \leq A_{available} \quad (4.3)$$

$$x_S \cdot A_{panel} \leq A_{available} \quad (4.4)$$

Due to the Piecewise Linearization Equations 4.5, 4.6, 4.7 and 4.8 must be true, in order to assure that the correct interval from the piecewise linearization is calculated.

$$x_S \geq \min_x_p \cdot y_{S,p} \forall p \quad (4.5)$$

$$x_S \leq \max_x_p \cdot y_{S,p} + M(1 - y_{S,p}) \forall p \quad (4.6)$$

$$LCOSE \geq x_S \cdot LCOSE_{a,p} + LCOSE_{b,p} - M(1 - y_{S,p}) \forall p \quad (4.7)$$

$$LCOSHP \geq x_S \cdot LCOSHP_{a,p} + LCOSHP_{b,p} - M(1 - y_{S,p}) \forall p \quad (4.8)$$

For the decision variables associated with the piecewise linearization, the following constraints, Equations 4.9 and 4.10 must be followed:

$$\sum_{n=1}^j x_{T,j} = 1 \quad (4.9)$$

$$\sum_{p=1}^P y_{S,p} = 1 \quad (4.10)$$

Also, Equations 4.11, 4.12, 4.13 and 4.14 must be satisfied:

$$Ew_{(h)}, Es_{(h)}, Ew_{(sold)}, Es_{(sold)}, Es_{(prod)}, Ew_{(prod)}, \in \mathbb{R} \quad (4.11)$$

$$x_{T,j} \in (0, 1) \forall j \quad (4.12)$$

$$x_S \in \mathbb{N}_0 \quad (4.13)$$

$$y_{S,p} \in (0, 1) \forall p \quad (4.14)$$

Chapter 5

Results

In the following chapter, the results obtained from the scenarios presented in chapter 4 are shown. Also, the different results obtained will be commented and analyzed in order to understand better which conditions, technologies, and locations are better for green hydrogen production. First, the results for the different scenarios from each location will be analyzed, and then, at the end of the chapter, a comparison between the different locations will be conducted as well.

5.1 Penafiel, Portugal

Table 5.1 shows the results obtained for the different scenarios in the Penafiel location.

First of all, it can be observed that for all the calculated scenarios, the contribution of wind energy is much higher than the contribution of solar energy. This may be due to the fact that, for the available area, 40000 m², the maximum number of solar panels that can fit is a total of 10301, while in this same area, much higher power can be installed with wind turbines. Since it can be observed that the difference between the levelized costs for electricity (LCOWE and LCOSE) are quite similar for wind and solar energy. However, for hydrogen production, it can be seen that the costs of wind generation (LCOWHP) are lower than those of solar generation (LCOSHHP).

Another interesting result is the fact that for the scenarios in which electricity sales are prioritized and hydrogen is used as a form of storage of surplus renewable energy production (scenarios 1, 3 and 5) the benefits obtained are higher. This is because electrolyzer costs are high, and despite the cost reductions assumed and the expected growth in electrolyzer capacity, selling the electricity generated will be more profitable than using this electricity for aiming only at hydrogen production.

Table 5.1: Penafiel Scenario Comparison

Scenario	1	2	3	4	5	6
N° Wind Turbines	13.00	10.00	15.00	12.00	20.00	18.00
N° Solar Panels	4,524.00	9,301.00	10,301.00	10,301.00	8,923.00	10,301.00
Budget Used (€)	24,999,959.77	24,999,784.46	24,966,751.68	24,833,706.27	24,999,981.04	24,947,632.13
Profit (€/y)	6,397,112.70	5,211,932.13	8,133,441.86	6,337,222.35	11,607,155.16	10,301,144.03
Electricity sold (MW/y)	70,335.34	0.00	88,494.48	0.00	111,043.31	0.00
Hydrogen produced (kg/y)	299,299.32	1,330,025.26	376,572.27	1,569,597.15	472,524.73	2,196,125.55
Wind share contribution	90.71%	78.51%	83.19%	79.83%	88.39%	85.59%
Solar share contribution	9.29%	21.49%	16.81%	20.17%	11.61%	14.41%
LCOWE (€/kWh)	0.28	0.29	0.23	0.23	0.18	0.18
LCOSE (€/kWh)	0.34	0.28	0.23	0.27	0.23	0.21
LCOWHP (€/kg)	1.47	2.07	1.34	1.93	0.99	1.28
LCOSHP (€/kg)	1.95	2.13	1.40	2.08	1.24	1.48

5.2 Monchique, Portugal

Table 5.2 shows the results obtained for the different scenarios in the Monchique location.

For the Monchique scenario, more renewable resource is available for both solar and wind energy compared to the Penafiel scenario.

As in the previous case, for the Monchique location, the contribution of wind energy is much higher than the contribution of solar energy. Regarding the levelized costs, for the Monchique location, it can be observed that for both electricity generation and hydrogen production, when using wind energy (LCOWE and LCOWHP) the costs are considerably lower than when using solar energy (LCOSE and LCOSHP). This happens because the nominal capacity of the wind turbines is much higher than the nominal capacity of a single panel, so in the same available area, the wind turbines can offer more capacity in less space needed. This leads to a reduction of levelized costs. In a way that the model prioritizes the installation of wind turbines, and with the leftover budget it installs PV solar panels.

Again, the scenarios where electricity sales are prioritized, and hydrogen is used to store surplus renewable production (scenarios 1, 3, and 5), turn out to be more cost-effective and profitable than when the electricity produced is used for hydrogen production (scenarios 2, 4, and 6).

Table 5.2: Monchique Scenario Comparison

Scenario	1	2	3	4	5	6
N° Wind Turbines	13.00	10.00	16.00	13.00	20.00	19.00
N° Solar Panels	5,156.00	9,823.00	5,619.00	6,114.00	10,301.00	6,270.00
Budget Used (€)	24,999,884.37	24,999,902.14	24,999,823.08	24,999,934.96	24,975,351.47	24,999,996.41
Profit (€/y)	13,667,445.76	7,123,502.85	14,540,879.12	8,466,508.82	20,358,117.23	13,473,660.62
Electricity sold (MW/y)	88,885.69	0.00	108,226.34	0.00	140,564.73	0.00
Hydrogen produced (kg/y)	378,236.96	1,655,592.30	460,537.61	1,924,035.18	598,147.79	2,726,586.72
Wind share contribution	90.65%	79.65%	91.63%	89.10%	88.19%	91.90%
Solar share contribution	9.35%	20.35%	8.37%	10.90%	11.81%	8.10%
LCOWE (€/kWh)	0.22230566	0.22868545	0.17655533	0.18054270	0.14177724	0.14250476
LCOSE (€/kWh)	0.26827742	0.24391478	0.29612369	0.28063122	0.18806099	0.25517064
LCOWHP (€/kg)	1.15593907	1.62912582	1.02955287	1.51365534	0.78087484	1.00247573
LCOSHHP (€/kg)	1.77246472	1.96425204	1.68772624	2.30246523	1.04840195	1.69277723

5.3 Llerena, Spain

Table 5.3 shows the results obtained for the different scenarios in the Llerena location.

For the case of Llerena, where there is a low wind resource with an average wind speed of 5.94 m/s and a high irradiance of 2116.97 kWh/m², the aim is to analyze what happens when the wind energy resource is not very high and the solar irradiance is elevated.

First, for scenario 1 the model does not recommend installing wind turbines, since LCOWE is higher than the selling price of electricity. However, for scenario 2 it does recommend the installation of wind turbines. Then, analyzing the rest of the scenarios, it can be observed that a similar trend continues. For the scenarios in which all electricity is used for hydrogen production (scenarios 2, 4 and 6) a higher profit is obtained than in the scenarios in which the sale of electricity is prioritized. Thus, when the price of electricity sales is lower than the levelized costs of generating this electricity, for example during hours of low electricity demand, the production of green hydrogen is an alternative to increase the profitability of renewable power plants.

On the other hand, the costs of solar energy are lower than those of solar energy, so the model is prioritizing the installation of PV panels before wind turbines, and once the number of solar panels reaches the limit of available surface area, the model suggests the installation of wind

turbines. Therefore, if a larger area is available, the model would still prioritize the use of solar panels over the installation of wind turbines.

Table 5.3: Llerena Scenario Comparison

Scenario	1	2	3	4	5	6
N° Wind Turbines	0.00	10.00	15.00	12.00	19.00	18.00
N° Solar Panels	10,301.00	10,301.00	10,301.00	10,301.00	10,301.00	9,430.00
Budget Used (€)	6,991,806.38	24,974,661.76	24,749,617.33	24,581,149.76	24,488,677.49	24,999,850.91
Profit (€/y)	2,757,704.92	3,957,024.82	2,681,894.32	4,598,785.42	4,847,441.48	7,416,342.54
Electricity sold (MW/y)	17,215.75	0.00	71,153.85	0.00	85,537.35	0.00
Hydrogen produced (kg/y)	73,258.52	1,131,372.07	302,782.36	1,284,387.96	363,988.72	1,712,463.82
Wind share contribution	0.00%	67.62%	75.80%	71.48%	79.87%	80.42%
Solar share contribution	100.00%	32.38%	24.20%	28.52%	20.13%	19.58%
LCOWE (€/kWh)	0.00000000	0.39536234	0.30897398	0.31617507	0.24892001	0.25018336
LCOSE (€/kWh)	0.22024221	0.22024221	0.19257229	0.19257229	0.17181986	0.18080858
LCOWHP (€/kg)	0.00000000	2.81343011	1.79625274	2.63223495	1.36121109	1.74911887
LCOSHP (€/kg)	1.19960889	1.85291748	1.20022201	1.88619603	0.97202383	1.34096518

5.4 El Almarchal, Spain

Table 5.4 shows the results obtained for the different scenarios in the El Almarchal location.

For the last location, it was decided to study how a drop in electricity sales prices would affect the model with respect to the previous scenarios while the selling price of hydrogen remains constant. This could happen in a Scenario where massive investment in renewable energy would lead to a reduction in the selling price of electricity, due to the fact that it will be easier and cheaper to cover the electrical demand. Thus, the aim of the study in El Almarchal location is to understand how can evolve green hydrogen production with cheaper electricity.

In this case, wind power continues to be prioritized over solar PV power in terms of both percentage of generation and lower costs of electricity generation and hydrogen production. In fact, for scenarios 1 and 3 the model does not recommend the installation of solar panels, this is because the model prioritizes the installation of wind turbines, and with the remaining budget, it is not profitable to install solar panels because the number of solar panels would be very low, and therefore LCOSE would be higher than the selling price of electricity.

On the other hand, scenarios 1 and 3 still predominate over scenarios 2 and 4. Therefore, the sale of the electricity produced is still more profitable than the production of hydrogen with the present electrolyzer cost and with a 40% reduction on those costs, although, comparing scenarios 5 and 6 it is observed that the profit obtained is almost similar. So, in the future, with the development of electrolyzer technology becoming more efficient, reducing production costs considerably, and increasing the electrolyzer capacity production, as well as the demand for green hydrogen production will be as much as profitable as selling the electricity generated.

Finally, in the El Almarchal scenarios, the turbines selected are of higher power than those selected in the previous cases because the average wind speed is very high, 9.18 m/s. This results in a lower number of turbines to be installed, but at the same time, being higher power turbines, the electricity and hydrogen produced are higher than for other scenarios.

Table 5.4: El Almarchal Scenario Comparison

Scenario	1	2	3	4	5	6
N° Wind Turbines	8.00	6.00	10.00	8.00	12.00	11.00
N° Solar Panels	0.00	4,235.00	0.00	4,254.00	8,099.00	7,946.00
Budget Used (€)	24,327,304.12	24,999,972.53	24,730,693.17	24,999,954.53	24,999,907.99	24,999,958.91
Profit (€/y)	15,223,781.99	8,379,978.53	17,367,575.99	11,249,345.99	17,774,486.45	17,294,314.50
Electricity sold (MW/y)	105,160.42	0.00	131,450.53	0.00	171,406.56	0.00
Hydrogen produced (kg/y)	447,491.16	2,031,216.79	559,363.95	2,390,179.82	729,389.62	3,361,773.25
Wind share contribution	1.00	0.83	1.00	0.94	0.92	0.92
Solar share contribution	0.00	0.17	0.00	0.06	0.08	0.08
LCOWE (€/kWh)	0.17684305	0.18176776	0.13991942	0.14287424	0.11247281	0.11336821
LCOSE (€/kWh)	0.00000000	0.35894619	0.00000000	0.31856326	0.19488305	0.19688432
LCOWHP (€/kg)	0.92158628	1.30522011	0.82014275	1.21254252	0.61904614	0.80349839
LCOSHP (€/kg)	0.00000000	2.50634486	0.00000000	2.47978411	1.08072324	1.41745939

5.5 Comparison between locations

After analyzing each Location individually, now, the results from the different locations will be compared in order to understand better how different factors can impact green hydrogen production.

Figure 5.1 and Figure 5.2 show a comparison of relevant results for the different locations. From which it can be observed:

- Nowadays, the production of green hydrogen is less profitable than directly selling the renewable electricity produced as scenarios 1, 3 and 5 showed, but in a future where electrolyzers cost may reduce considerably, green hydrogen production may become as profitable as selling generated electricity. Anyways, green hydrogen production during the surplus of renewable resources could be established as an alternative for energy storage, such as batteries, due to the shortage of materials to produce them.
- **Profit:** The more renewable resources, especially wind, the greater the benefit obtained, in this case for the locations of El Almarchal (Spain) and Monchique (Portugal) resulted to be the more profitable.
- **Electricity and Hydrogen production:** The same is true for the electricity and the hydrogen sold, the greater the renewable resources, the greater the production, being El Almarchal the location with bigger wind and solar resources being the most profitable in terms on production and, on the other hand, Llerena is the location with less wind resource and the location with less production.
- **LCOWE and LCOWHP:** For the wind levelized cost, again, the locations with a bigger wind resource are the most favorable with lower costs.
- **LCOSE and LCOSHP:** However, for the levelized cost, the lower values are obtained in the scenarios where more solar panels are installed. And, as solar panels in most scenarios were used as a complement of the wind turbines with the remaining budget, the results are more irregular. Anyways, Llerena was the location where more solar panels were installed and therefore, the location with lower LCOSE and LCOSHP.

In summary, locations with higher wind resources have proven to be more optimal for green hydrogen production, while solar energy has been used as a complement, in most scenarios, to take advantage of some percentage of the remaining budget of the wind turbine installation. This is because the possible power to be installed in a given area is much higher using wind turbines, which have a larger nominal power capacity, while the possible power to be installed from solar photovoltaic panels is very limited to the available area so in order to match the installed power of wind turbines would require an extremely large area.

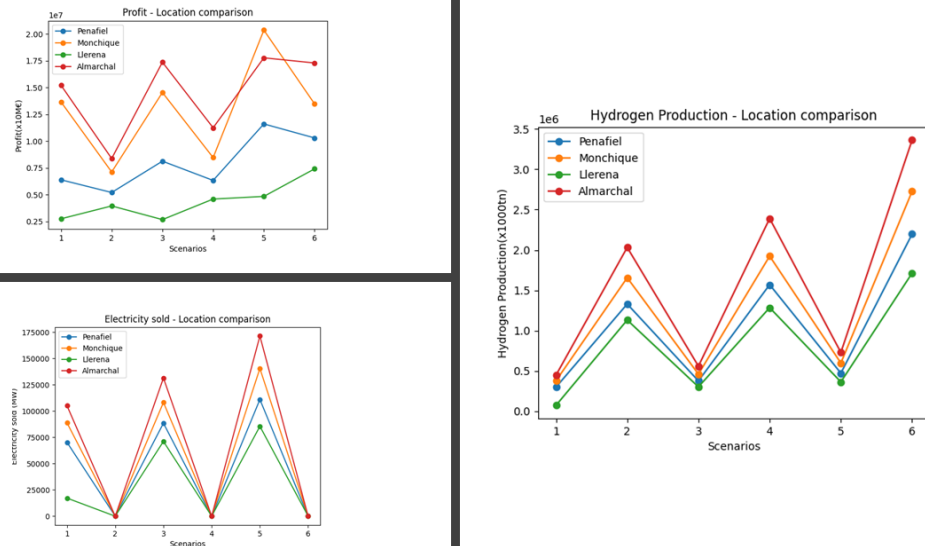


Figure 5.1: Locations Comparison Results 1

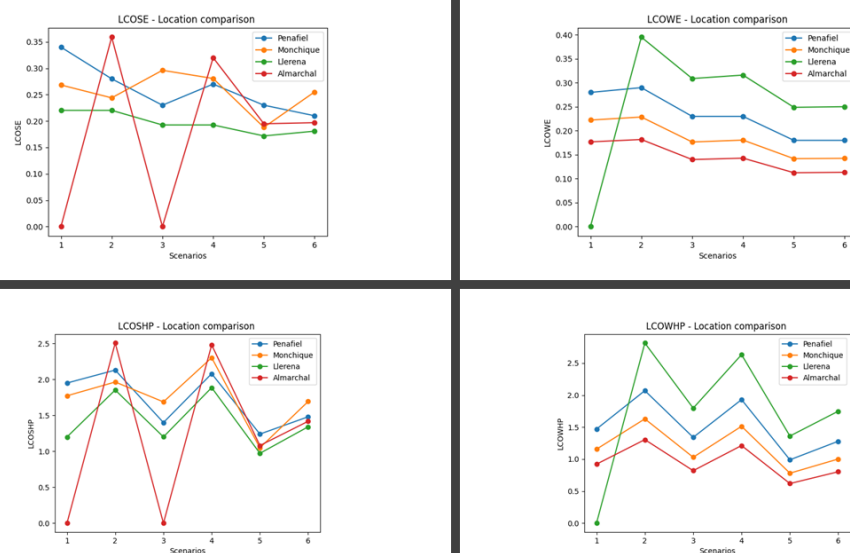


Figure 5.2: Locations Comparison Results 2

Chapter 6

Conclusions and future work

This dissertation presented an optimization model for the installation of a green hydrogen production plant powered by a hybrid renewable energy system composed of wind and solar photovoltaic energy. The optimization problem has been implemented with the PuLP library in Python programming language. The main goal of the optimization problem was to maximize the profits from selling electricity and hydrogen produced in the plant. For this, the model had to select the best combination of wind turbines and photovoltaic solar panels to install given an initial budget of 25M€.

Another main goal of this dissertation was to analyze the results obtained from applying the optimization model in different locations in the Iberian Peninsula, as it is expected that both countries will become the main producers of green hydrogen in Europe due to their vast renewable energy resources potential. the following list summarizes the main conclusions achieved:

- Wind energy is the most promising renewable source for the production of green hydrogen, due to its high power rating and lower costs compared to solar energy. Also, by installing bigger turbines, as seen in El Almarchal scenarios, electricity and hydrogen production may increase.
- Photovoltaic energy can act as a good complement to wind energy in order to guarantee the supply when wind resources may not be available. However, the payback for the investment is not so high.
- Nowadays, the production of green hydrogen is less profitable than directly selling the renewable electricity produced, but in a future where electrolyzers cost may reduce considerably, and electrolyzer capacity increase, green hydrogen production may become as much as profitable as selling the electricity generated and could become an alternative to the use of fossil fuels helping to reduce CO₂ emissions in several sectors as transportation or industry. In fact for the more optimistic Scenarios, the profitability of selling the electricity generated or using this electricity to produce green hydrogen was almost the same.

- The Iberian Peninsula has the potential to become the main producer of green hydrogen in Europe, due to the vast renewable resources in Spain and Portugal. But a further comparison with other European countries must be conducted in future works.

6.1 Objectives achieved and limitations

The optimization model created is able to provide relevant information when analyzing the investment of a green hydrogen production plant from hybrid generation with solar energy, helping to determine the best configuration of wind turbines and panels to install, distributing the available budget in the most efficient way and maximizing the profit obtained from the sale of electricity and hydrogen. This model can also help to understand which locations, countries, or regions have more potential giving annual estimations of the electricity and hydrogen to be produced and to understand how costs and meteorological data can affect the final output. Note that the model was only tested in Portugal and Spain, but could be tested in any region by introducing the corresponding meteorological data and costs from the region.

However, most of the data collected came from reports and academic papers, due to the difficulty of obtaining real data from wind and solar suppliers. Also, the meteorological data gathered from PVGIS and Global Wind Atlas can provide a good approximation of the renewable resources in the selected locations, but in order to gather more accurate data a deeper study must be conducted by installing meteorological measuring equipment in the different locations. At last, another limitation of the model is the fact that the price of electricity varies throughout each hour of the day and throughout each day of the year. However, when calculating the model on an annual basis, an average fixed value for the price of electricity over the year had to be defined.

6.2 Future work

Based on the obtained results and knowing the main limitations of the model, in future work will be interesting to study the following approaches:

- To explore and test the model in other locations where green hydrogen production has great potential, such as countries with huge renewable potential (Chile, Brazil, Australia or Morocco), and countries with lower renewable costs (India or China).
- To compare the option for green hydrogen production as a storage system for a surplus of renewable energy with the option of using batteries. Or a hybrid system with hydrogen storage with batteries.
- To make a model based on hourly rather than annual data, for wind, solar and electricity price data, where it would be possible to analyze during which hours of the day it is convenient to produce hydrogen or to sell the electricity to the grid.

- To conduct a deeper study of the meteorological data in the locations selected by installing the appropriate measuring equipment, or purchasing this meteorological data from companies that offer this information.
- To integrate the price of the transportation to future models will provide additional valuable analysis.

6.3 Summary

During this dissertation, an optimization model for the installation of a green hydrogen power plant was developed. Helping to maximize the profits obtained by choosing the best configuration to be installed regarding wind turbines and solar panels. Also, several locations were tested in the Iberian Peninsula in order to understand how renewable resources could impact hydrogen production.

For the production of green hydrogen, wind energy is more efficient than solar energy, also, nowadays is not as profitable to produce hydrogen as to sell the electricity produced from renewable sources, but in a next future, with the reduction of costs and the improvement of technology green hydrogen can become a strong alternative to the use of fossil fuels during the production process of other techniques such as grey hydrogen, helping to decarbonize different industrial and transportation sectors.

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