IPS Instituto Politécnico de Setúbal
Escola Superior de Tecnologia do Barreiro

FLÁVIA INÊS DE SOUSA FRANCO

MODELING OF A HYDROGEN PRODUCTION PLANT SUPPORTED BY WIND AND SOLAR PHOTOVOLTAIC SOURCES

Research Dissertation Report of the Master's Degree in Biological and Chemical Engineering

ADVISOR
Doctor Fátima Serralha

SUPERVISOR
Doctor Rui Borges

October 2020

FLÁVIA INÊS DE SOUSA FRANCO

MODELING OF A HYDROGEN PRODUCTION PLANT SUPPORTED BY WIND AND SOLAR PHOTOVOLTAIC SOURCES

JURY

President: Doctor Lurdes Gameiro, ESTBarreiro/IPS
*Supervisor**:*** Doctor Rui Borges, Direção Geral de Energia e Geologia
Member: Engineer João Marques, Lisboagás – Sociedade Distribuidora de Gás Natural de Lisboa, S.A. – yielded to Galp Energia S.A.

October 2020

“I cannot teach anybody anything. I can only make them think.”

Socrates

ACKNOWLEDGMENTS

I want to leave a special thanks to all those who accompanied me on this journey and who have somehow contributed to its realization.

First of all, I want to thank my family for everything, for the affection, love and especially for patience.

To Pedro for all the love, affection and patience over the last few months.

To Raquel and Viriato for their unconditional support and encouragement throughout all the years of friendship.

To Nuno, Alexandre, Sofia and the others for the companionship and consideration in these last 2 years.

To my advisor Rui Borges for the tireless help, the support provided throughout the time and for the learning opportunity.

To my co-advisor Fátima Serralha for affection, support and always good mood.

To the DGEG team for the prompt readiness to receive me and for all the help provided.

To the Secretary of State, João Galamba, and his team for participating in the discussion of results.

To all of you, my sincere thanks.

RESUMO

Cada vez mais é notório o impacto ambiental ao qual o planeta Terra se encontra sujeito devido ao consumo energético da humanidade. Uma das consequências deste consumo energético são as alterações climáticas, provocadas pelas emissões e acumulação de gases com efeito de estufa na atmosfera, em particular de CO_2. Por essa razão, as alterações climáticas tornaram-se um tema fulcral do debate político, que se tem centrado na discussão do tipo de medidas a adotar para mitigar o impacto das alterações climáticas, mas também para, no médio/longo prazo, controlar as suas causas. Portugal sendo um dos membros integrantes da União Europeia e duplo signatário do Acordo de Paris adotou objetivos ambiciosos para atingir a neutralidade carbónica até 2050, permitindo a criação de modelos de consumo energético mais sustentáveis, resilientes e ordenados para os objetivos pretendidos.

Neste âmbito, o hidrogénio apresenta-se como um pilar sustentável e complementar do sector energético, podendo ser utilizado na estratégia de transição para uma economia descarbonizada. Deste modo, Portugal aprovou recentemente uma Estratégia Nacional para o Hidrogénio, que entre os seus objetivos prevê a instalação de um projeto industrial de produção de H_2 através da eletrólise da água, alimentado por parques renováveis dedicados (com base em energia solar fotovoltaica e/ou energia eólica) e que terá sede em Sines.

Esse projeto industrial constitui o objeto de estudo da presente dissertação. Neste trabalho usámos o software energyPLAN para construir um modelo de simulação do funcionamento desse projeto industrial. Primeiramente foram elaborados diversos cenários para a avaliação do projeto tendo em conta diferentes condições meteorológicas e modos de produção. De seguida procedeu-se à análise em termos técnico e económicos.

Os resultados obtidos permitiram concluir, do ponto de vista técnico que a fonte eólica apresenta-se como uma fonte de produção mais rentável do que a potência fotovoltaica. A instalação de uma central de produção de hidrogénio requer vultuosos investimentos sendo os eletrolizadores a componente mais exigente do ponto de vista de investimento de capital. Por essa razão, as soluções em que se obtém maior produção anual de H_2 não são necessariamente as soluções mais interessantes do ponto de vista económico, verificandose que os resultados economicamente mais rentáveis requerem somente 1 GW de eletrolisador alimentados por energia solar fotovoltaica. Numa perspetiva futura, conclui-se que, do ponto de vista dos custos de produção por unidade de produto, há uma gama relativamente ampla de expectativas de retorno do investimento para a qual o hidrogénio verde será capaz de competir com o hidrogénio produzido através de combustíveis fósseis.

Palavras-chave: hidrogénio, eletrólise, cenarização, eólica, fotovoltaica.

ABSTRACT

The environmental impact to which planet Earth is subject is increasingly evident due to the energy consumption of humanity. One of the consequences of this energy consumption is climate change, caused by emissions and the accumulation of greenhouse gases in the atmosphere, in particular CO_2. For this reason, climate change has become a central theme of the political debate, which has focused on discussing the type of measures to be taken to mitigate the impact of climate change, but also, in the medium/long term, to control its causes. Portugal, being one of the European Union's members and a double signatory to the Paris Agreement, adopted ambitious goals to achieve carbon neutrality by 2050, allowing the creation of more sustainable, resilient and orderly energy consumption models for the intended objectives.

In this context, hydrogen presents itself as a sustainable and complementary pillar of the energy sector and can be used in the strategy of transition to a decarbonized economy. In this way, Portugal recently approved a National Hydrogen Strategy, which among its objectives foresees the installation of an industrial H_2 production project through water electrolysis, powered by dedicated renewable parks (based on photovoltaic solar energy and/or wind energy) and will be based in Sines.

This industrial project is the object of study of this dissertation. In this work we used the energyPLAN software to build a simulation model for the operation of this industrial project. First, several scenarios were developed for the evaluation of the project taking into account different weather conditions and production methods. Then, the analysis was carried out in technical and economic terms.

The results obtained allowed us to conclude, from a technical point of view, that the wind source is presented as a more profitable production source than the photovoltaic power. The installation of a hydrogen production plant requires large investments, with electrolyzers being the most demanding component in terms of capital investment. For this reason, the solutions in which greater annual H_2 production is obtained are not necessarily the most interesting solutions from an economic point of view, as the most economically profitable results require only 1 GW of electrolyzer powered by photovoltaic solar energy. In a future perspective, it is concluded that, from the point of view of production costs per unit of product, there is a relatively wide range of expectations of return on investment for which green hydrogen will be able to compete with hydrogen produced by fuels fossils.

Keywords: hydrogen, electrolysis, scenarization, wind, photovoltaic.

GENERAL CONTENTS

Contents

LIST OF FIGURES

LIST OF TABLES

SYMBOLS AND ABBREVIATIONS

CCTG	Combined cycle gas turbine
CER	Chlorine evolution reaction
CH_3OH	Methanol
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon Dioxide
DGEG	Directorate-General for Energy and Geology
EU	European Union
FCs	Fuel cells
GFEC	Gross Final Energy Consumption
GHG	Greenhouse gas
H&C	Heating and cooling
H_2	Hydrogen
HER	Hydrogen evolution reaction
KOH	Potassium hydroxide
Kt	Kilotons kt
LCOE	Levelized cost of electricity
LCOH	Levelized cost of hydrogen
LULUCF	Land Use, Land-Use Change and Forestry
Mt CO_2eq.	Million equivalent metric tonnes of carbon dioxide
NaCl	Sodium chloride
NaOH	Sodium hydroxide
NECP	National Integrated Energy and Climate Plan

NH_3	Ammonia
NZEB	Near-zero energy buildings
O&M	Operation and maintenance
OER	Oxygen evolution reaction
PA	Paris Agreement
PEM	Polymer electrolyte membrane
PSA	Pressure swing adsorption
PV	Solar photovoltaic
RES	Renewable energy sources
RNC2050	Roadmap for Carbon Neutrality 2050
STM	Steam methane reforming
TMN	Transition metal-nitride
Toe	Tons of oil equivalent
VGO	Vacuum gas oil

1. Introduction

Over the last few decades, the negative impact of CO_2 emissions that the planet has been subjected to has become more notorious. It is now clear that the energy consumption patterns will have to change very quickly, and on a global scale, if the worst effects of climate change are to be avoided. In 2015, the Paris Agreement (PA) defined that paradigm changes in society are necessary so that the average global temperature does not exceed 1.5°C above the pre-industrial average, in order to control the effects of climate change. Portugal, being a double signatory of the PA prepared a roadmap for identifying decarbonization vectors and their potential of reduction on the diverse national economic sectors. Under the framework of this roadmap, Portugal developed a National Energy and Climate Plan and recently adopted a National Hydrogen Strategy, in which, lays out the role of hydrogen as an integrated and sustainable pillar in the energy transition.

This dissertation work aims to analyze the operation of an H_2 production plant from the electrolysis of water, with characteristics similar to those of the project announced for the Sines region by the National Hydrogen Strategy. Given the fact that this industrial project intends to satisfy most of its energy needs based on dedicated solar and wind power, the analysis involves the dimensioning of renewable production plants of these same resources.

The main objective will be the production of H_2 from which various scenarios with different characteristics of the photovoltaic and wind power plants will be modeled and evaluated.

This dissertation contains 5 chapters. The current chapter presents a brief introduction to the theme under study and the objectives intended for its implementation.

Chapter 2, corresponding to the literature review, is divided into sub-chapters and aims to contextualize the Portuguese energy system and its future perspectives, hydrogen and its properties, and also the expected role of hydrogen in the energy system of Portugal.

The energy system modeling in chapter 3 compares different types of software in modeling and selects the most appropriate one for the analysis of this project. Also, it describes the methodology defined for the technical and economic analysis of the industrial plant.

The obtained results from the technical and economic project are described in chapter 4.

Finally, all the conclusions and perspectives for future work are described in chapter 5.

2. State of the art

2.1 The Portuguese energy system

Currently, the Portuguese energy system is in a transition period that aims to expand the use of renewable energy sources (RES) in order to reduce greenhouse gas (GHG) emissions and energy imports dependency.

These objectives are framed by a legislative package promoted by the European Union (EU), called 2020 Climate and Energy package, established that by 2020 member states should achieve a reduction of 20% in GHG emissions relative to 2005, the introduction of 20% of RES in Gross Final Energy Consumption (GFEC) with a sectoral target of 10% RES in transport, and 20% savings in Primary Energy Consumption achieved by gains in energy efficiency. These gains are measured against the projections of the EU Reference Scenario (PRIMES2007) for the year 2020. It is also required that each Member State must establish/monitor shares of renewable energy in the production of heat and cold, electricity and also in transport. [1]

In 2018, the portuguese energy imports dependency reached 77.0% (Figure 1) making Portugal one of the countries in the EU with the greatest external dependence. It should be noted that this dependency comes largely from the import of fossil fuels, as the portuguese energy system does not use any indigenous fossil energy sources, such as oil or natural gas. [2] [3]

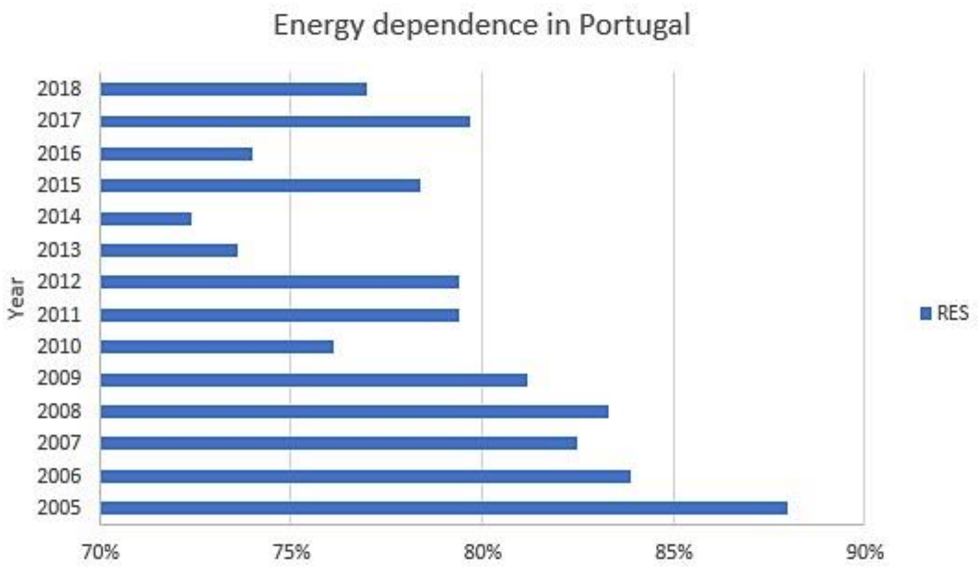

Figure 1: Energy dependence since 2005 until 2018. [3]

According to the synthetic energy balance, the primary energy consumed during 2018 reached 21,7 million tons of oil equivalent (toe) of which 75.5% was supplied by oil, natural gas and coal. In its turn, the final energy consumption was 15,7 ktoe, in which oil and natural gas represented 59.5% as shown in Figure 2. [4]

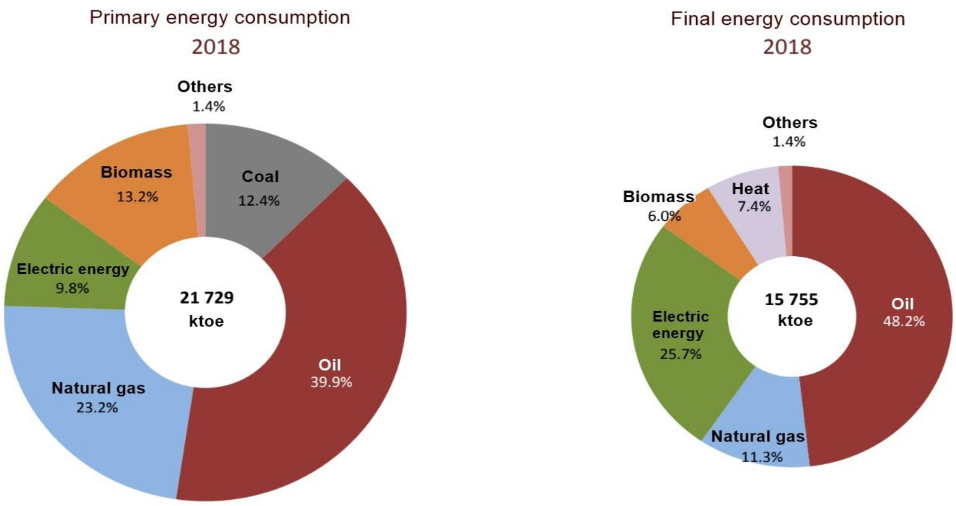

Figure 2: Consumption of primary and final energy. [4]

The official data on the penetration of RES is calculated according to a methodology layed out in Directive 2009/28/CE, normally referred to as the “RES directive” or “RED”. Thus, the fraction of RES on GFEC is calculated and published yearly by the Directorate-General for Energy and Geology (DGEG) and can be observed in Figure 3. [4]

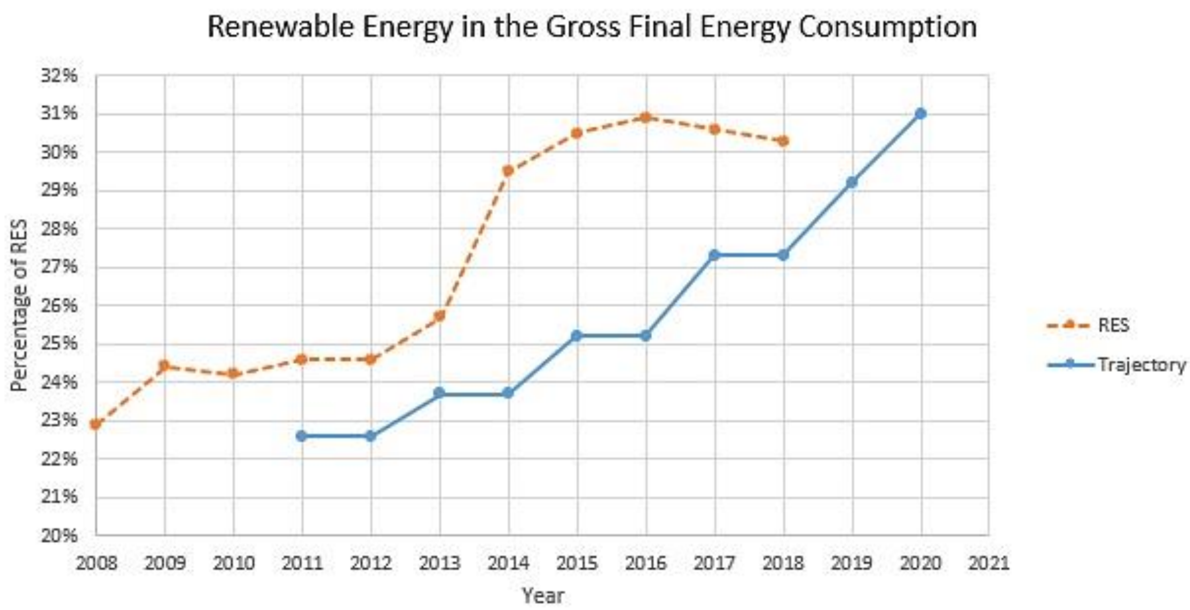

Figure 3: Percentage of renewable energy in GFEC. The orange line is the fraction of renewable energy in the GFEC. The blue line is the trajectory defined by the RES Directive. Adapted from DGEG (2019).

As it is possible to see, the use of RES has increased since 2012 and has always been above the indicative trajectory defined by the RES Directive.

The RES Directive also sets a mandatory target of 10% RES in transport and defines the monitoring of RES penetration in electricity and heating and cooling (H&C). Figure 4 presents the percentage of RE in the transport sector, where it is possible to see the increase over the last decade.

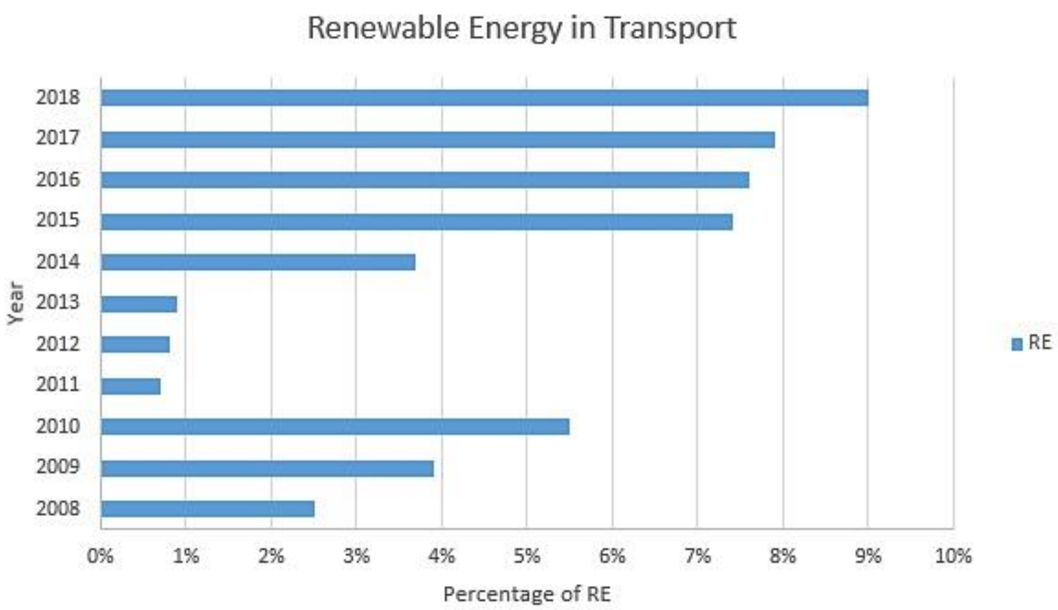

Figure 4: RE in transport. Adapted from DGEG.[6]

The transport sector, due to its heavy technological dependence on the internal combustion engine, offers a particularly difficult challenge for the penetration of RES, registering a total of 9.0% RES in its final energy consumption. This value is due to utilization of biofuels, such as biodiesel and bioethanol in road transport, and also electricity (mainly in rail transport). [5 6]

Currently, the portuguese electricity generation park is changing due to the growing installation of renewable power, specially wind and solar photovoltaic (PV), that is progressively substituting for thermal generation based on fossil fuels. In 2018, the generated electricity had a contribution of 52.6% from RES. Figure 5 presents the percentage of RE in the electricity sector over the last decade.

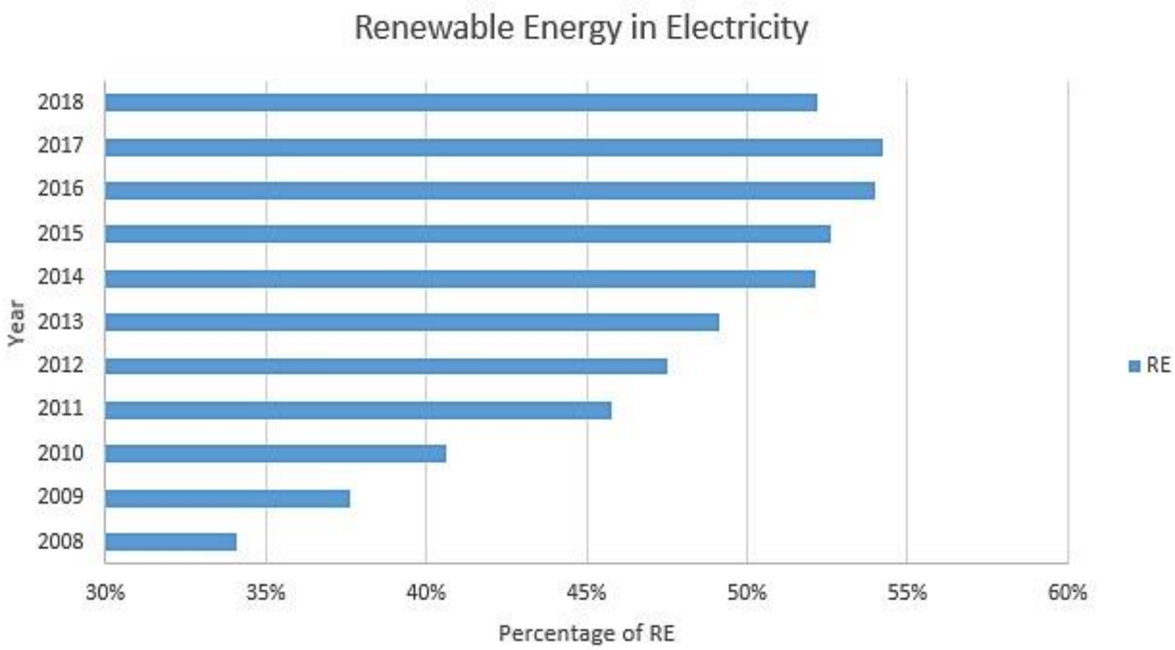

Figure 5: RE in Electricity. Adapted from DGEG. [6]

In the heating and cooling sector, renewable energy sources achieved 41.2%. Figure 6 presents the RE in this sector since 2008.

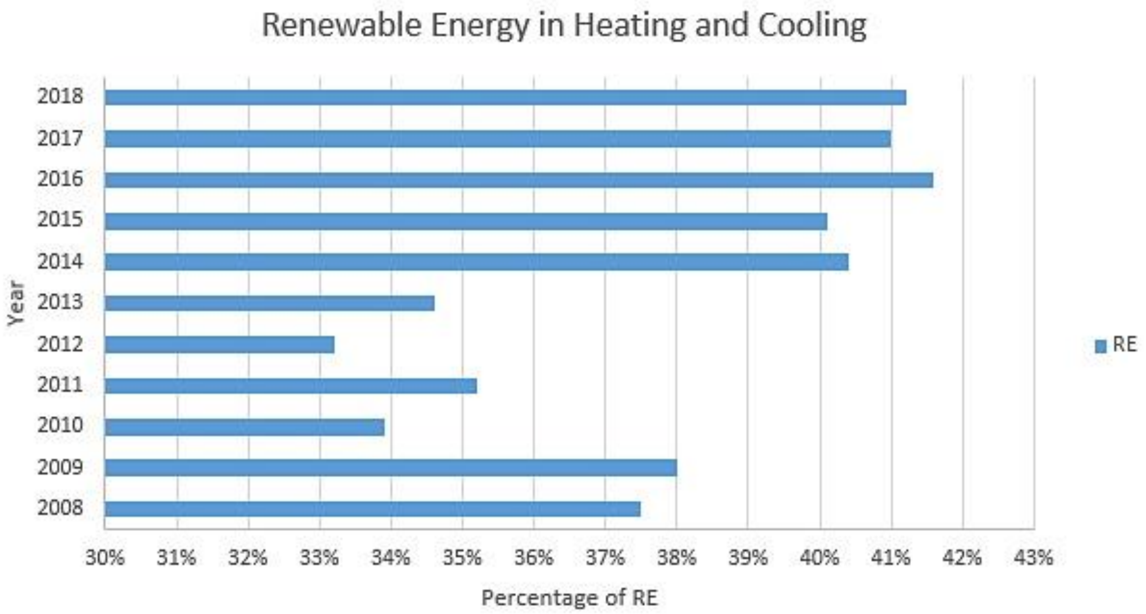

Figure 6: RE in Heating and Cooling. Adapted from DGEG. [6]

Overall, Portugal seems on track to achieve all the targets set for 2020.

These changes, especially on electric production have favored a decrease in the energy import dependency of 10% during the first decade of the 21st century, although this decrease is not linear because of the strong correlation with the variability of hydrological resources. [7]

The GHG emissions, in 2017, stood on 78.0 million equivalent metric tonnes of carbon dioxide (Mt CO_2eq.) considering the sector Land Use, Land-Use Change and Forestry (LULUCF). This value, in Figure 7, corresponds to an increase of 29,12% relative to 1990 emissions, justified by the forest fires of 2017. [8]

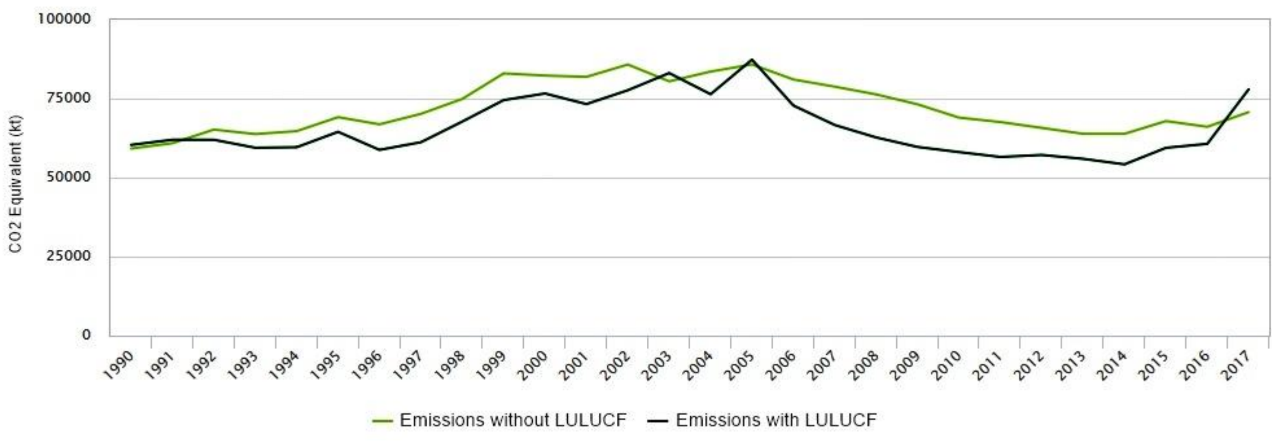

Figure 7: Emissions of CO_2 since 1990 until 2017. [8]

However, total emissions show a reduction of 18% compared to 2005 levels, confirming a trajectory of approach to the European targets defined for 2020 and 2030. [8]

Despite the efforts made and the notable improvements, Portugal still remains very dependent on the outside for its energy supply, thus impacting in economic and environmental terms. Industry, transport and the electricity generation sector are currently the sectors of activity with the greatest influence on final energy consumption and also on GHG emissions, and those that require the greatest effort for emissions reduction.

2.1.1 Future perspectives on the energy system

In 2015, the Paris Agreement (PA) defined that paradigm changes in society are necessary so that the average global temperature does not exceed 1.5°C above the pre-industrial average, in order to control the effects of climate change. To enter into force at least 55 countries, representing 55% of GHG emissions, would have to deposit their instruments of ratification, approval and acceptance. [9] This was achieved on November 4th, 2016.

Portugal became a double signatory of the PA in April of 2016, due to the fact that it signed for itself and as part of the EU signature. In 2019, the Government prepared the Roadmap for Carbon Neutrality 2050 (RNC 2050) for identifying decarbonization vectors and their potential of reduction on the diverse national economic sectors, collaborating in the most ambitious objectives in the PA.[10] [11]

This roadmap has established some visions and guidelines for the evolution of the portuguese energy and LULUCF sectors.[10] Part of the Roadmap focuses on renewable resources and their efficient use, as well as the strengthening of sinks due to their ability to absorb carbon dioxide from the atmosphere. These measures are intended to reduce the costs associated with the effects of climate change and simultaneously creating a more efficient economy.

In the decade 2007-2017, Portugal emitted an average liquid total of 60 million tons (Mt) of CO_2 and that is the value to reduce till 2050 for achieving carbon neutrality.

For that it will be necessary to get electricity from green resources like wind or solar photovoltaics. The decarbonization of transport will depend on the mass adoption of public transport, electric vehicles and green fuels culminating in a 98% reduction of GHG comparatively to 2005. In buildings, the use of heat exchangers, solar thermal and surface insulation will allow a reduction of 95% in GHG emissions. The use of biomass and electrification as a replacement for fossil fuel burning in industry, can reduce emissions in the sector by 80%. The emissions from animal production can be reduced with the introduction of better feeding and a more efficient management in manure systems. For agriculture GHG emissions will be reduced by the introduction of mineral fertilization and the planting of biodiverse pastures.

The rise of decarbonized energy vectors can contribute to reduce emissions by a further 4%. These vectors include hydrogen produced by electrolysis from renewable sources and biomass for heat generation.

In brief, the RNC2050 allows the identification of guidelines and a long-term planning for achieving a more competitive and carbon neutral economy by 2050. Current technology makes it possible to reach these goals and assure that change is beneficial to all citizens.[10]

Portugal was the first country in the world to adopt a compromise on carbon neutrality and the RNC 2050 was first presented at the COP22 in Marrakech in 2016.

As a signatory of the PA, the European Commission also has established targets to be achieved by the EU in 2030. These are to reduce, at least, 40% in GHG emissions relative to 1990, to decrease energy consumption by 32.5% by means of energy efficiency gains and increase the share of RES in gross final consumption to 32%. In this way, also strategic packages were adopted that intend to act in the different impacting areas. Here we highlight the Clean Energy Package for all Europeans, the Mobility Package and the Climate 2030 Energy Package. [12]

The Clean Energy for all Europeans package aims to provide an energy transition, promote economic growth and stimulate job creation. This legislative package obliges Member States to formulate and deliver to the European Commission a National Integrated Energy and Climate Plan (NECP) for the horizon 2030. The efforts proposed by the different national NECP must combine to reach the overall EU targets described in the previous paragraph. The NECP 2030 document will be the energy and climate policy throughout 2021-2030. [13]

In the Portuguese NECP the need to change the economic paradigm and respond to the threats of climate change are aligned with the vision of achieving carbon neutrality in 2050 layed out in the RNC 2050. This strategic choice requires an association of technological possibilities and different policy options, as a carbon neutral economy demands joint action in different areas, in which energy efficiency will be a main priority.

For energy efficiency a transition phase is required, which in Portugal will largely pass through the electricity sector. Portugal can create a decarbonized electricity sector by tapping on endogenous RES, such as sun, wind and water, and also because of the existing virtue of a safe electrical system able to deal with the intermittency of renewable energies. In the electroproduction sector the NECP defines a RES contribution of at least 80% by 2030.

In addition to the evolution of technology, it is considered that informed citizens represent an important vector for the adoption of more efficient and sustainable choices, thus reinforcing the efforts in the fight against global warming.

The natural gas system will also be able to contribute significantly for the achievement of these goals, through the insertion of renewable gases such as hydrogen or biomethane, in the transport and distribution networks. These components, specially hydrogen, can store energy and promote the decarbonization of industry and NECP states the intention of implementing a hydrogen production industry. [14]

The Portuguese National Energy and Climate Plan has established the following targets for 2030 (Figure 8).

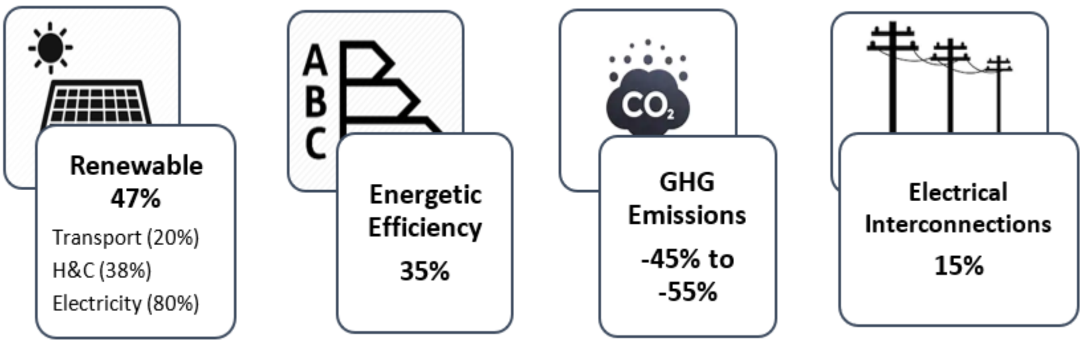

Figure 8: National targets established by Portugal. Own source according to PNEC (2019).

- **Renewables (47%):** Over time Portugal introduced renewable energies and is today a reference in European leadership. To further increase renewable penetration to 47% of GFEC, the evolution of installed capacity, the production of electricity from renewable sources, the mass adoption of electric vehicles, the insertion of renewable gases and, essentially, innovation and research of green technologies with lower costs are crucial parameters. For that purpose, sectoral targets have been established.

- **Renewables in transport (20%):** The promotion of public transport, the expansion of electric mobility, as well the accession to biofuels and hydrogen are indispensable for achieving this target. Road traffic should progressively reduce fossil fuel consumption and incorporate green alternatives, and these measures should also be incorporated in the maritime, aviation and rail transport sectors.

- **Heating and Cooling (38%):** The efforts on energy efficiency and electrification of consumption, are expected to induce a reduction in fossil fuels consumption in different sectors. To achieve the established goal it will be necessary to promote the use of biomass, heat pumps (one of the most efficient equipments for heating and cooling), high efficiency cogeneration (that allows significant energy savings and is especially appropriate for highly energy intensive industries), renewable gases (by incorporation on the natural gas transport and distribution networks) and thermal solar (in conjunction with other components such as heat pumps or biomass boilers) on this sector.

- **Electricity (80%):** For the decarbonization of electricity production it will be necessary to significantly increase RE capacity, such as onshore/offshore wind, hydroelectricity (reinforcing the conclusion of Alto Tâmega Hydroelectric Complex with capability of 1.2 GW), solar PV, biomass, geothermal and waves.

- **Energy Efficiency (35%):** Portugal intends to reduce energy consumption, primary or final, by 35% in 2030. This reduction is measured by comparison with the projections of energy consumption in 2030 obtained in the EU Reference Scenario (PRIMES 2007 model). To achieve this goal, it is necessary to optimize some sectors, such as:

    - **Buildings:** it is necessary to rehabilitate and make buildings more efficient, thus reducing energy needs. The near-zero energy buildings (NZEB) are getting more attention because they have a higher energy performance and their energy needs are almost nonexistent;

    - **Industry:** it is recommended that resources be used more efficiently assuring the same productivity and competitiveness in industries;

- **Transport and mobility:** to increase energy efficiency it's crucial investing on public transport and electric mobility;

- **Equipments:** the replacement of old and actual equipments for new electrical equipments will allow a reduction in the energy requirements;

- **Agroforestry:** the conscious use of energy makes it possible to minimize costs. In this way forestry and agricultural practices can be more efficient and the installation of more effective technologies will be promoted.

- **GHG Emissions (-45% a -55%):** intends to guarantee the reduction of the national emissions compared to 2005 levels in different sectors, especially in transport, industry, electricity and residual waters. These parameters will have an impact on production and consumption patterns, the organization of spaces and cities and mobility for work or leisure. For effective decarbonization, it is necessary to ensure that all sectors minimize emissions regardless of their technological maturity. Through Figure 9 it's possible to see the reduction on GHG emissions and a perspective for the future.

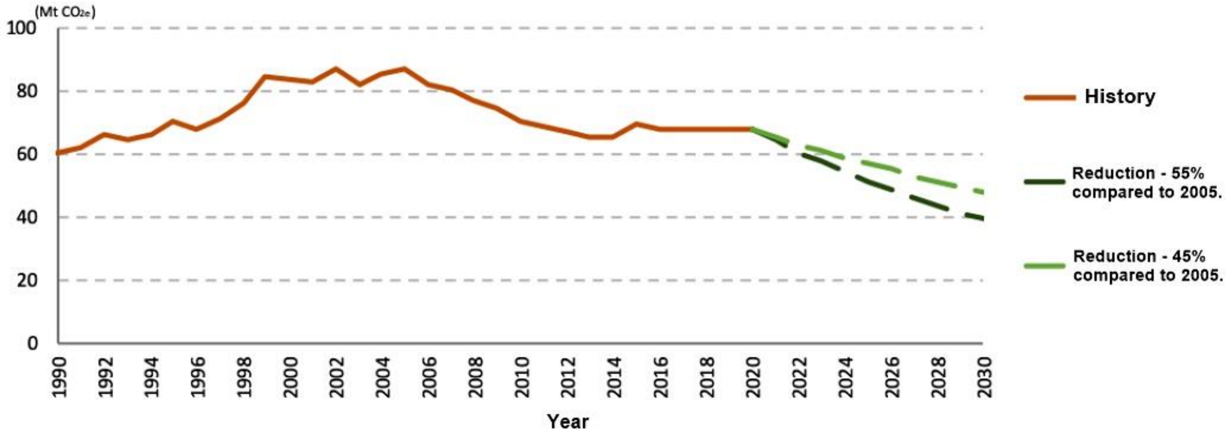

Figure 9: Evolution of GHG since 1990 and minimization goals established. Adopted from PNEC (2019).

- **Electrical Interconnections (15%):** The establishment of electrical interconnections enables a better development of the Iberian internal market and a better performance through the monitoring and management of energy systems.

The NECP has recently been complemented by the National Hydrogen Strategy. The objectives of the NECP remain unchanged, but hydrogen provides a larger variety of technological pathways to achieve decarbonization. This issue will be addressed in the following section.

2.2 Hydrogen

Molecular hydrogen (H_2) can be the key for addressing many environmental challenges given the fact that it is a non-polluting energy carrier, so for that can be called the Energy of the 21st Century. Hydrogen is the most common and simpler chemical element in the Universe, but its occurrence in the molecular form is rare. In our planet, hydrogen presents itself mostly combined with oxygen and carbon to form water and organic compounds, and therefore it must be separated and extracted.

Molecular hydrogen is characterized as a non-colored, tasteless, odorless, very light (14.4 times lighter than air) and extremely flammable gas at normal temperature and pressure (1 atmosphere and 0 °C respectively). Other physical characteristics are displayed in Table 1. [15] [16] [17]

Table 1: Hydrogen characteristics [17]

Characteristics	***Value***	***Unit***
Molecular weight	2.02	g/mol
Density	0.09	kg/m^3
Specific energy		
• Higher heating value	142	MJ/kg
• Lower heating value	120	MJ/kg
Melting point	- 259.20	°C
Boiling point	- 252.77	°C
Critical pressure	13.0	bar
Critical temperature	- 240.0	°C

H_2 cannot be considered a primary energy source, such as natural gas or coal, however, it is an energy vector [18] produced within the traditional energy system, from fossil fuels or from renewable sources. [19] [20]

As an energy vector H_2 can be used either as a fuel or as a means for storing energy from the transformation of other forms with high efficiency. H_2 can be inserted in the global energy system (Figure 10), standing out in the storage of excess electric energy production from RES. [21]

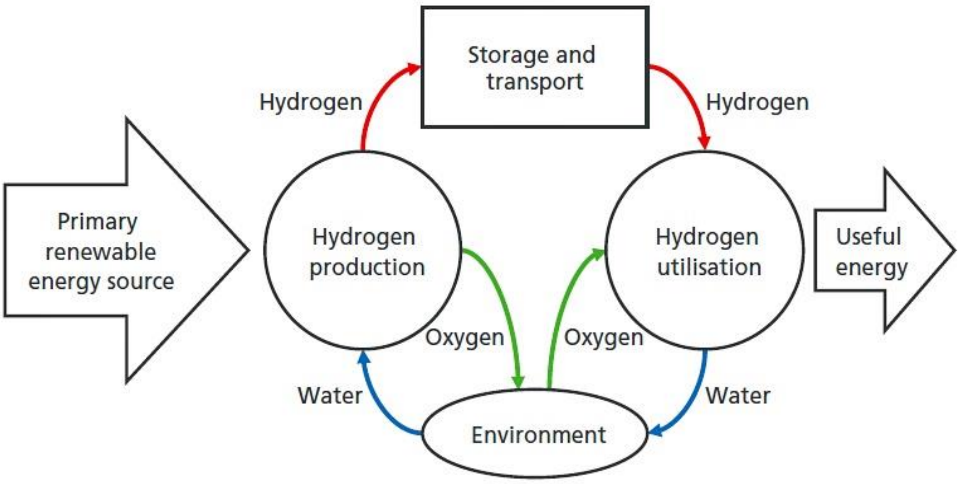

Figure 10: The hydrogen cycle. Adopted from AP2H2. [20]

As a fuel, hydrogen has a higher energy content by mass than any other standard liquid fuel, around three times larger than diesel and gasoline (that have a low heating value of 46 MJ/kg approximately), although with a lower volumetric density. The combustion of H_2 has no carbon emissions while gasoline emits 0.86 kgC/kg. H_2 not only has a significant potential as a fuel in its own right, it can also be used as a product for the fabrication of synthetic fuels when chemically bonded with other components, such as CO_2. [18] [22] The technology that promotes hydrogen as a fuel is becoming very important, because it allows a cleaner and more renewable energy transition, with evident benefits for the environment.

As an energy vector, H_2 can play a major role in future energy systems where the penetration of RES is expected to be very significant. In such systems, with a high dependence on weather and climate conditions, there can be very large fluctuations in production, with periods when production largely exceeds demand followed by periods when production can be very small. By converting excess energy production into H_2, energy could be stored for use in periods of low production. Hydrogen allows storage from the short to the long term and could help smoothing production in highly intermittent energy systems.

For achieving these goals, it is necessary that renewable H_2 becomes economically competitive, having in consideration some parameters like production, storage and distribution. [16]

On the production side, it's important that the negative environmental impacts associated with possible emission of GHG are minimized, that the costs are reduced and the technologies that allow increasing the process efficiency are available. [16] [18]

Storage and transport are two components that strongly influence the value chain of hydrogen. Storage can have different forms depending on H_2 use, and its viability depends on safety, lower weight, volumetric capacity and desorption kinetics. Transport will be influenced by the areas of supply and the availability of infrastructure, also the mode of supply can contribute to the increase in costs and emissions.

2.2.1 Hydrogen production

The production of hydrogen requires physical-chemical processes to synthesize and isolate this molecule.

When produced from RES, H_2 is commonly referred to as green hydrogen, when produced from fossil fuels or from sub products of industrial processes it is designated as brown and grey hydrogen, respectively. [16] The term "blue hydrogen" has been used for H_2 produced from the reformation of natural gas followed by capture and storage of the emitted CO_2.

Worldwide, 96% of hydrogen in utilization has been produced from fossil fuels and only 4% has been produced from RES. Hydrogen can be created using different sources (Figure 11). [16] [23]

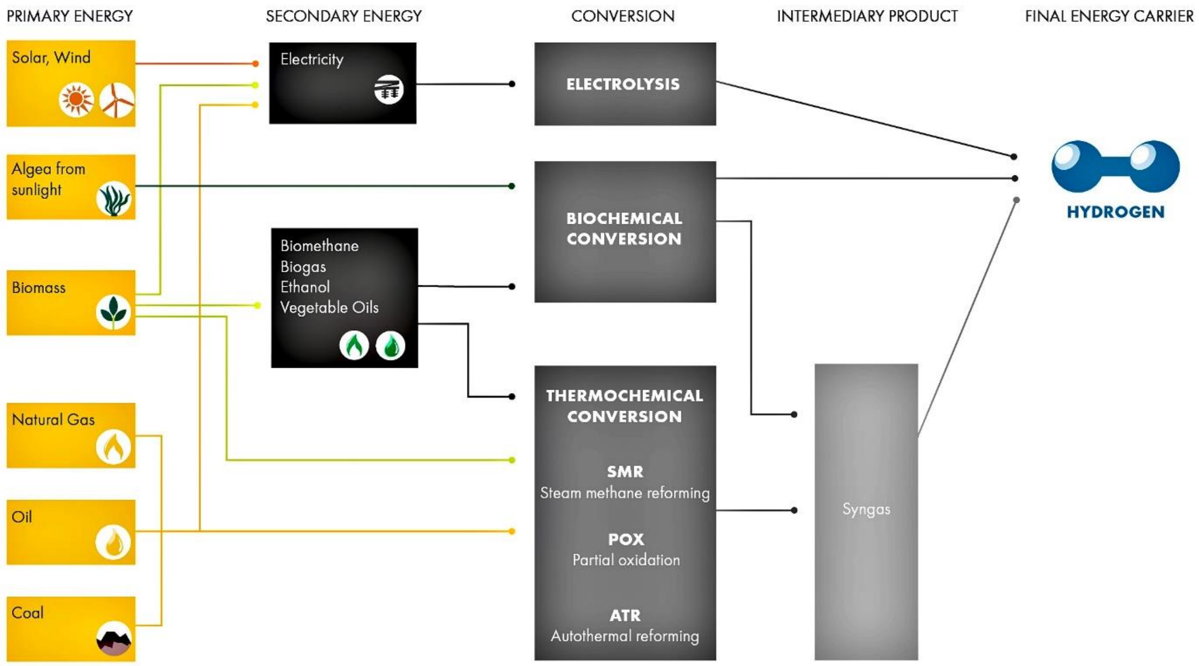

Figure 11: Different sources for hydrogen production. [23]

2.2.1.1 Hydrogen from fossil sources

Of all hydrogen produced from fossil sources, about 18% is produced from coal, 29% from liquid hydrocarbons and 49% from natural gas, with hydrocarbon reforming and gasification as the most common production routes. [18] [24] The reforming is the most economical form to produce hydrogen, achieving values below 2€/kg H_2. [16]

- **Reforming**

Hydrocarbon reforming has different ways of producing hydrogen, of which steam reforming (SR) is the most common. Normally the feed is natural gas and the process is designed as steam methane reforming (SMR). This endothermic catalytic process consists of 3 steps: syngas generation; water-gas shift (WGS) and gas purification. In the first stage (eq. 1), an endothermically catalytic reaction of natural gas and steam is converted into syngas (mixture of carbon monoxide (CO) and H_2) and requires temperatures between 700 and 900 °C and pressures between 3 and 25 bar.

$$CH_4 + H_2O \rightleftharpoons 3H_2 + CO \qquad (1)$$

Then the syngas is fed into a WGS reactor (eq. 2) to increase the quantity of hydrogen, culminating in a steam with H_2 and CO_2.

$$CO + H_2O \rightleftharpoons H_2 + CO_2 \tag{2}$$

The final step of the process, gas purification, requires the H_2 rich steam to be submitted to pressure swing adsorption, from which the pure hydrogen gas is obtained.

The heat necessary for the reaction in the SMR process can be supplied by concentrated solar thermal energy, therefore minimizing the associated CO_2 emissions. The energy efficiency of hydrogen production achieves 70 - 85% in industrial scale. [18] [23]

2.2.1.2 Hydrogen from renewable energy sources

Electrolysis is the most common route of production of hydrogen from RES, followed by biomass conversion. Below these two main processes are described.

- **Biomass**

Biomass is a renewable organic material which includes forest residues, organic municipal solid waste and also animal wastes, agriculture crop residues and dedicated crops. There are two paths for conversion of biomass into hydrogen gas, thermo-chemical conversion and biological conversion. The most commonly used route is the thermo-chemical based on the pyrolysis/gasification process.

Normally the biomass has to be heated in a reactor at high temperatures and under pressure. This step oxidizes the material and produces a gas constituted by H_2, CO, CH_4 and CO_2. The gas stream is subjected again to high temperatures in order to increase hydrogen content. Subsequently in a pressure swing adsorption (PSA) unit, in which the pressure and partial pressure are alternated to promote adsorption and desorption in order to remove existing impurities, it is produced hydrogen with a high purity level.[25] [26]

- **Electrolysis**

Water electrolysis is an electrochemical process based on the use of direct electric current for splitting water into hydrogen and oxygen. An electrolyzer is composed of two electrodes (anode and cathode, positive and negative respectively) and a conductive liquid designed as the electrolyte, in which the electrodes are immersed. Typically, potassium hydroxide (KOH) is added to increase the conductivity of water. [23 27]

The process is based on the passing of an electric current between anode and cathode through the electrolyte. In this way, the water will split in hydrogen, released from the cathode, and oxygen from the anode. The general chemical equation for the electrolysis reaction is (eq. 3):

$$2H_2O \rightarrow 2H_2 + O_2 \tag{3}$$

The electric current necessary for the process can be produced from renewable energy sources such as wind, biomass or sun. The H_2 produced with this technology has a high level of purity given the fact that the product stream is dried, and the impurities have been removed.

Here we highlight the most common electrolysis technologies such as alkaline electrolyzer and polymer electrolyte membrane (PEM), which differ in efficiency, operational conditions and the material used for electrolyte. [27]

Alkaline electrolyzers are the most mature and established technology. They normally consist of a solution of water and 25% to 30% of KOH, although sodium chloride (NaCl) and sodium hydroxide (NaOH) are also used in the electrolyte. It's necessary to use a diaphragm for separating the electrodes, keeping the product gases apart and ensuring the efficiency and safety (Figure 12). This component has to be permeable to water molecules and hydroxide ions.

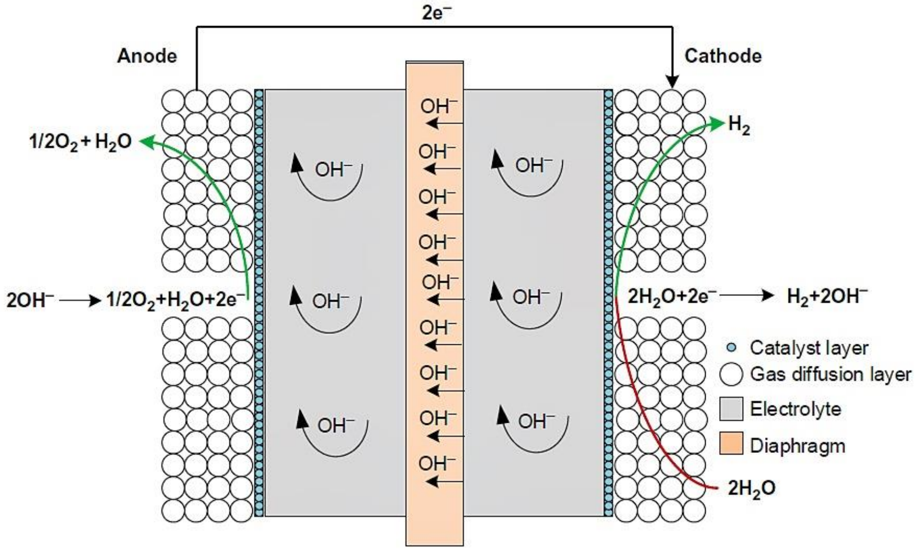

Figure 12: Schematic illustration of the alkaline electrolyzer cell. [27]

The process initiates with the application of electric current between both electrodes. In the cathode the water molecules react with electrons to form OH- ions and H_2. The hydroxide ions pass through the diaphragm towards the anode, where they release the electrons into the electric circuit and combine to form oxygen and water molecules. [26] [28]

Although alkaline electrolysis is the more mature technology, there remain 3 major limiting issues: operating with low pressure, the limited current density due the losses in the diaphragm, and the cross-diffusion of product gases. [27]

Polymer electrolyte membrane is the process where H_2 is obtained with highest purity. This system is constituted by a polymer membrane that only allows protons to pass, by the anode and the cathode catalysts, and the electrode layers where the current is applied. Figure 13 shows a schematic representation of a PEM electrolyzer.

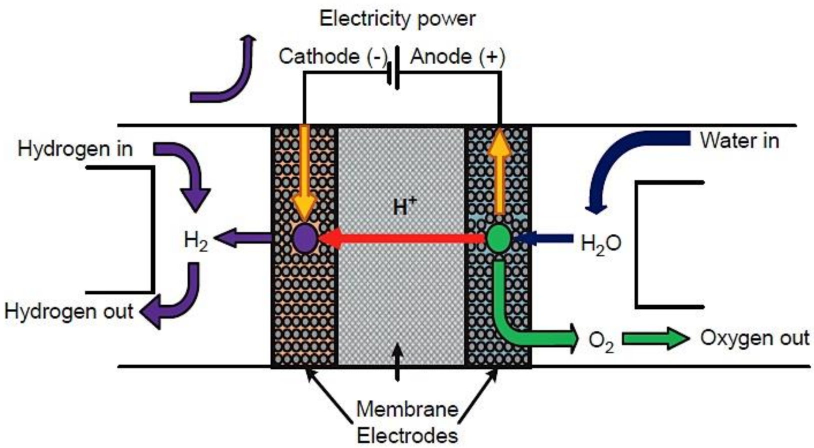

Figure 13: Schematic illustration of the PEM cell. [27]

This process favors the removal of liquids and gases from the catalyst surfaces. Thus, in the process, the water molecules dissociate into oxygen (O^-) and hydrogen ions (H^-) on the anode catalyst. The oxygen is removed, and protons pass through the membrane towards the cathode, where they receive electrons and are converted into hydrogen gas (H_2). [27] Nevertheless, this method is limited by the cost of the catalyst and the lifetime of the membrane.

The different types of hydrogen production from renewable or non-renewable sources are compared in Table 2, where it is highlighted the efficiency and also the CO_2 emissions of each process.

Table 2: Study of parameters for different H_2 production methods

		Technology			
		Fossil Source	**Renewables Sources**		
		Steam reforming	Biomass	Alkaline electrolyzer	PEM electrolyzer
Parameters	**Feedstock** [29]	Hydrocarbons	Biomass	H_2O + Electricity	H_2O + Electricity
	Efficiency [29]	70 – 85%	35 – 50%	50 – 60%	55 – 70%
	Maturity [29]	Commercial	Commercial	Commercial	Near term
	Advantages	No oxygen requirement [30]	Mitigating CO_2 emissions [29]	No pollution [30]	
	Disadvantages	Highest GHG emissions [30]	Seasonal availability and high handling costs [29]	High capital costs [30]	
	CO_2 Emissions (measured in tons) [31]	300 million	600 million*	0	

*Zero net emissions because biomass pulls CO_2 from the air.

Through Table 2 is possible to see that steam reforming is the most common way of production having the highest efficiency, comparatively with the other technologies, and does not consume oxygen for the H_2 production. In maturity terms the major methods are in a commercial scale despite the PEM electrolyzer requiring a high capital cost. An outstanding feature in the hydrogen production technology is that the biomass method allows to mitigate the CO_2 emissions and the Alkaline and PEM electrolyzer present zero emissions, quite advantageous compared with steam reforming that produces large annual emissions of CO_2.

However, electrolysis techniques have the disadvantage of using water as raw material. This water is generally of high purity and its production in large volumes is costly. Despite 70% of the world's surface being covered with water, only 4% of this water is suitable for human consumption. With the continuing growth of the world's population and its water needs, several suggestions have been considered for the direct production of hydrogen from seawater, since this technology can also produce fresh drinking water, an important production for arid zones. [32]

The direct use of seawater for electrolysis still remains a challenge given the reactions that occur with the components of seawater. In this way, one of the problems to overcome is the chlorine evolution reaction (CER), resulting from the splitting of ionic components, that settle on the anode and compete with the oxygen evolution reaction (OER), a process of generating molecular oxygen. The deposition of these elements, such as particles of chlorine or sodium, on the anode limits the equipment and production lifespan. [32] [33]

Another difficulty in this splitting process is the generation of insoluble precipitates on the electrode's surface. Precipitate such as magnesium hydroxide can intoxicate the hydrogen evolution reaction (HER) catalysts. The reduction in the poisoning of the process has been attempted by using catalysts possessing surface areas with numerous active sites. However, the chloride anions can also corrode the electrodes limiting the development of a seawater splitting process.

Only a small number of studies on water electrocatalysts have been reported, nevertheless a transition metal-nitride (TMN) is a very promising candidate to this process due to its high corrosion-resistance and also for being mechanically strong and electrically conductive. [32] [33] The scientific literature shows that seawater electrolysis is still al its technological beginnings and it will take some years before it can achieve a technological readiness level compatible with industrial scale applications.

2.2.1 Hydrogen applications

In the future it's expected that renewable resources produce all electricity, however due to the intermittency of RES, energy storage is really important and H_2 can be one of the solutions to this challenge given its capacity for storage during larger periods of time with larger amounts (Figure 14).[34] This characteristic makes H_2 an important element for the energy transition.

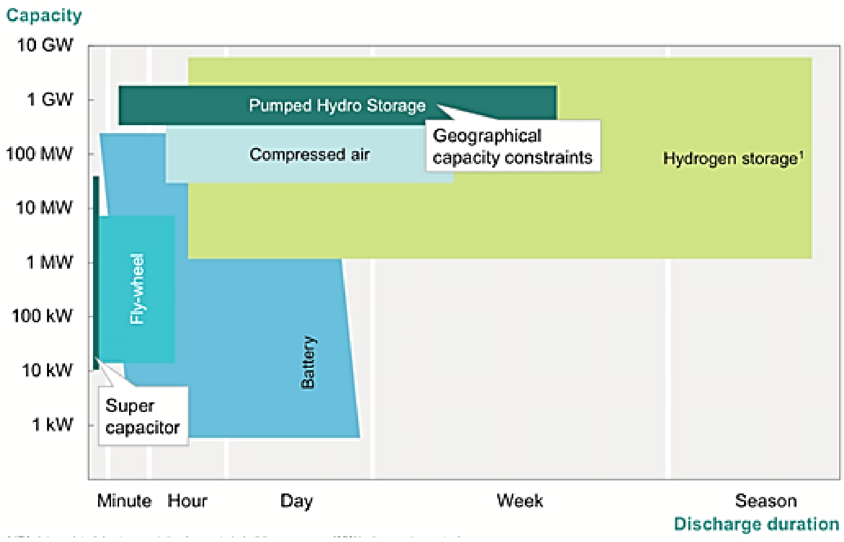

Figure 14: Energy storage. [34]

Figure 14 shows that a normal battery can store smaller quantities (1 kW – 1 MW) for shorter periods compared with hydrogen that provides a much larger storage capacity range, from 1 MW to almost 10 GW during long periods, evidencing its advantages over compressed air or pumped hydro storage. In this way, with H_2 it is possible to store energy in periods of abundant production to be used in periods of production scarcity, provide network stabilization services during storms or other events that cause interruptions in the power sources, or provide electricity in remote areas that cannot be reached by electricity grids.

The different storage technologies, such as compressed hydrogen in tanks, underground storage or through chemical compounds allow the transport and conversion back in electricity in locations far from the point of production. [34]

In addition to storage capacities H_2 also presents different ways of use, thus being able to be grouped into two large groups: as a feedstock or as an energy vector.

As a feedstock hydrogen has been used for decades in different industrial processes, where it is possible to highlight its use as a raw material for the chemical industry and in metallurgic industry as a reducing agent.

It is an essential building element for the manufacture of ammonia (NH_3), hence fertilizers and methanol (CH_3OH), and for processing the intermediates of oil products in refineries. Thereby it is estimated that 55% of the total H_2 production in the world is directed for ammonia synthesis, 25% for refineries, 10% for the methanol sector and the remaining 10% for other general applications. [35]

Hydrogen can be applied for processing crude oil into refined fuels or for removing contaminants, like in hydrocracking. For this application it is estimated that 75% of the hydrogen is obtained from the reforming of natural gas or hydrocarbon fuels. [35]

Given its capacity for being an energy vector, this element can be incorporated in the natural gas networks to increase the calorific power or can be converted into CH_4 (methane) for the injection in this network.

Also stored H_2 can be converted into electricity through fuel cells (FCs). [34] [35] In the energy field H_2 is being used into FCs where it is combined with oxygen to produce electricity and useful heat, having water vapor as its exhaust product. These fuel cells are being introduced in the transport sector, given the fact that they allow the decarbonization of road transport as there are no associated CO_2 emissions. The international market has a few models of passenger cars with hydrogen-powered fuel cells. The prototype passenger cars with these characteristics are now as reliable as traditional combustion engine cars.

In electricity generation, stationary fuel cells are being used for decentralized power supply in off-grid areas. Currently, a main factor very important is the backup power applications, such as firstly emergency power supply or secondly uninterruptible supply. This type of FCs presents a higher electrical efficiency, up to 60%, when compared with conventional thermal power plants. Beyond efficiency, FCs in current operation are characterized for emission-free electricity production and a long autonomous operation and service life that require low maintenance costs. [35]

In isolated regions of Portugal there are some applications that require the off-grid use of electricity, such as telecommunication antennas, pumping water systems and buildings far away from the national electric grid. So, in such places hydrogen could be produced through renewable or hydraulic systems, allowing the storage of energy in H_2 for further transformation according to needs. [5]

2.3 Hydrogen in Portugal

The Sines Refinery, in southern Portugal, started operation in September of 1978 and is presently one of the largest in Europe. This plant has a distillation capacity of 10.9 million tons per year, which represent 220 thousand barrels per day. [36]

The refinery essentially produces diesel (41.5%) and petrol (28.7%) and other components such as jet fuel, liquefied petroleum gas, fuel oil or naphtha (used in the petrochemical industry). Production is based on the refining of two types of crude, the sweet crude that has less than 1% of sulfur, and the sour crude that has the highest content in sulfur.

In 2007, Galp Energy, approved a project for improving the refinery system through the installation of a hydrocracking unit. The unit entered operation in January of 2013.[37] The new unity receives a less noble product, vacuum gas oil (VGO), from other portuguese refineries and also from importation, to convert into more valuable products such as diesel or jet petrol. For this operation it is necessary a hydrocracker, operating in presence of hydrogen and a catalyst, that “cracks” the heavy long-chain molecules of VGO into shorter molecules resulting in a clean-burning fuel. [38] The hydrogen necessary for this process comes from steam methane reforming, of natural gas, and purified to 99.5% by a pressure swing adsorption unit. This unit also includes a sulfur recuperation unit to eliminate the toxic gases derived from the hydrocracking process. [39]

The largest natural gas cogeneration plant in Sines produces steam and electric energy to feed the refinery and also to inject in the electric grid. This plant has operated since October 2009, producing 668 GWh/year of electricity and 1.8 Mton of steam. [37]

However, as already stated above, the hydrogen used in the refinery is from a non-renewable source. There is a growing awareness for the need of producing renewable H_2 and a number of projects have been announced recently. A project released by the EDP Group intends to produce hydrogen in Ribatejo CCTG (combined cycle gas turbine) Plant with a non-pollution method. [40] The Ribatejo Thermoelectric Plant was the second largest combined cycle plant, built during 2004, fed with natural gas and a capacity of approximately 1180 MW. [41] [42]

This pilot project intends the production of hydrogen by an electrolyzer with a capacity of 1 MW and a capacity storage of 12 MW from 2022. This process will consume energy from the grid to produce hydrogen that will be burnt together with the natural gas to generate electricity. [40]

Beyond this main project, EDP also intends to study the feasibility of production of hydrogen with offshore wind energy. [43]

Portugal has recently adopted a National Hydrogen Strategy in 30 July of 2020. This National Strategy intends to advance the use of hydrogen as an integrated and sustainable pillar in the energy sector, promoting an energy transition strategy for a decarbonized economy. The measures and targets for the hydrogen incorporation promote and streamline the consumption and production in different economic sectors.[44]

This strategy should be understood as an aid for the NECP 2030 not defining a new objective for global decarbonization beyond those already defined. It will be guided by the objectives of incorporating renewables into GFEC and emission reductions. [44]

The key projects and future initiatives include: [44]

- Anchor project of industrial production of green hydrogen in Sines;
- Decarbonization of transport: promotes and support hydrogen and synthetic fuels as an addition to electricity and biofuels used to decarbonize this sector;
- Decarbonize the national industry: the decarbonization through the hydrogen in many subsectors, such as steel production;
- Use of waste water for hydrogen production;
- Development of a collaborative laboratory: development of R&D activities related to the hydrogen value chains and which allows the emergence of new industries, through the laboratory with national and international references.

Currently, Portugal is in negotiations with the Netherlands for creating a unit that will produce hydrogen just using renewable resources. [45]

The project includes the construction of an electrolyzer factory in industrial scale, a solar power station, with 1GW capacity, and a factory for the production of photovoltaic solar panels and also a hydrogen plant. The construction should start in the beginning of 2021, but the hydrogen production is not expected to start until 2025. [46]

This project will be located in Sines because of the deep-water port, for being one of the places with the lowest price of solar energy and for having a natural gas supply network, being this plant valued at 600 million euros. When in operation, it's expected to produce up to 100 thousand tons of hydrogen per year, reducing the emissions at 18.6 million tons annually by the decarbonization of transports, heat production and industry. [47]

It is expected that the implementation of this project will reduce energy imports and the energy dependence of the country, positioning Portugal as an exporter of green energy. For the export to Northern Europe hydrogen will be stored and transported in a gaseous state, for subsequent use in pharmaceutical, steel or fertilizer industries. [46]

This is a project of an unprecedented scale in worldwide terms and with a deep impact in the industry and energy sectors of Portugal. The present study is therefore dedicated to understanding the combination of technologies and operating modes that could render such projects competitive in technical and economic terms. The details of that analysis are presented in the following chapters.

3. Energy system modeling

3.1 Energy modeling tools

Energy planning and security of energy supply are two problems of paramount importance in a modern global economy. Since the energy crisis of the 1970s, energy planning has been in permanent evolution. It was therefore necessary to develop models for analyzing demand patterns, for quantifying pollutant gas emissions or for reducing the services costs. [48] [49] The correct addressing of these problems allows development of informed investment strategies in supply and the timely satisfaction of demand. However, modern energy planning is a complex challenge that can only be adequately treated with the assistance of computerized technologies, both software and hardware. [50] These tools are also being adjusted because of the emergence and strong growth in renewable energy. These adaptations culminated in multiple modeling systems with different characteristics that depend on the desired detail and the main objectives. [51]

When modeling a H_2 production plant with the characteristics of the object of this study, where the electricity that powers the electrolyzer is produced by renewable energy sources, one has to take into account the intermittence of those sources. This effect means that major changes in electricity output can occur in very short periods of time, so it is important to use a modeling tool that can accommodate high temporal resolution, typically one hour. The level of intermittence has an impact in the instantaneous electrolyzer operation and energy exchanges with the national electricity grid. On the other hand, the modeling tool will have to allow estimating the contribution of these short time changes over a larger time scale, typically one year. This is generally the time scale for which many parameters are evaluated, such as annual H_2 production, annual exchanges with the electricity grid or annualized investment costs.

It was decided to compare the characteristics of three different modeling tools that have been recently used to make prospective studies for the portuguese energy system: EnergyPLAN, MARKAL/TIMES and LEAP. This modeling systems have been used in different energy planning studies: MARKAL/TIMES provided the analytical tool for the development of the RNC2050, that studies different possible paths from the point of view of technical and economic feasibility, for achieving a carbon neutral economy by 2050. LEAP was used to prepare the PNEC2030 by developing a bottom-up model of the portuguese energy system.

LEAP was also used in combination with energyPLAN for the development of the National Hydrogen Strategy.

Table 3 presents and compares some relevant characteristics of these three modeling tools. [51]

Table 3: Parameters of chosen energy modeling systems

Energy Models	**Number of users**	**Simulation**	**Scenario**	**Top-down**	**Bottom-up**	**Operation optimization**	**Investment optimization**
EnergyPLAN [51]	High	Yes	Yes	-	Yes	Yes	Yes
MARKAL-TIMES [51]	High	-	Yes	Partial	Yes	-	Yes
LEAP [51]	Very high	Yes	Yes	Yes	Yes	-	-

The parameters chosen to compare the different modeling tools can be described as:

- **Simulation:** represents the operation of an energy system that delivers an amount of energy.
- **Scenario:** possible evolution of the energy system under a set of well-defined assumptions;
- **Top-down:** utilizes macroeconomic data for determination of growth in energy demand and prices;
- **Bottom-up:** identifies the energy technologies, the alternative and investments options for the determination of growth in energy demand and prices.
- **Operation optimization:** allows to optimize the technological configuration of an energy system;
- **Investment optimization:** allows the optimization of the investments in an energy system.

Through Table 3 it is possible to see that only LEAP and energyPLAN can be used as simulation tools which, as stated above, is a necessary characteristics for analyzing the operation of the H_2 production plant in different time scales. They also allow operation and investment optimization and are bottom-up type.

It is also possible to analyze if the different softwares includes the energy sectors through Table 4.

Table 4: Energy sectors included in the modeling systems

Software	***Energy Consuming Sectors***			***Simulation of RE penetration***	
	Heat	Electricity	Transport	100% electricity	100% RE system
EnergyPLAN [51]	Yes	Yes	Yes	Yes	Yes
MARKAL/TIMES [51]	Yes	Yes	Yes	-	-
LEAP [51]	Yes	Yes	Yes	Yes	Yes

In Table 4 one can highlight that LEAP and energyPLAN software are the only two capable of assuming energy systems with 100% of electricity and RE systems.

Other characteristics of these software are also analyzed in Table 5.

Table 5: Geographical coverage, methodology and resolution of the modeling software

Characteristics	***Modeling Software's***		
	EnergyPLAN	MARKAL/TIMES	LEAP
Geographical coverage [52]	Multi-node	Multi-node	Single-node
Methodology [52]	Simulation	Dispatch optimization; Single objective investment optimization	Simulation
Resolution: [52]			
• *In time*	High	Low	Low
• *In space*	Medium	Medium	Low
• *In sector coupling*	High	High	High

EnergyPLAN presents a multi-node geographical coverage, such as MARKAL/TIMES, however it presents a high resolution in time, making use of the entire hourly distribution of a year production and load curves, and a high sector coupling that increases with the number of systems considered for analysis. The sector coupling is very important because it combines sectors, such as transport, industry and electricity. Comparatively with the other software's, energyPLAN presents better options in all the parameters. [52]

In this way, it is very important to establish some guidelines and objectives for choosing an energy modeling system. In this dissertation it is pretended to:

- Study the operation of a hydrogen production plant based on water electrolysis;
- Analyze production of H_2 based on different technologies for powering the electrolyzer;
- Analyze production in different time scales (from one hour to one year);
- Evaluate the costs associated with this project.

Having in consideration the topics above, the chosen software was the energyPLAN since it has a simple interface, operates as a simulation tool and has a high time resolution. Also, energyPLAN is a free download operating system with a low modeling complexity which allows a fast adaptation when conjugated with the online training exercises, favoring the acquisition of knowledge.

3.1.1 energyPLAN

The energyPLAN model was first developed in Denmark by Henrik Lund in 1999, having been expanded until version 15.0, which was launched in August 2019 and is used in this study. The main goal of this software is to assist the design and the simulation of energy planning and provide economic and technical analyses for different technical and investment strategies. [50] [53] This system is optimized with the use of hourly steps for one year, which includes the transport and industrial sectors and also the heat and electricity supplies. [50] [53] Through Figure 15 one can see the basic diagram for operation of the energyPLAN software.

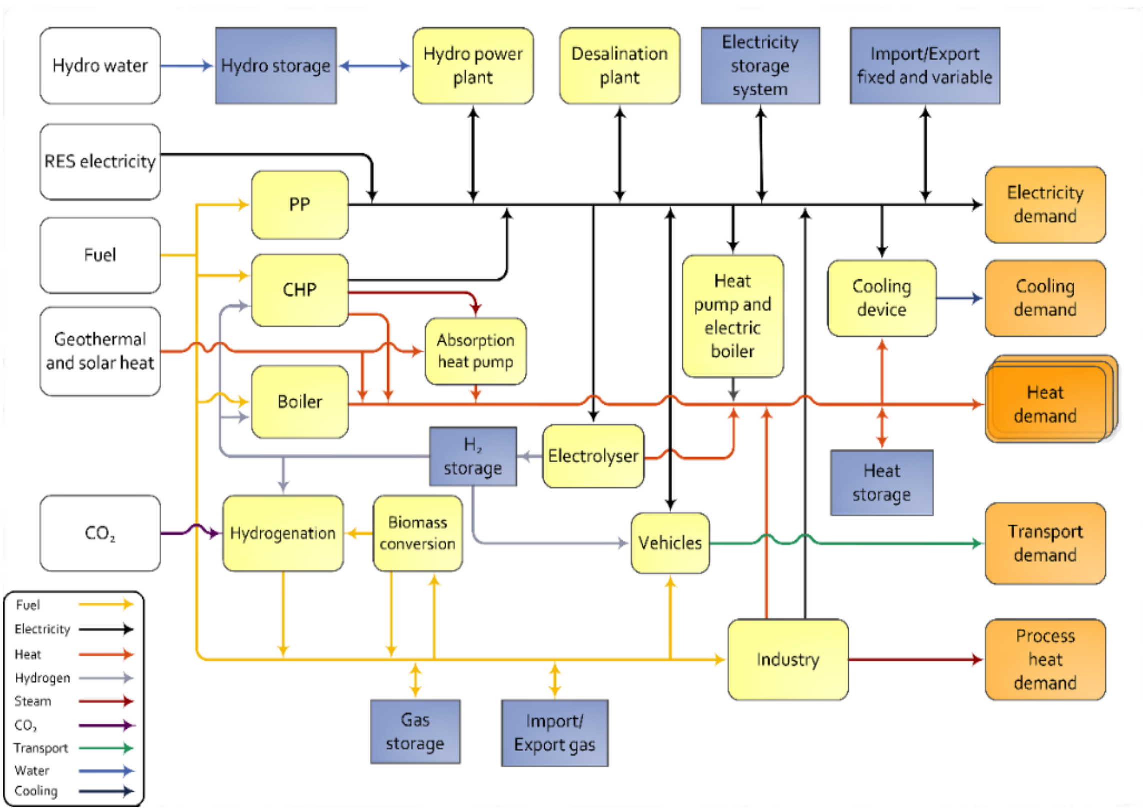

Figure 15: Illustration of how energyPLAN works. [53]

The diagram presented in Figure 15 corresponds to an input/output model. General inputs are the different RES and conventional technologies, demand, capacities of energy plants, costs and also different simulation strategies including import, export and excess electricity production. The outputs are the energy balances, fuel consumptions, imports or exports as well as CO_2 emissions. [53] [54]

In the inputs section, the three types of technical data normally required are:

- Annual production profiles (in one hour intervals);
- Total annual demand or production (TWh/year);
- Installed capacity by technology (MW).

The annual production profiles correspond to data for a leap year, with a file having 8784 points sized between 0 and 1 by default. [54]

EnergyPLAN can be utilized for different system analysis and optimization, such as technical analysis (design and analysis of large and complex energy models in different technical simulation strategies), market exchange analysis (analysis of the energy exchanges in international markets) and feasibility studies (calculated through the total annual costs of the systems with different simulations and designs). [53]

The optimization of the energy system at the technical level aims to minimize the import/export values and also, if applied, identify the options that operate with the lowest fuel consumption. Energy imports are required when the existing production units cannot satisfy demand, while energy exports occur when production exceeds demand. Market optimization in turn, aims to adjust supply and demand at the lowest possible cost, thus minimizing the system's operation costs. [54] [55]

3.2 Methodology

To achieve the above goals, some methods have been adopted:

- Assumption and modeling the year 2030 by considering two distinct weather conditions: a sunny year and a windy year;

- Acquisition and analysis of hourly renewable production data for the two weather profiles;
- Establishment and analysis of hydrogen production regimes;
- Economic analysis of each different configuration of the project.

3.2.1 Data analysis and selection

Given the fact that this study will be implemented in Portugal, firstly it is necessary to identify the type of climate. Portugal has a typical Mediterranean climate with well-defined seasons, namely dry and hot summers and rainy and cold winters.

The public announcements on the planned Sines facility have made clear that the H_2 plant will depend on dedicated renewable energy parks for supplying the electricity necessary for operation of the electrolyzers. These are expected to be solar photovoltaic and wind energy. Having this in consideration, two different weather conditions were defined for this study, a sunny year and a windy year. These choices were supported with the analysis of statistical data on total yearly electricity production by different technologies. Through the monthly renewable energy statistics (February 2020) provided by DGEG [56], it was possible to analyze the RES production from 2011 until 2019 (Figure 16).

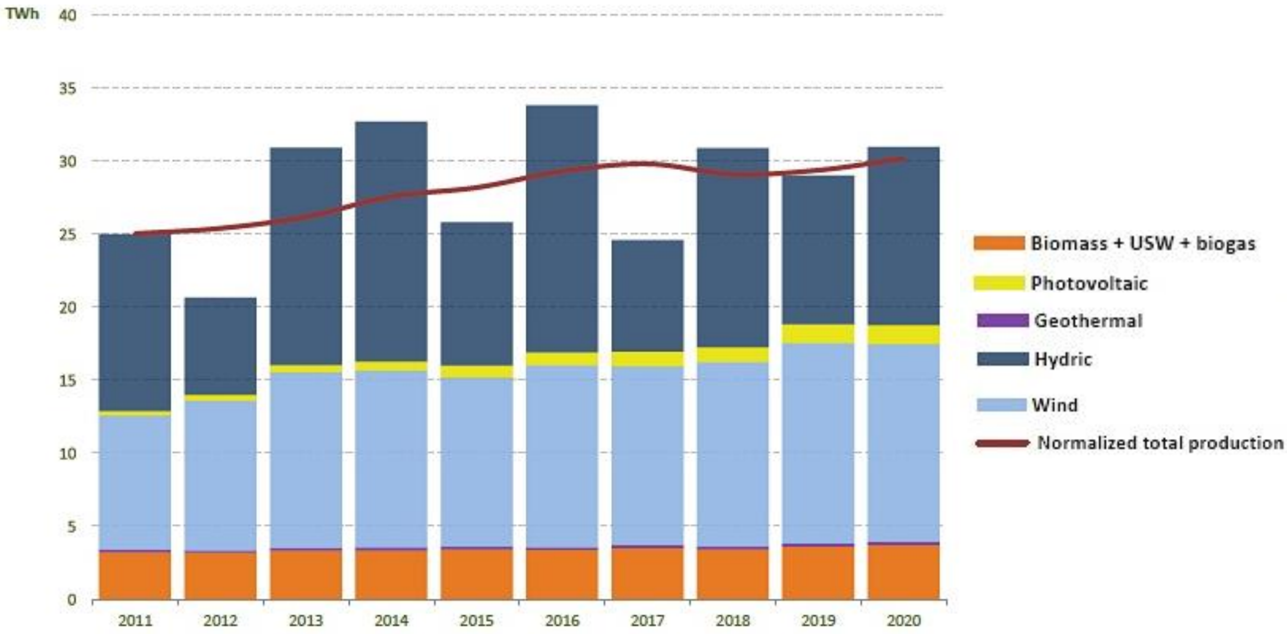

Figure 16: Electric energy produced by RES.[56]

Bases on the data mentioned above, the two weather conditions were identified as follows:

- For the period 2011 to 2019 the productivity of each technology (solar PV and wind) was determined by diving the respective total annual production by the installed capacity;

- From these values it was possible to identify 2012 as a sunny year (high productivity of solar PV production and low productivity of wind production) and 2016 as a windy year. Therefore, the production curves of solar PV and wind in 2012 were used as the characteristics profiles of production for a sunny 2030, while the production curves of 2016 where used as characteristics production profiles for a windy 2030;

- For each of the two technologies, the three years of higher productivity where chosen and an average productivity was calculated;

- This average productivity was used to estimate the total annual production of 1 GW capacity for each technology in 2030;

- In order to obtain this estimated production in 2030 it was necessary to introduce correction factors in energyPLAN.

Annex I provide the details of this calculation.

The production profiles were elaborated through the production diagrams (in MW), available from the REN (Redes Energéticas Nacionais) website together with the Excel software, being acquired data on special regime production of solar and wind power. The data had to be transformed from 15 minute intervals to one hour intervals. At this stage four files were obtained: two for the sunny year (solar PV and wind distributions for the year 2012 in one hour intervals) and two for the windy year (also, solar PV and wind distributions of the year 2016 in one hour intervals). These files were the base of our work.

In addition to the renewable production profiles defined, the value of the installed capacity of each renewable technology and the capacity of the electrolyzers were also considered. For both parameters were defined integer values in the range from 1 to 3 GW.

Table 6 presents the parameters considered in this modeling process.

Table 6: Values considered in modeling

Parameters	***RES power***	
	Photovoltaic Power	Wind Power
Corrective factor	- 0.56	- 0.34
Electrolyzer power	[1 , 3] GW	
RES power	[1 , 3] GW	

3.2.2 Description of H_2 production scenarios

In this study one of the objectives is the analysis of hydrogen production and, as such, it was necessary to define production scenarios corresponding to different production profiles of the electrolyzers. As a general rule, it was attempted to simulate operation based on the idea, that has been made public, that this H_2 production facility operates independently from the electricity grid. For any of the defined scenarios the parameters previously presented were applied.

In terms of the simulation with energyPLAN, the system under analysis in this study consists of an electrolyzer powered by a solar PV panel or a wind turbine, or a combination of both. This system is connected to the national electricity grid with which it can exchange electricity in both directions, depending on scenario characteristics. Figure 17 represents the installation scheme for H_2 production, in which one can see the renewable sources used and a possible recourse to the national grid in order to produce H_2.

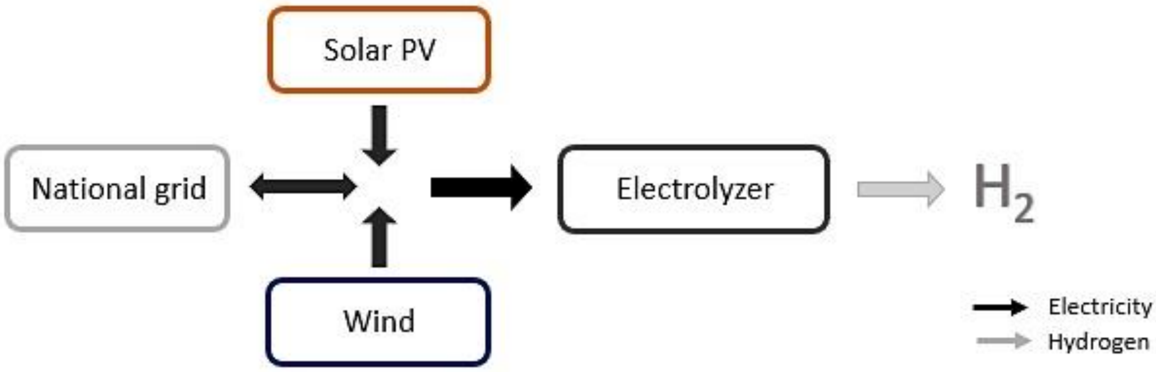

Figure 17: Hydrogen production scheme. The black arrows represent the origin of the electricity to power the electrolyzer while the gray arrow represents the product obtained.

Scenario A: H_2 Production in Constant Regime

The electrolyzer load in this scenario assumes a constant profile and with H_2 yearly production values between 1 and 7 TWh/year.

Scenario A analyses a limiting case, where there is a net self-sufficiency of the production plant, i.e., over a one-year period the system has net zero exchanges with the electricity grid. The system will have to exchange electricity with the national grid if the load is below (export) or above (import) generated power. Therefore, we chose, for each configuration, and electrolyzer load value for which the imports and exports of electricity have the same annual value, i.e. when we get a neutral yearly import balance (imports = exports).

In the energyPLAN software (Figure 18), the electricity production will assume the curve of distribution associated to the chosen renewable technology and respective installed capacity, while electrolyzers load will assume a constant distribution.

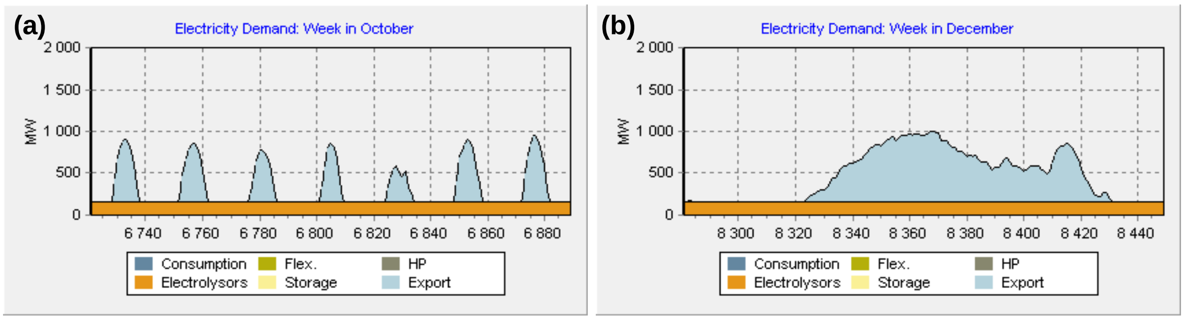

Figure 18: Demand of electricity, in Scenario A, in a sunny year with: (a) photovoltaic power; (b) wind power.

The graphs of production and imports for this scenario can be seen through Figure 19.

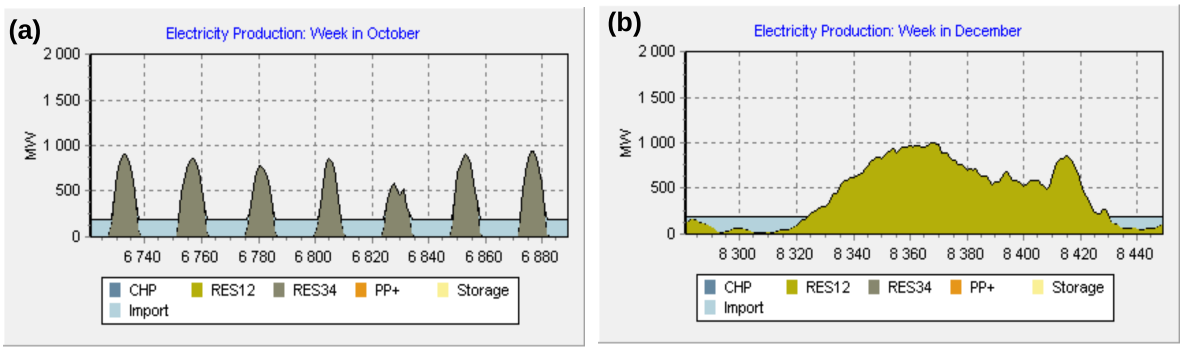

Figure 19: Electricity production with (a) photovoltaic power and (b) wind power. The blue color represents the imports necessary for the production of H_2. The gray and green color represents the production of electricity by the photovoltaic power and wind power, respectively.

Scenario B: H_2 Production in Self-sufficiency Regime with Single RES

In this case, the electrolyzer load follows the generated power curve, with H_2 production occurring only as long as there is renewable electricity production and all renewable electricity is used for powering the electrolyzers (Figure 20). It is a regime that does not require energy imports from the national grid, although we consider that excess electricity production is injected in the grid. In this simple self-sufficiency regime, the electrolyzers are only powered by photovoltaic power **or** wind power.

To ensure proper functioning of the electrolyzers, in the case where output power from RES exceeds the electrolyzers capacity, and in order to not overcharge, they will operate, for short periods, at a maximum of 50% above their nominal capacity. Output power from RES that exceeds this threshold is injected in the national grid.

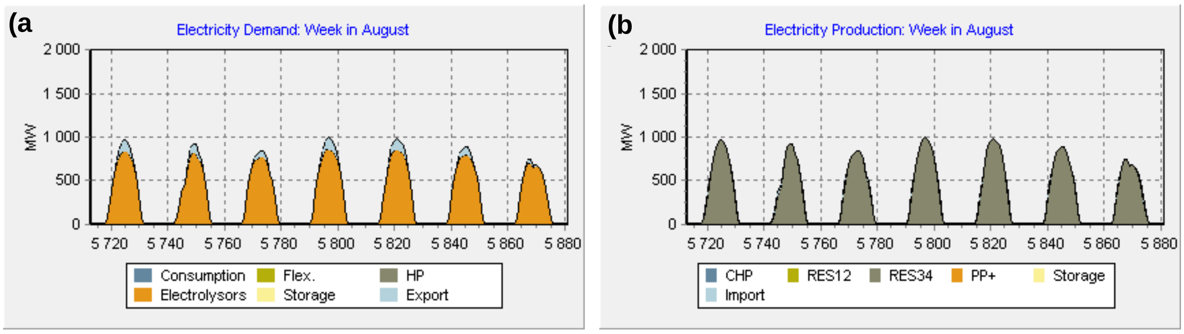

Figure 20: Electrolyzer load (a) and Production (b) of electricity, in Scenario B, with photovoltaic power in a sunny year.

Scenario C: H_2 Production in Self-sufficiency Regime with Combined RES

This scenario assumes the same parameters as scenario B, however in this self-sufficiency regime the electrolyzers are powered by different combinations of photovoltaic power **and** wind power.

In energyPLAN, the generated power is obtained from the sum of distribution files for photovoltaic and wind power with different combinations of nominal capacity. Photovoltaic power assumes a grey color and wind power assumes the green color (Figure 21 - b).

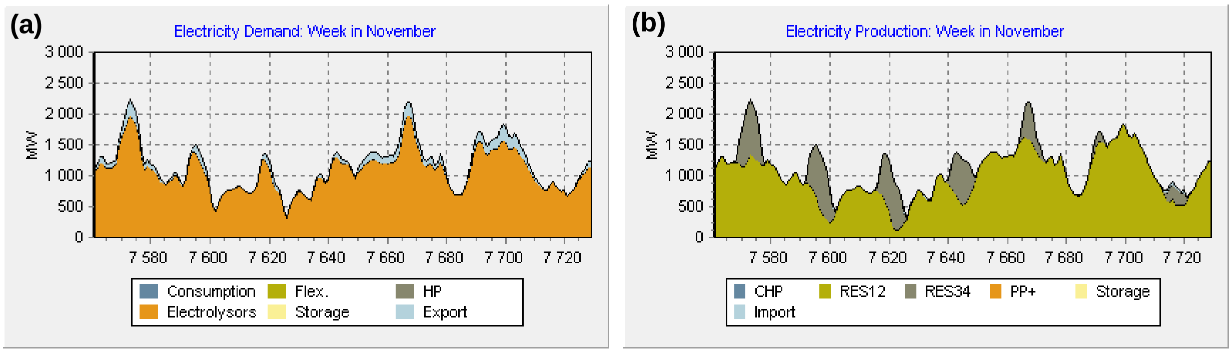

Figure 21: Electrolyzer load (a) and Production (b) of electricity in Scenario C, in a sunny year.

Scenario D: H_2 Production in Self-sufficiency Regime with Single RES and a minimum load of 20% of electrolyzer nominal capacity

The electrolyzer load also follows the generated power curve, however it has a minimum load value of 20% of the nominal capacity of the electrolyzers. This leads to a need for imports from the national grid if the RES generation power is below this minimum load. The electrolyzers are still restricted to a maximum load 50% above the nominal capacity. This parameter will be applied in single self-sufficiency regime in EnergyPLAN (Figure 22).

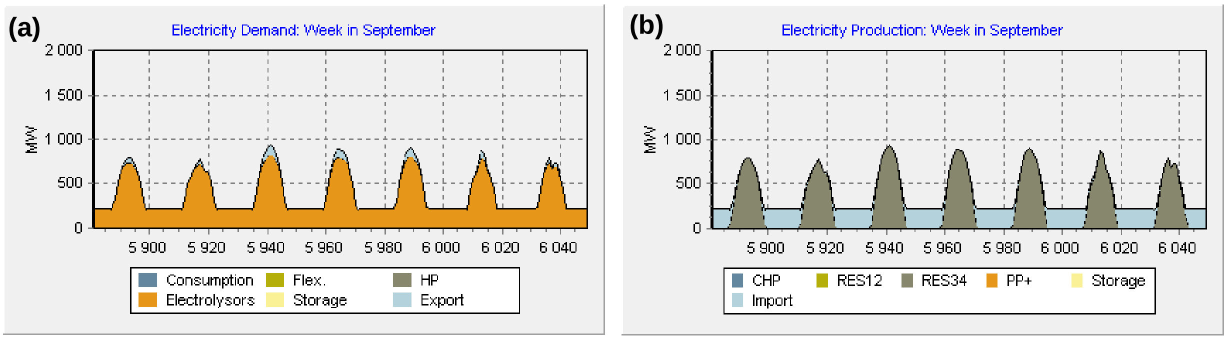

Figure 22: Electrolyzer load (a) and Production (b) of electricity in Scenario D with photovoltaic power, in a sunny year.

Scenario E: H_2 Production in Self-sufficiency Regime Combined RES and a minimum load of 20% of electrolyzer nominal capacity

This scenario follows the same guidelines as scenario D, however, it is applied with the combined RES technologies (Figure 23).

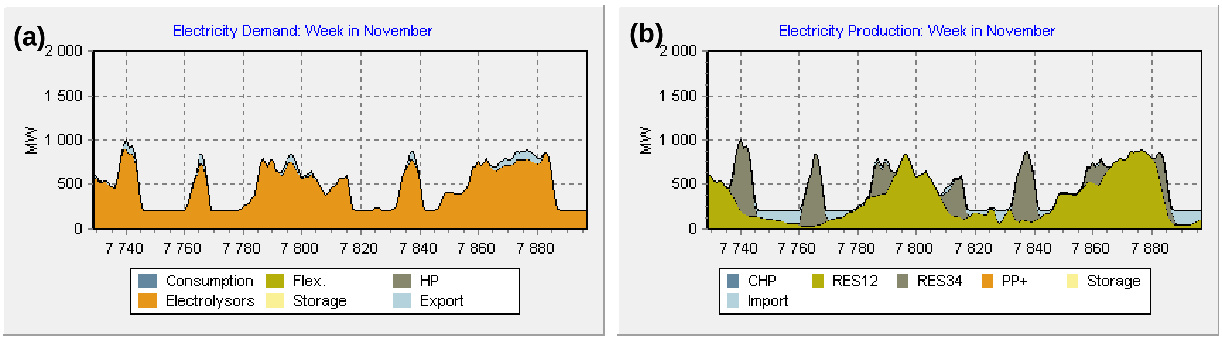

Figure 23: Electrolyzer load (a) and Production (b) of electricity in Scenario E in a sunny year.

Table 7 presents the summary of the scenarios presented above.

Table 7: Scenario characteristics.

Scenario	*Regime*	*Renewable power (GW)*	*Electrolyzer Power (GW)*	*H_2 fixed value (TWh/year)*	*Exchanges with national grid*
A	Constant		[1, 3]	[1 , 7]	Yes
B	Single RES			Not applied	No
C	Combined RES			Not applied	No
D	Singles RES with a minimum load of 20% of electrolyzer	[1 , 3]	[1 , 3]*	Not applied	Yes
E	Combined RES with a minimum load of 20% of electrolyzer			Not applied	Yes

* Operate at a maximum of 50% above their nominal production power.

3.2.3 Technical analysis

For each of the scenarios described in the previous section, the technical simulation provides data on the production of electricity from RES (solar PV and/or wind), H_2 production and electricity exchanges with the national grid. The results are obtained in one-hour intervals over one year. This allows a technical analysis on different times scales but in this work the focus is on annual values. From these results it is also possible to estimate the volumes of water necessary for the electrolysis reaction in each scenario. The outcome of the technical analysis is presented and discussed in section 4.1 and 4.2.

3.2.4 Economic analysis

The economic viability of this project will be assessed from the study of the costs for implementing each configuration, which will include investments, operation and maintenance cost of equipment, and variable costs of water and exchanges with the national electricity grid.

Cost analysis in energyPLAN is based on a Cost Data sheet associated with the scenario files, in which the base parameters were set to calculate the costs. This file contains the interest rate, the Investment and Fixed O&M (operation and maintenance) of renewable energy (which are photovoltaic, wind and wind offshore production type) and electrolyzer. The prices of water and electricity were also taken into consideration.

The main costs calculations were based on a discount rate of 3%, as this is the value that has been used in other costs estimation exercises at the DGEG, namely for the National Energy and Climate Plan. The annualized investment costs are calculated by the expression:

$$\mathrm{a} = = \frac{Ci}{(1-(1+i)^{-n}}$$

where:

a – annualized investment costs

C – total cost of investment of each technology

i – discount rate

n – lifespan of the equipment

For the Investment and Fixed O&M costs of electrolyzer and RES, the Techno-economic assumptions of the PRIMES model for the year 2030 were followed, and for the price of electricity for the same year, the values traded in the MIBEL electricity futures market were used.[57]

The values associated in the parameters above can be observed in Table 8 and Table 9.

Table 8: Value of interest rate and electricity cost defined for the economic data

Parameter	***Value***
Interest rate (%)	3

Table 9: Values for Investment and Fixed O&M for Renewable Energy and Electrolyzer in 2030 expressed in $€_{2015}$

Prod. Type	***Investment*** *(M€ pr. MW)*	***Period*** *(years)*	***O&M*** *(% of Inv.)*
Renewable Energy			
Photovoltaic	0.55	25	2.3
Wind	1.159	25	1.2
Wind Offshore	2.86	25	1.5
Electrolyzer	0.466	variable*	3.2

*The lifespan of the electrolyzer was considered to be 50,000 hours, and its duration in years depends on the operation profile.

The electricity grid access was stipulated with base in the Rates and Prices for electricity and other services in 2020 [58]. For the price of potable and industrial water were utilized the tariffs for the Sines Industrial and Logistics zone in 2020 [59]. Values of these costs for 2030 were estimated by applying an average annual inflation rate of 1.5%. The prices assumed for access to the electricity grid and water consumption in 2030 are shown in Table 10.

Table 10: Assumed prices and tariffs for electricity and water in 2030 expressed in $€_{2015}$

Parameter	***Value***	
	Purchase	**Sale**
Price of electricity	29.8 €/MWh	LCOE of each configuration up to a maximum of 20 €/MWh
Electricity network access rate		0.4905 €/MWh
Water	**Potable**	
	1.89 €/m^3 + 19,777 €/year access tariff	
	Industrial	
	0.39 €/m^3 + 19,555 €/year access tariff	

With the cost data complete with all the necessary parameters, the total costs for each scenario and configuration were evaluated.

Therefore, from the economic evaluation of this project several parameters were obtained, such as:

- Annualized Investment Costs and Operation and Maintenance Costs in 2030;
- Electricity imports and exports earnings in 2030;
- Electrical grid access costs in 2030;
- Variable costs with potable or industrial water in 2030;
- LCOH (Levelized cost of hydrogen) and LCOE (Levelized cost of electricity).

All values are presented in $€_{2015}$.

The economic analysis of this project will be present in chapter 4.3, where we also present a sensitivity analysis on the influence of the discount rate, the type of wind technology and access to the national electricity grid in the levelized cost of hydrogen.

4. Results

In this chapter the results obtained from the technical and economic modeling will be presented and discussed. In the technical analysis we evaluate H_2 production for different ways of feeding the electrolyzers. In the economic analysis we consider and evaluate the total costs and levelized cost of hydrogen for each scenario.

4.1 Technical analysis

4.1.1 Scenario A – H_2 production in Constant Regime

The first analysis is based on the understanding of how hydrogen production works for the case of constant electrolyzer load. Two options are considered, one where the electrolyzers are powered by solar photovoltaic electricity, the other where the source of power for the electrolyzers comes from wind electricity.

For the electrolyzer to work in a constant regime, energy exchanges with the electricity grid are necessary at all times, to compensate for the variable profile of the RES production. This is a significant deviation from the perspective that the H_2 plant should be essentially autonomous from the national grid. Nevertheless, as production under constant load represents the most basic mode of operation, it will be analyzed but considering that annual net exchanges with the grid are close to zero. This is not necessarily the best economic option, but it provides a reference point for comparing the different options in this scenario. Figure 24 demonstrates this zero import balance for the case of a 1 GW electrolyzer powered by 1 GW of photovoltaic electricity. We started by analyzing imports and exports of electricity for a certain fixed value of H_2 production.

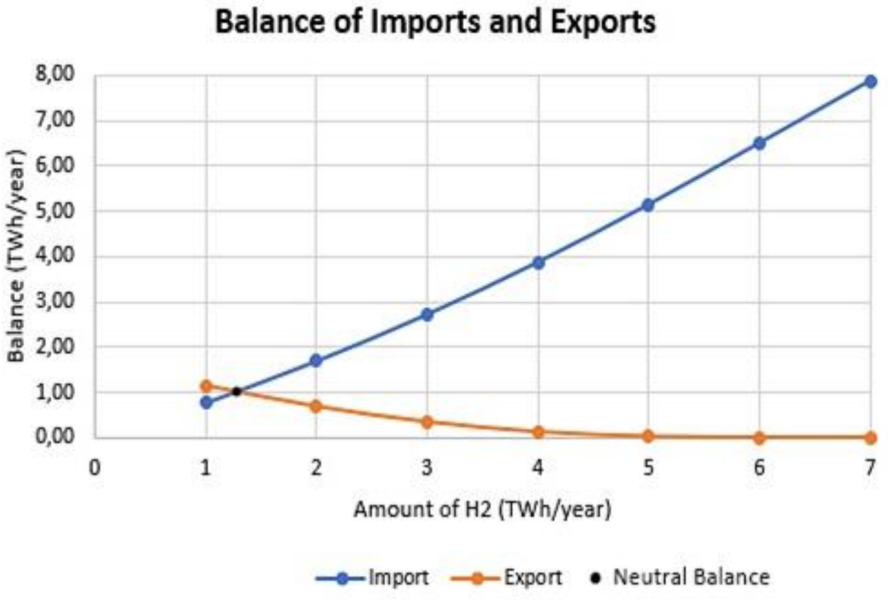

Figure 24: Electricity imports and exports in a sunny year for a 1 GW electrolyzer powered by photovoltaic power with 1 GW. In this case, the point where electricity imports and exports are equal corresponds to an annual production of 1.3 kton of H_2.

One can see that for this regime substantial electricity exchanges with the national grid are necessary, for all the range of parameters defined.

A plot of the import balance, resulting from the subtraction of exports from imports, shows the net electricity exchanges for this production process and allows a simpler perception of the point of zero import balance for each case (Figure 25).

Negative values of the import balance correspond to annual net electricity exports to the national grid, and positive values correspond to net import values from grid.

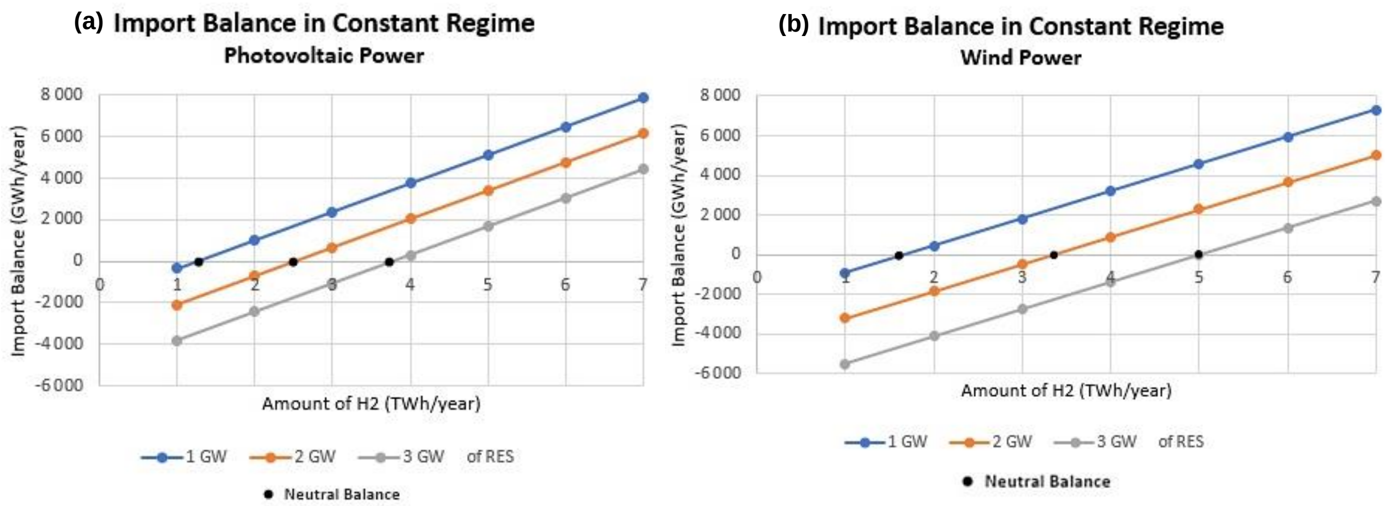

Figure 25: Import Balance in a sunny year with: (a) photovoltaic power; (b) wind power.

Figure 25 presents the variation of the electricity import balance, in a sunny year, with the annual production of H_2. It can be seen that the use of wind power (Figure 25 - b) allows a higher H_2 production with less exchanges with the grid (in GWh/year) when compared with the use of photovoltaic power (Figure 25 – a), which can be justified with the fact that, in general, wind power provides higher equivalent full load hours than solar photovoltaic power.

It is possible to see that an increase in the installed capacity of RES results in more electricity exports to the grid and the neutral import balance corresponding to larger value of H_2 production. Through this neutral balance the annual production of H_2 in kilotons (kt) was calculated for both RES (Figure 26).

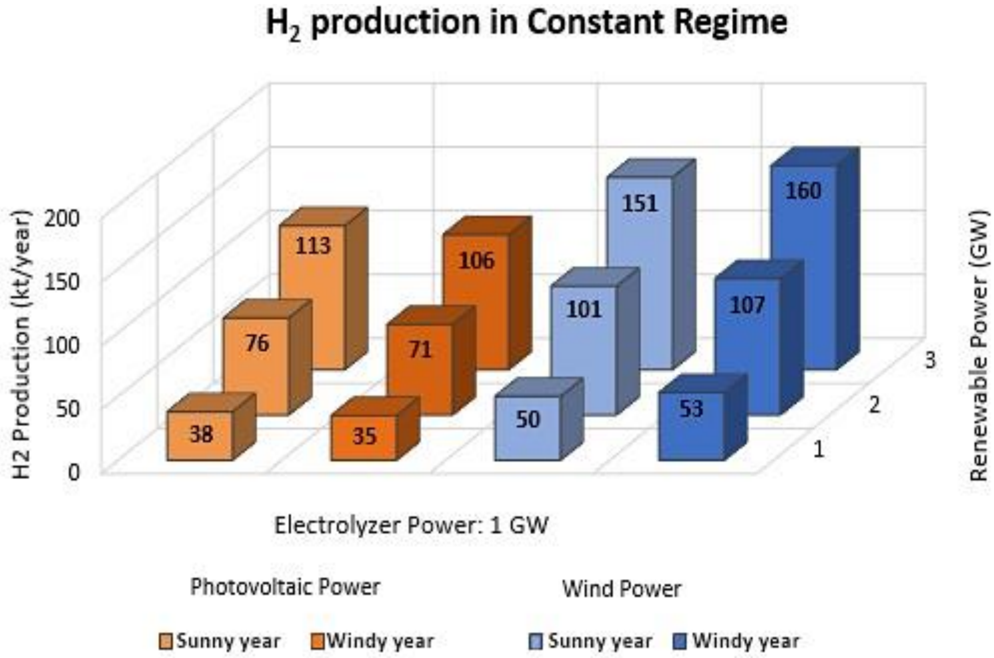

Figure 26: H_2 production in Constant Regime.

The figure above presents the annual H_2 production in scenario A for an electrolyzer with nominal capacity of 1GW. In this scenario, of constant electrolyzer load, H_2 production is independent of electrolyzer capacity. This stems from the fact that we are analyzing values of H_2 production that are fixed in advance, and therefore are not affected if electrolyzer nominal capacity is increased.

Wind power represents the most productive option, with 3 GW of renewable capacity producing approximately 160 kt in a windy year. As expected, the photovoltaic power is more productive in a sunny year than in windy year, with 3 GW of renewable power producing 113 H_2 kt/year.

In short, despite H_2 production from photovoltaic and wind power achieving some considerable values, it requires large amounts of electricity exchanges with the national grid and the renewable power would not be used to its fullest, this stems from the fact that we are using a fixed value of H_2 production and if the RE produce more than the required value it will not be harnessed for the hydrogen manufacture.

4.1.2 Scenario B – H_2 Production in Self-sufficiency Regime with Single RES

Having these characteristics in consideration Scenario B was created in order to evaluate a H_2 production mode that uses all RES power for feeding the electrolyzers and does not import electricity from the national grid.

Nevertheless, exchanges with the grid can happen in the case of excess electricity production by the associated RES. This can happen when the nominal capacity of the RES is higher than the nominal capacity of the electrolyzer (e.g. in the case where electrolyzer capacity is 1 GW and PV capacity is 3 GW). In such cases, there are periods in which the RES power can significantly exceed significantly the capacity of the electrolyzer. Electrolyzers, and particularly PEM electrolyzers, can operate above nominal capacity and therefore we allow the electrolyzer to operate at a load of 50% above the nominal capacity for short periods of time. Above this limit, the excess electricity production is considered to be injected in the national electricity grid. Although this is not relevant as a technical modeling problem, it is important from the point of view of cost estimation. This maximum load problem is always considered in scenarios B, C, D and E.

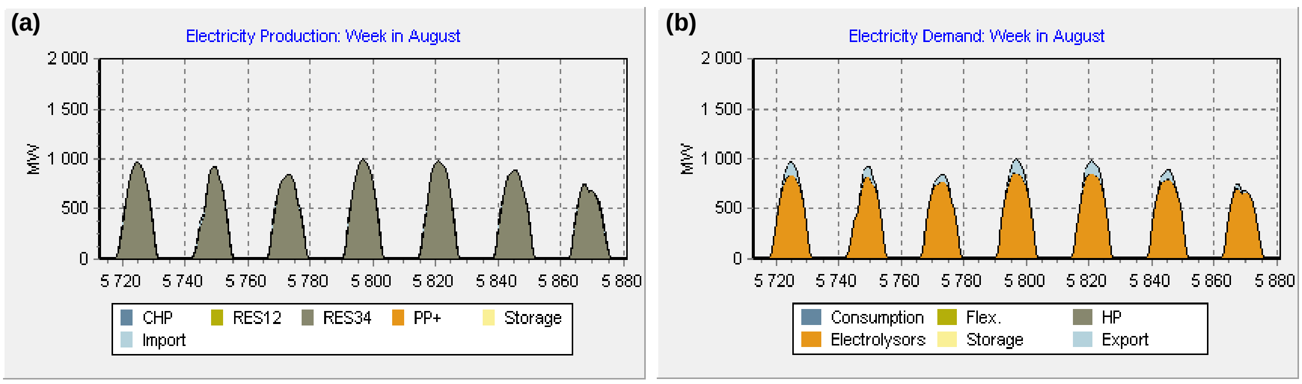

Figure 27: (a) Electricity production with 1 GW of photovoltaic power; (b) Load curve for a 1 GW electrolyzer.

Figure 27 – a represents the intermittent production curve of the photovoltaic park given the fact that during night periods there is no production. In Figure 27 – b the blue color represents the production from the renewable park and the orange color represents the electrolyzer load curve.

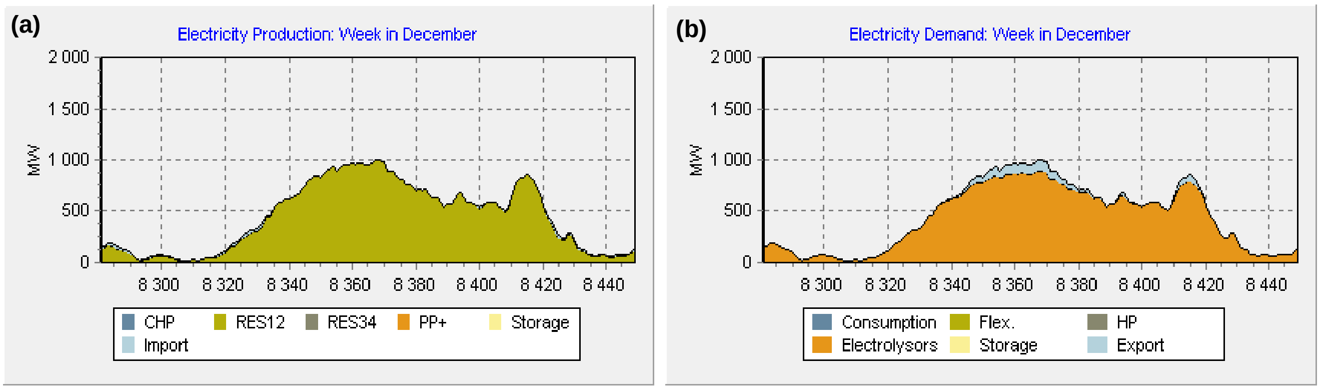

Figure 28: (a) Electricity production with 1 GW of wind power; (b) Load curve for a 1 GW electrolyzer.

A characteristic electricity production curve with wind power is shown in Figure 28 – (a) and Figure 28 – (b) shows the electrolyzer load in conditions of self-sufficiency operation. This renewable energy source presents a different production pattern from that of solar PV power allowing a continuous, although variable, operation of the electrolyzer.

The H_2 production with photovoltaic power was calculated and the results are represented in Figure 29.

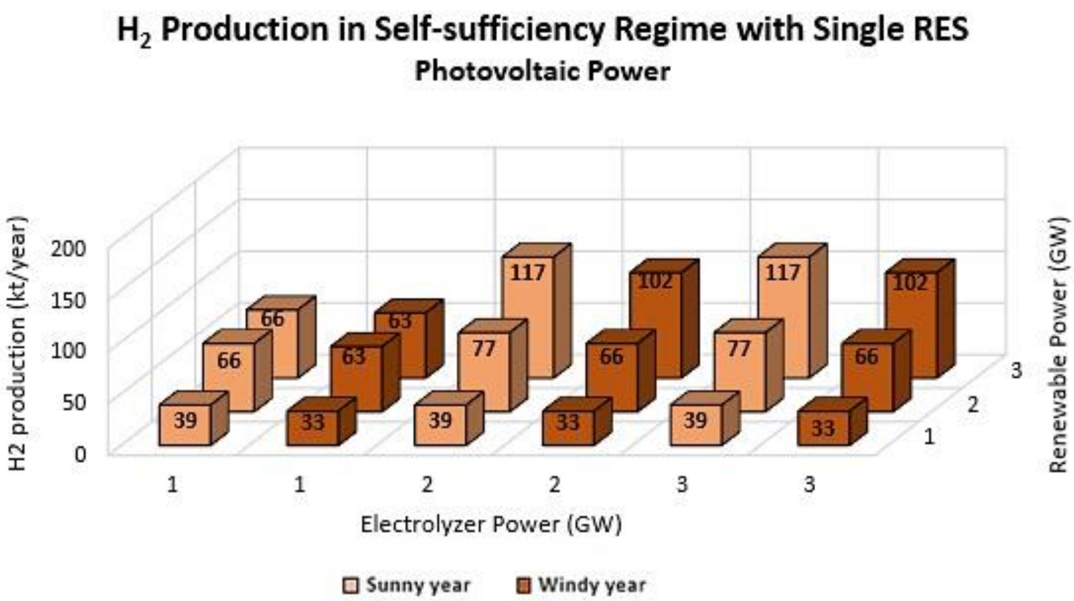

Figure 29: H_2 production in Self-sufficiency Regime with photovoltaic power in sunny and windy year.

Considering Figure 29, one can highlight that in this type of regime the highest value of H_2 production is approximately 117 kt/year, achieving the maximum with 3 GW of renewable potential combined with 2 GW of electrolyzer power. In this case, the weather conditions present some variations in the amount of hydrogen produced, per example, for 2 GW of electrolyzer and 3 GW of RES the production varies between 102 (windy year) to 117 (sunny year), which means an increase of 14.7%.

Annual H_2 production with 3 GW of RES power and 2 GW or 3 GW electrolyzer is the same. The load curves for these two cases are represented in Figure 30.

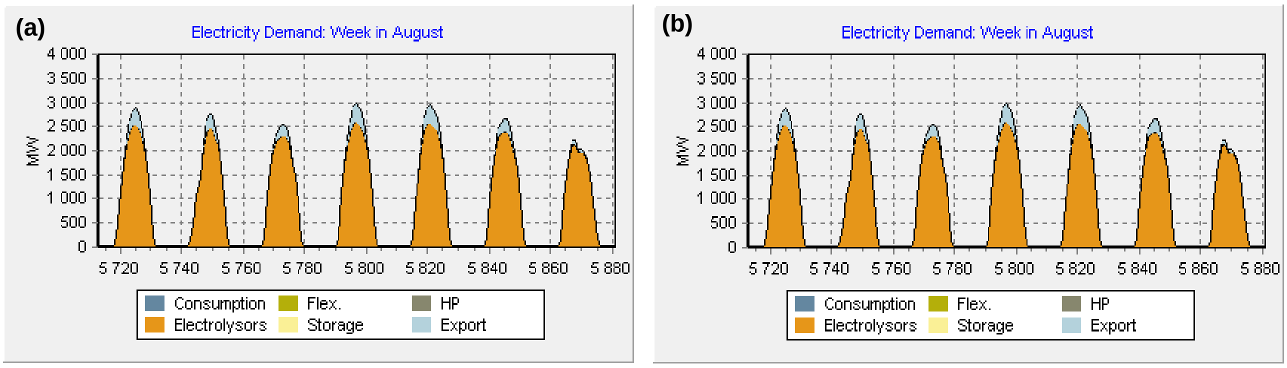

Figure 30: Electricity production by 3GW of photovoltaic power with: (a) 2 GW of electrolyzer; (b) 3 GW of electrolyzer.

It is possible to see that the electrolyzers load curve is equal for both cases which is justified with the fact that the electrolyzer operates at a maximum of 50% above its nominal capacity, i.e. the 2 GW electrolyzer is allowed to operate at 3 GW for short periods of time. So, in this configuration (3 GW of solar PV nominal capacity) the load curve of the 2 GW electrolyzer is the same as the 3 GW electrolyzer. The load is maximized in order to reduce all electricity imports needed, although there are some exports of excess production to the grid, as described in scenario A. In conditions of energy self-sufficiency of the H_2 plant (no imports from the grid), the use of photovoltaic power makes it necessary to turn off the electrolyzers at night.

The H_2 production in the Self-sufficiency Regime with Single RES was also analyzed for the case of electrolyzers powered by wind production (Figure 31).

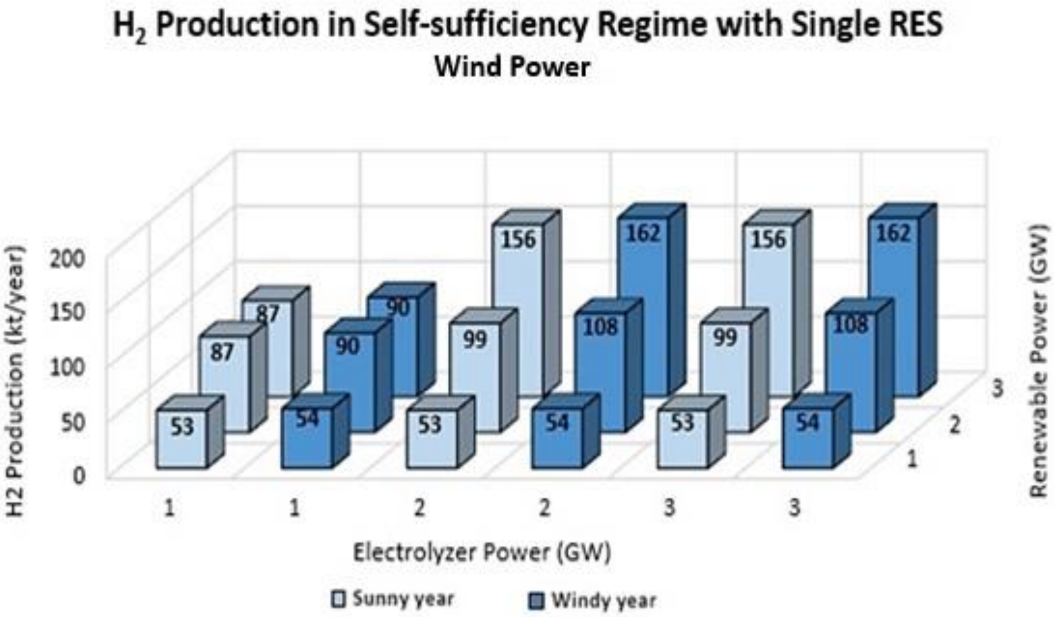

Figure 31: H_2 production in Self-sufficiency Regime with wind power in sunny and windy year.

With this configuration a higher value of H_2 production is achieved comparatively with the photovoltaic power in self-sufficiency regime. In this case, the different weather conditions result in smaller relative variation in production, in which it is verified an increase from 156 ktH_2/year (sunny year) to 162 ktH_2/year (windy year), corresponding to an increase of 3.8%.

It is possible to produce more with this renewable power, whereby one can say that it will be a much more favorable resource than photovoltaic power, with maximum production achieved for 2 GW of electrolyzer and 3 GW of renewable wind power.

An example of a duration curve of the electrolyzer powered with solar photovoltaic, in this scenario B, is present in Figure 32. One can see that the maximum value registered is 864 MW and the electrolyzer is turned off for half of the year, while the average power is about 203 MW. The number of equivalent production hours is 1783.

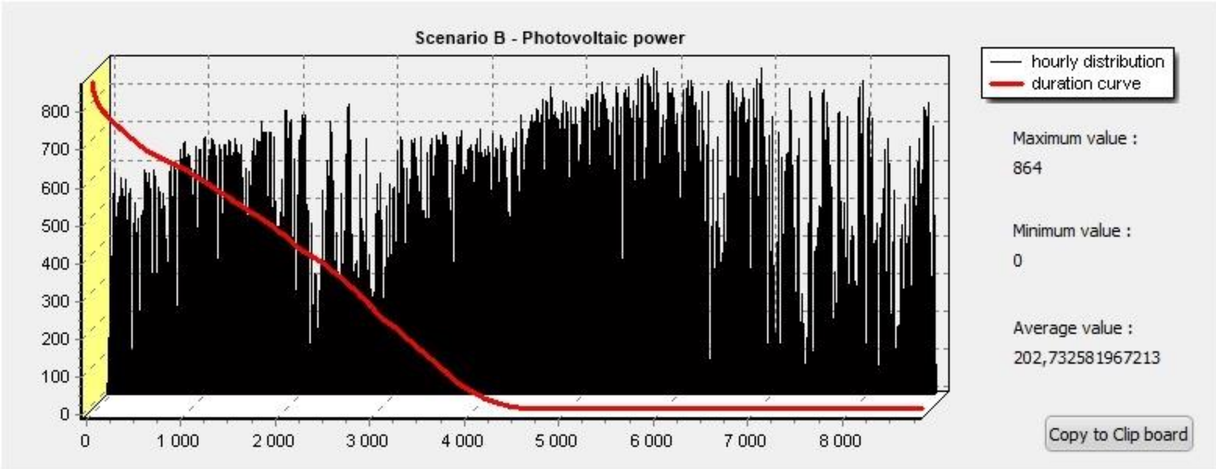

Figure 32: Example of a distribution curve, in a sunny year, with 1 GW of electrolyzer and 1 GW of photovoltaic power.

The distribution curve with wind power is represent in Figure 33.

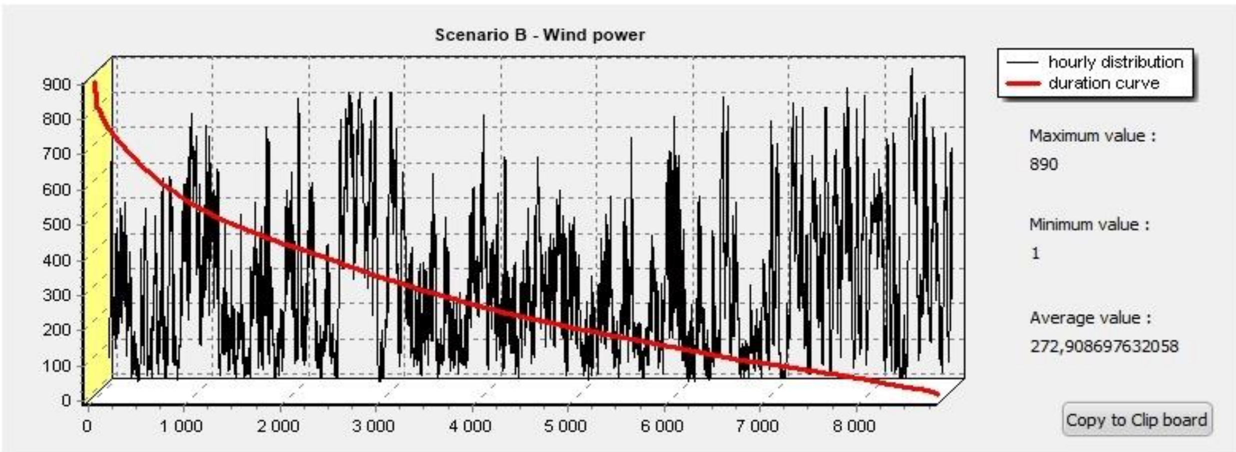

Figure 33: Example of a distribution curve, in a sunny year, with 1 GW of electrolyzer and 1 GW of wind power.

In this case, the maximum value hit is 890 MW and the average value is, approximately, 273 MW. The number of equivalent production hours will be higher, 2398 hours, comparatively with the example presented before. The fact that this power is not intermittent like photovoltaic and has a higher number of equivalent hours of production justifies that the electrolyzers powered by wind power are more productive.

Being a scenario of self-sufficiency, imports from the national network will not be necessary, however there are some that only happen due to difficulty in making a perfect adjustment, at the level of simulation, between production and consumption (Figure 34).

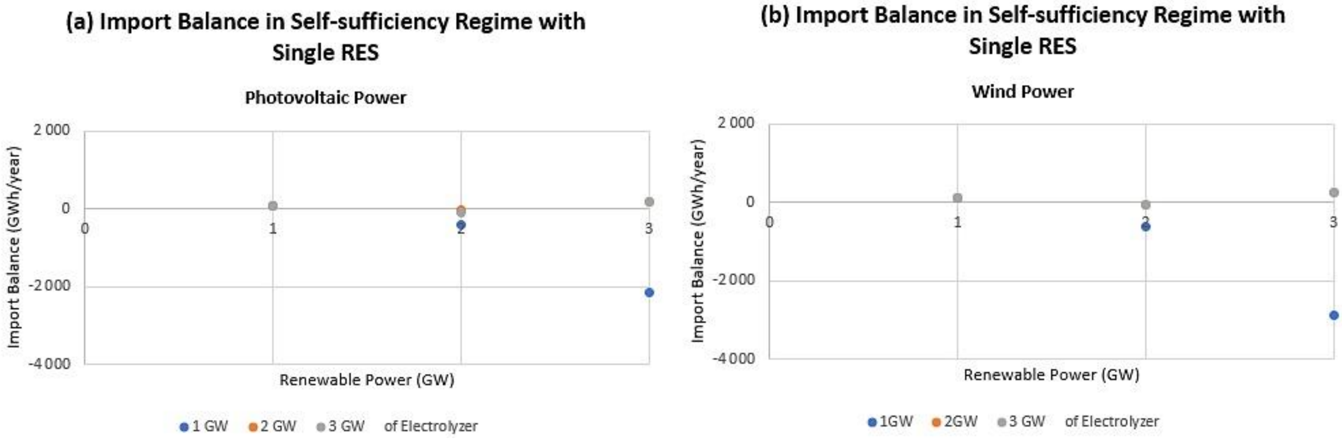

Figure 34: Import Balance in Self-sufficiency Regime with Singles RES, in a sunny year, with: (a) photovoltaic power; (b): wind power.

As expected, the import balance in this case is lower when compared with the constant regime, giving the characteristics of the production regime. The configurations with the electrolyzer working on wind power presents more exports to the national grid, achieving is maximum with 3 GW of renewable power.

4.1.3 Scenario C – Production in Self-sufficiency Regime with Combined RES

Considering the higher productivity and better use of the photovoltaic and wind power in this type of regime, Scenario C was conceived. In this scenario the annual H_2 production was estimated using a combination of both RES. As in scenario B, the electrolyzer only consumes power from the associated wind and solar farms. Excess electricity production is treated as in scenario B. Table 11 shows the nomenclature used to identify each combination.

Table 11: Nomenclatures for Scenario C

Value of Electrolyzer	*Nomenclature*	*Constitution*
1 GW	1P **or** 1W	1 GW of Photovoltaic **or** 1 GW of Wind
2 GW	1P 1W	1 GW of Photovoltaic **and** 1 GW of Wind
3 GW	2P 1W	2 GW of Photovoltaic **and** 1 GW of Wind
	1P 2W	1 GW of Photovoltaic **and** 2 GW of Wind

The Figure 35 shows an example of the electricity production by the combined renewable resources and the load curve of the electrolyzer. One can see that with the combined sources there are fewer periods without electricity production comparatively to the production of H_2 only with photovoltaic power.

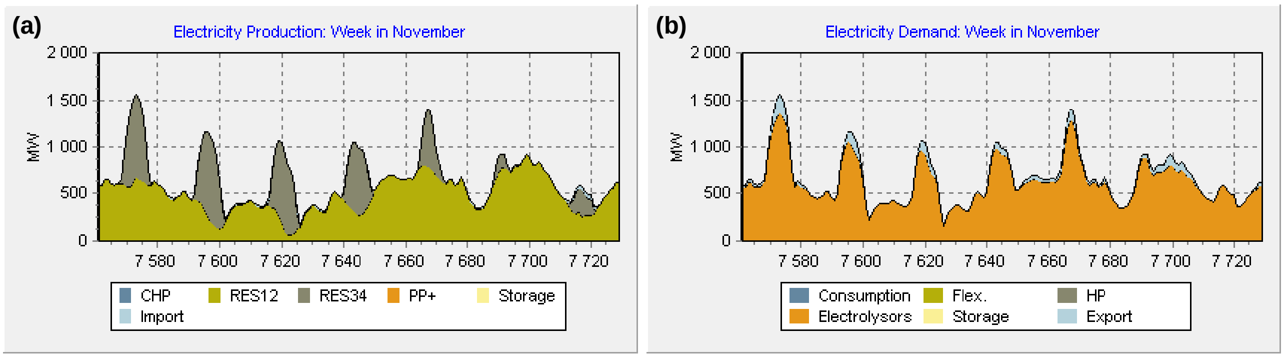

Figure 35: (a): Example of electricity production with 1 GW of photovoltaic power combined with 1 GW of wind power. Green color represents the wind power and grey color the photovoltaic power; (b): Load curve for 1 GW of electrolyzer.

So, with these conditions the H_2 production was calculated for both weather conditions, sunny and windy year (Figure 36).

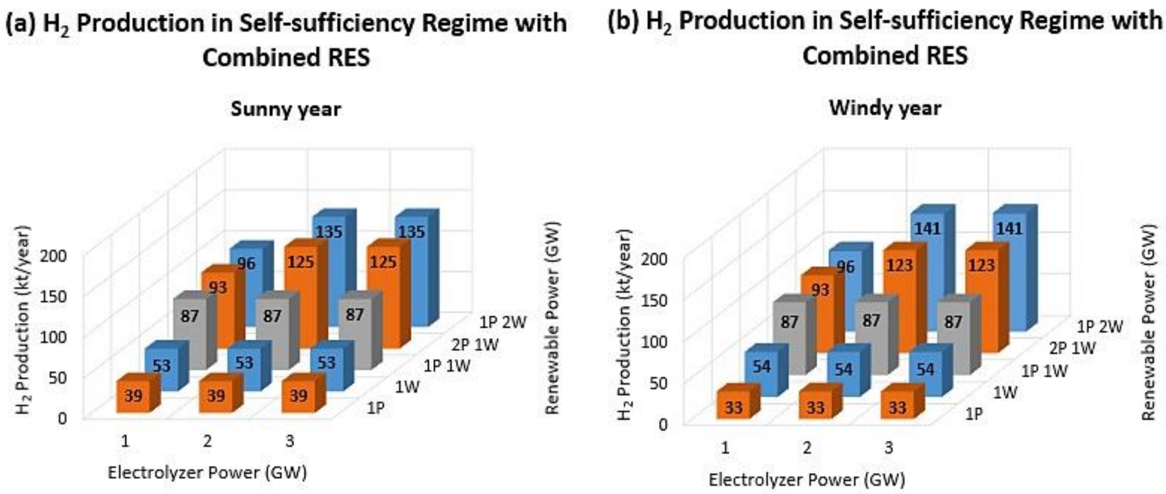

Figure 36: H_2 production in Self-sufficiency Regime with Combined RES in a: (a) sunny year; (b): windy year.

Through Figure 36, one can verify that this regime allows an intermediate production level between the solar only and wind only options analyzed in scenario B. In this scenario, the weather conditions have a smaller impact on production, especially with 1 GW of wind power that has 53 kt/year in a sunny year and increase for 54 kt/year in a windy year. The most notable production differences are verified with 1 GW of photovoltaic power that decreases from 39 kt/year to 33 kt/year, and with 1 GW of photovoltaic power combined with 2 GW of wind power that present 135 kt/year (in a sunny year) and increase to 141 kt/year (in a windy year).

Similar to the Constant Production Regime (Scenario A), the Self-sufficiency Regime with Combined RES, namely 1 GW of photovoltaic power combined with 1 GW of wind power, does not change its production with the increasing electrolyzer capacity. Despite the combination, the production power of the combined park is always below 1.5 GW (i.e. below the maximum allowed load for the 1 GW electrolyzer), which means that even with the increase in the electrolyzer capacity for 2 or 3 GW this capacity will be not utilized because there is not enough power generation.

In other renewable power, namely, 2P 1W and 1P 2W, it is verified that the increasing electrolyzer power consumes all the produced power.

This type of production allows a better use of both renewable potentials, with larger values of H_2 per year when combined together.

The import balance of this scenario is outlined in Figure 37.

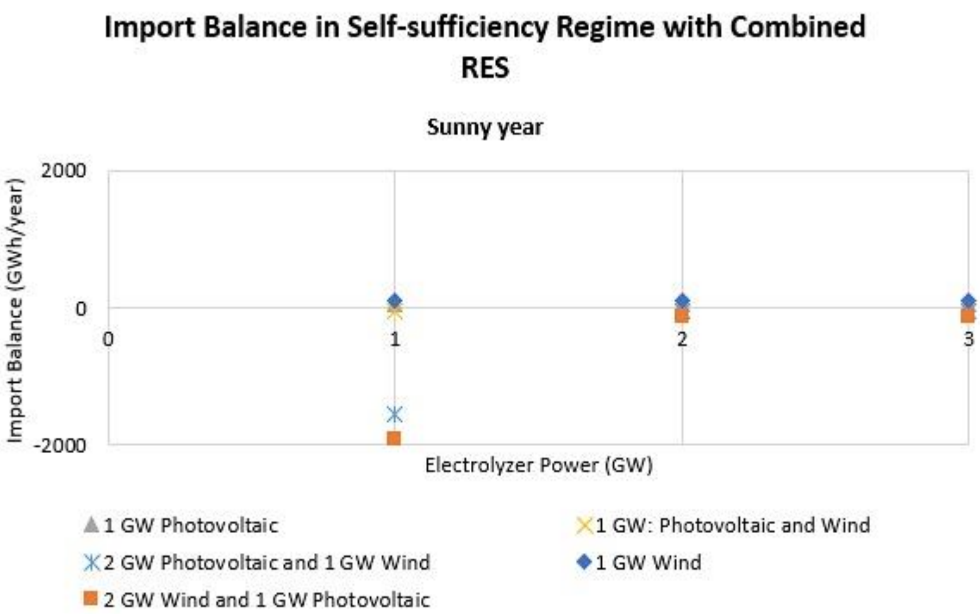

Figure 37: Import Balance in Self-sufficiency Regime with Combined RES, in sunny year.

As expected, the imports in Scenario C are inexistent given the maximum use of renewable resources. With 1 GW of electrolyzer combined with 2W 1P power or with 2P 1W power there are more exports to the national grid. This happens because the electrolyzer only operates at a maximum of 50% above its nominal capacity, with the remaining power produced exported when it is not consumed. The import balance of a sunny year is almost equal to that of a windy year, however, the latter shows a little more exports to the grid from wind power.

With all the characteristics taken in consideration for each scenario, the electrolyzers reach to minimum values very close to 0 (Figure 38).

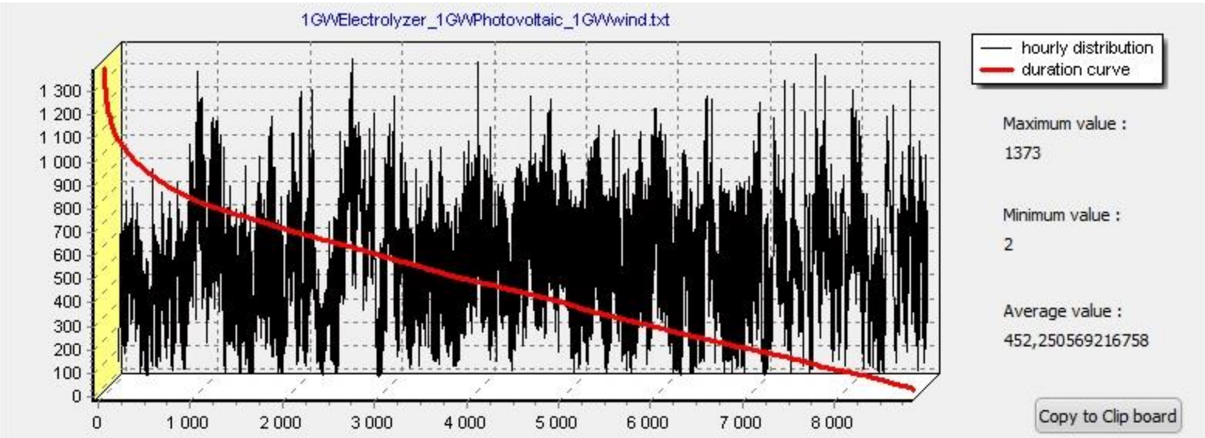

Figure 38: Example of a distribution curve for Combined RES (1 GW of photovoltaic with 1 GW of wind power) with 1 GW of electrolyzer, in a sunny year.

As it is possible to see through the example from Figure 38 the maximum value hit is 1,373 MW and the electrolyzer has a maximum capacity of work of 1.5 GW (resulting from 1 GW with the increase of 50%). The average value from this example is 452.3 MW, a value higher when compared with photovoltaic or wind power. This average value is higher given the fact that the wind power is a renewable source less intermittent when compared to photovoltaic power and presents a higher number of equivalent production, culminating in a higher average production value when both renewable resources are combined.

4.1.4 Scenario D – H_2 Production in Self-sufficiency Regime with Single RES and a minimum load of 20% of electrolyzer nominal capacity

In order to avoid time periods when the electrolyzers must be turned off, scenario D was created to guarantee a minimum level of production of the electrolyzers in a continuous way.

A minimum production level corresponding to a load of 20% of electrolyzer nominal capacity was applied to all distributions of scenarios B and C.

Table 12 presents the minimum load value for each electrolyzer nominal capacity.

Table 12: Minimum load value for each electrolyzer nominal capacity

Electrolyzer Capacity	***Minimum Load (20% Applied)***
1 GW	200 MW
2 GW	400 MW
3 GW	600 MW

An example of the electricity production and the load curve of the electrolyzer can be seen in Figure 39.

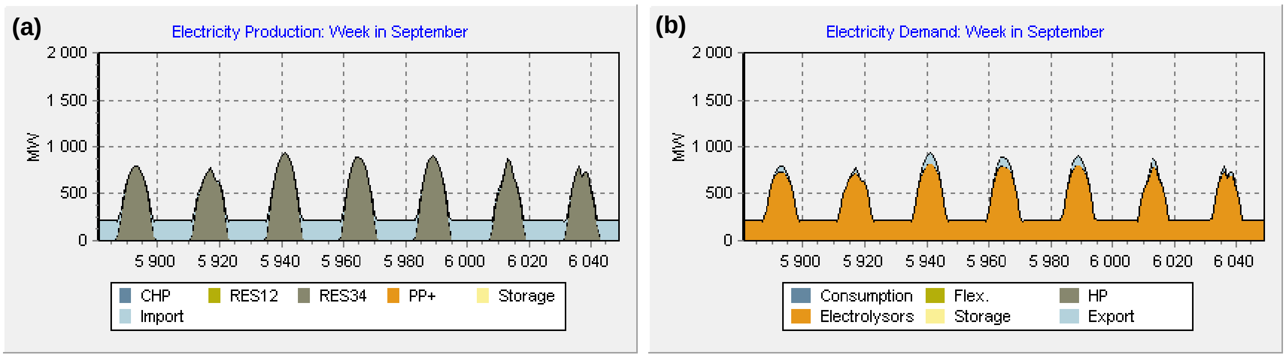

Figure 39: (a): Example of electricity production with 1 GW of photovoltaic power; (b): Load curve for 1 GW of electrolyzer. The production has a minimum of 200 MW.

Through the analysis of Figure 39 one can see that in this case the production never fall below the 200 MW ensuring the continuous production without the need to turn off the electrolyzers when there is no production from renewable sources.

In this scenario with a total use of the renewable resources and the import of energy from the national grid to ensure a minimum functioning, it is expected that this system achieves a higher H_2 production, and through Figure 40 it is possible to confirm this hypothesis.

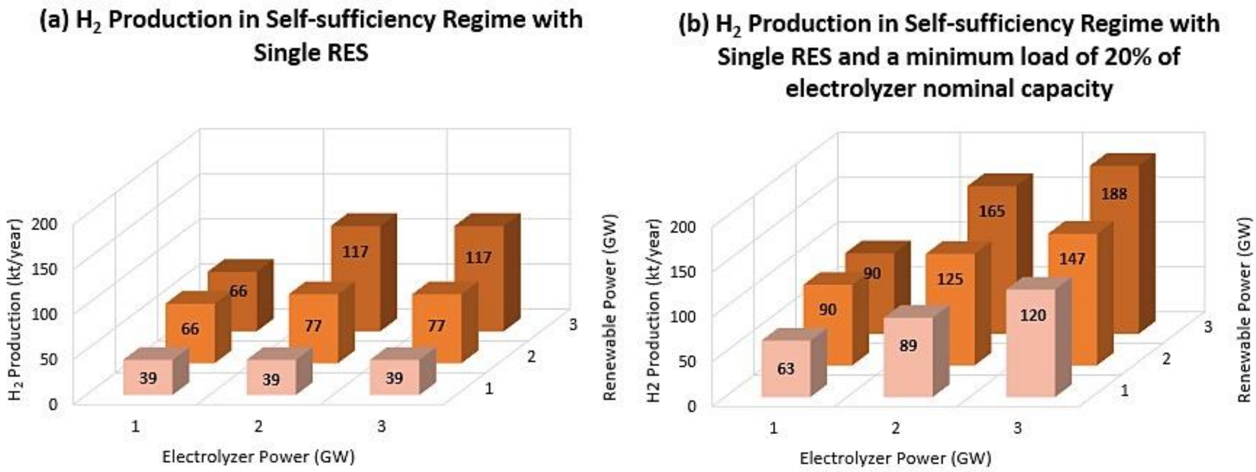

Figure 40: H_2 production with photovoltaic power in a sunny year with: (a): Production in Self-sufficiency Regime with Single RES in scenario B; (b): Production in Self-sufficiency Regime with Single RES and a minimum load of 20% of electrolyzer nominal capacity.

The production with a 20% minimum power (Figure 40 - b) presents a H_2 maximum of 188 kt/year, approximately more 71 kt/year (a 165% growth) than in a simple self-sufficiency regime like scenario B (Figure 40 - a). One can retain that the best option of production is 3 GW of electrolyzer with 3 GW of renewable power.

This increase of H_2 production is also verified in a Self-sufficiency Regime with wind power, although the difference from scenario B to scenario D is less pronounced, passing from 156 kt/year to 183 kt/year (+ 17%) in a sunny year, Figure 41 presents.

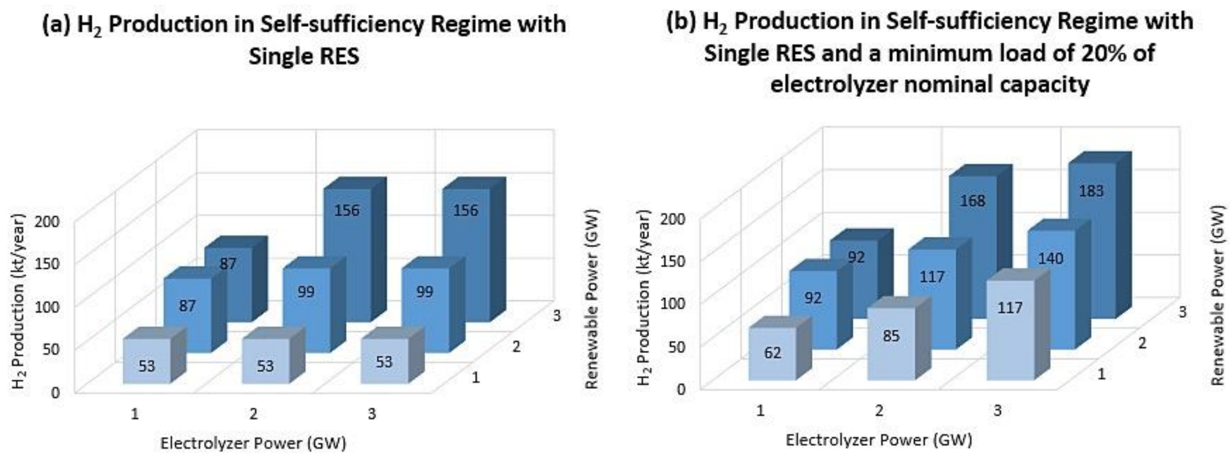

Figure 41: H_2 production with wind power in a sunny year with: (a): Production in Self-sufficiency Regime with Single RES; (b): Production in Self-sufficiency Regime with Single RES and a minimum load of 20% of electrolyzer nominal capacity.

In a windy year this type of regime also presents more H_2 production, especially if it is produced with just photovoltaic power passing from 102 kt/year to 171 kt/year (+ 68%), a higher increase compared with the other weather condition, with wind power the H_2 production passes from 162 kt/year to 187.5 kt/year (+ 16%). Both productions can be seen in Figure 42.

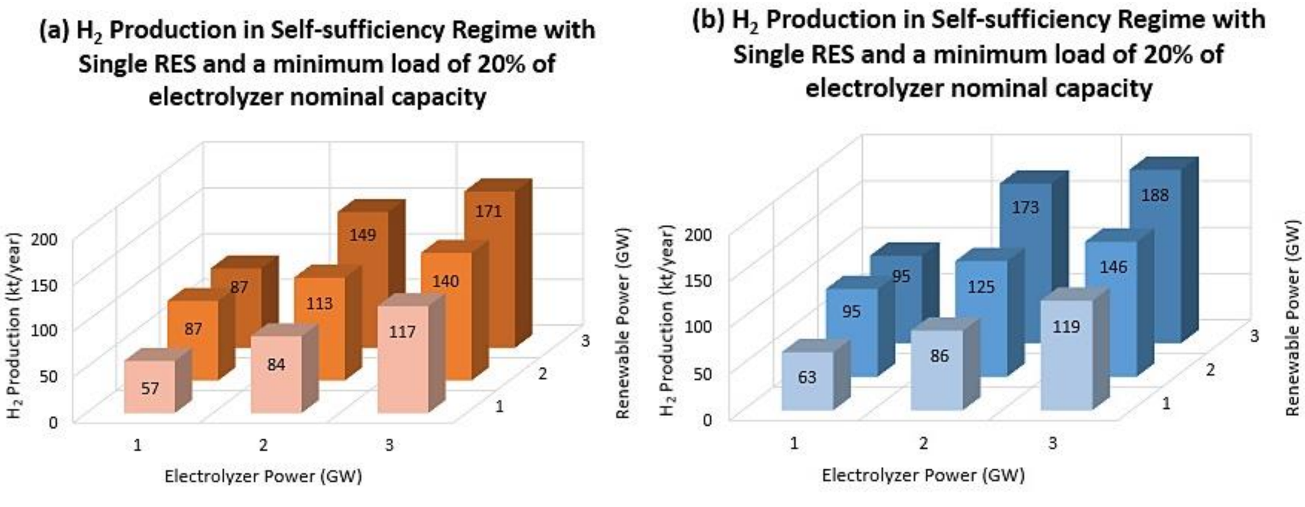

Figure 42: H_2 Production in Self-sufficiency Regime with Single RES and a minimum load of 20% of electrolyzer nominal capacity, in a windy year, with: (a) photovoltaic power; (b): wind power.

Given the application of this characteristic, the distribution curves assume a new shape (Figure 43).

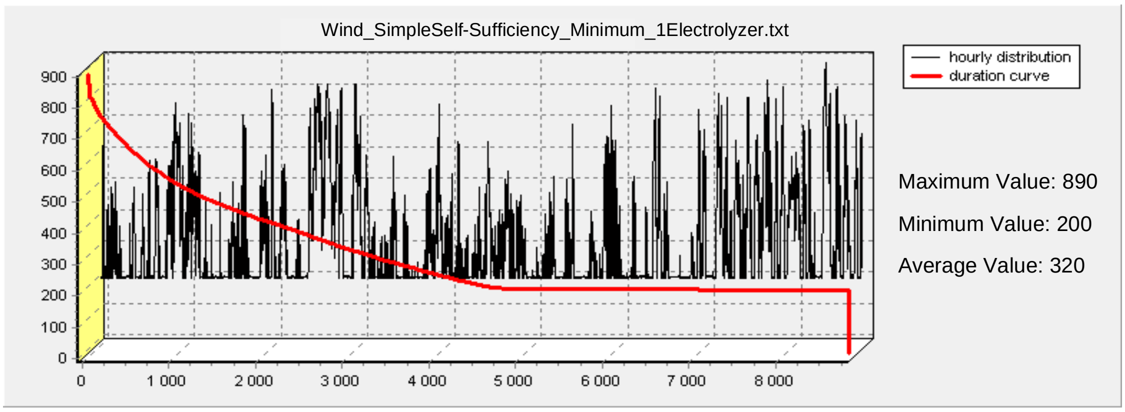

Figure 43: Distribution curve for 1 GW of wind power, in a sunny year, with 1 GW of electrolyzer and 20% of minimum production.

In the figure above it is possible to see that the duration curve is restricted to a minimum of 200 MW never falling below this value, as expected. The average value in this case is 320 MW and the 890 MW is the maximum achieved.

Given the fact that this is a scenario that requires imports from the national grid, the import balance will be more positive. The Figure 44 demonstrates the differences from scenario B to scenario D in the import balance in a sunny year with photovoltaic power.

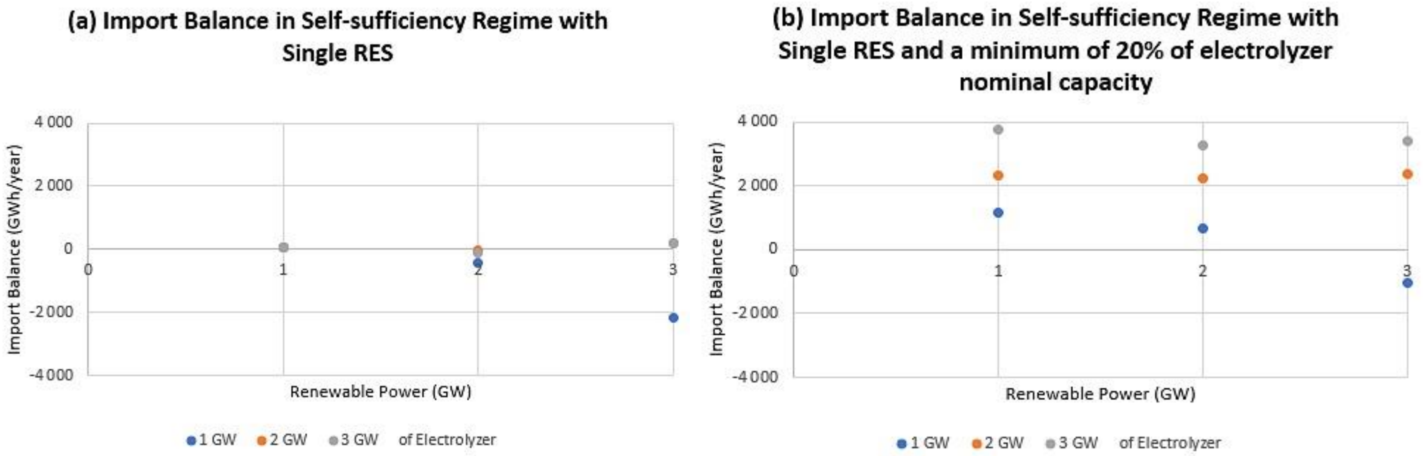

Figure 44: Import balance, in a sunny year, with photovoltaic power in: (a) Self-sufficiency Regime with Single RES; (b): Self-sufficiency Regime with Single RES and a minimum load of 20% of electrolyzer nominal capacity.

The Figure 44 – b shows that a higher value of imports is required to optimize the functioning of the regime. This balance is the one that best shows the differences between the scenarios selected. It is also verified that with the increase in electrolyzer nominal capacity is necessary more volumes of imports.

The import balance with wind power in a scenario D will require less imports and can be seen in Figure 45.

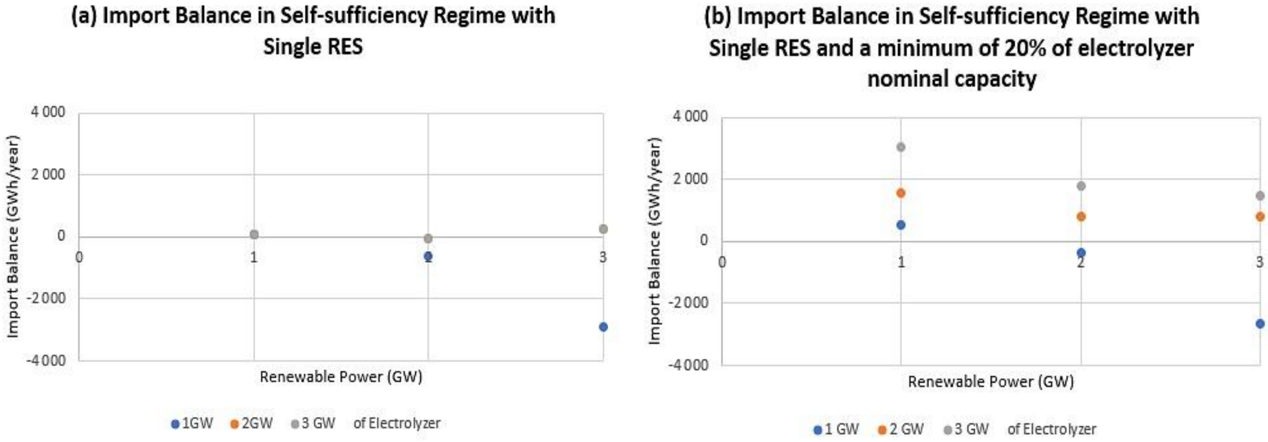

Figure 45: Import balance, in a sunny year, with wind power in: (a) Self-sufficiency Regime with Single RES; (b): Self-sufficiency Regime with Single RES and a minimum load of 20% of electrolyzer nominal capacity.

Figure 45 shows that with wind power in this scenario it is necessary less imports than with photovoltaic power, and also, with 3 GW of electrolyzer is verified a higher export to the grid than with the previously.

4.1.5 Scenario E - H_2 Production in Combined Self-sufficiency Regime with a minimum electrolyzer load of 20% nominal capacity

Figure 46 presents an example of electricity production and load curve of 1 GW electrolyzer for this scenario, where it is verified that the production never falls below the 200 MW.

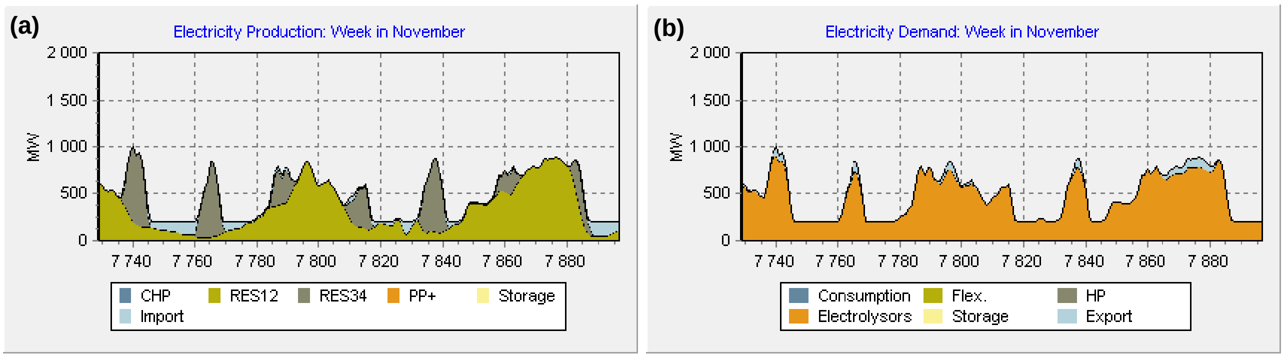

Figure 46: Example of electricity production with 1 GW of photovoltaic power combined with 1 GW of wind power; (b): Load curve for 1 GW of electrolyzer. The production has a minimum of 200 MW.

In this scenario it is expected that the differences between the Self-sufficiency Regime with Combined RES and a Self-sufficiency Regime with Combined RES and a minimum load of 20% of electrolyzer nominal capacity will be also noticeable (Figure 47).

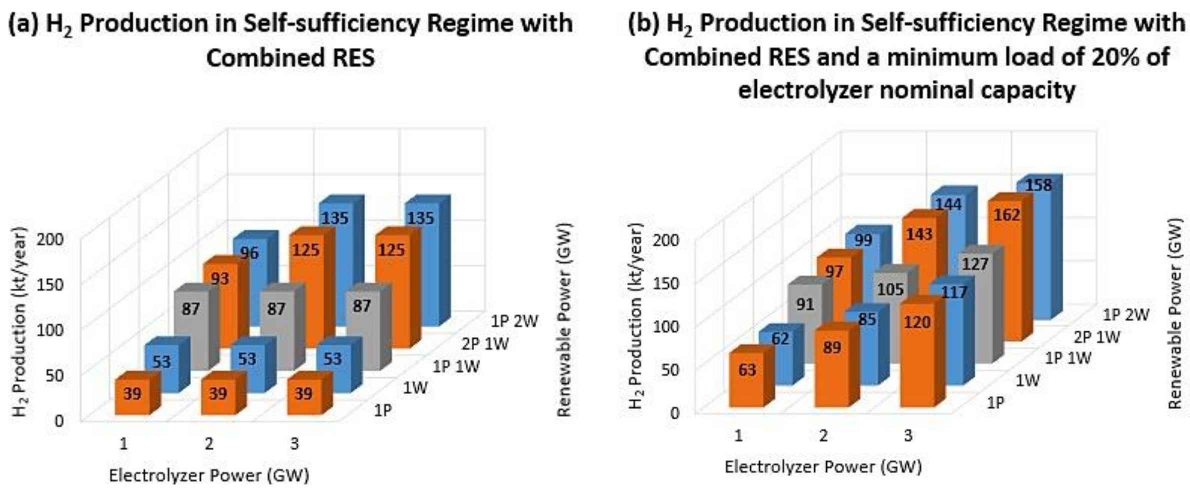

Figure 47: H_2 production in a sunny year with: (a): Production in Self-sufficiency Regime with Combined RES; (b): Production in Self-sufficiency Regime with Combined RES and a minimum load of 20% of electrolyzer nominal capacity.

As previously said, the H_2 production in this scenario is slightly higher, being the maximum value obtained with 3 GW of electrolyzer and 3 GW of renewable power (combination of 2 GW of photovoltaic and 1 GW of wind power).

When the hydrogen is produced in a windy year with these parameters, there is a slight growth in production, however in that case the maximum value is obtained with 3 GW of electrolyzer and 1 GW of photovoltaic combined with 2 GW of wind power.

The import balance of both scenarios can be seen in Figure 48.

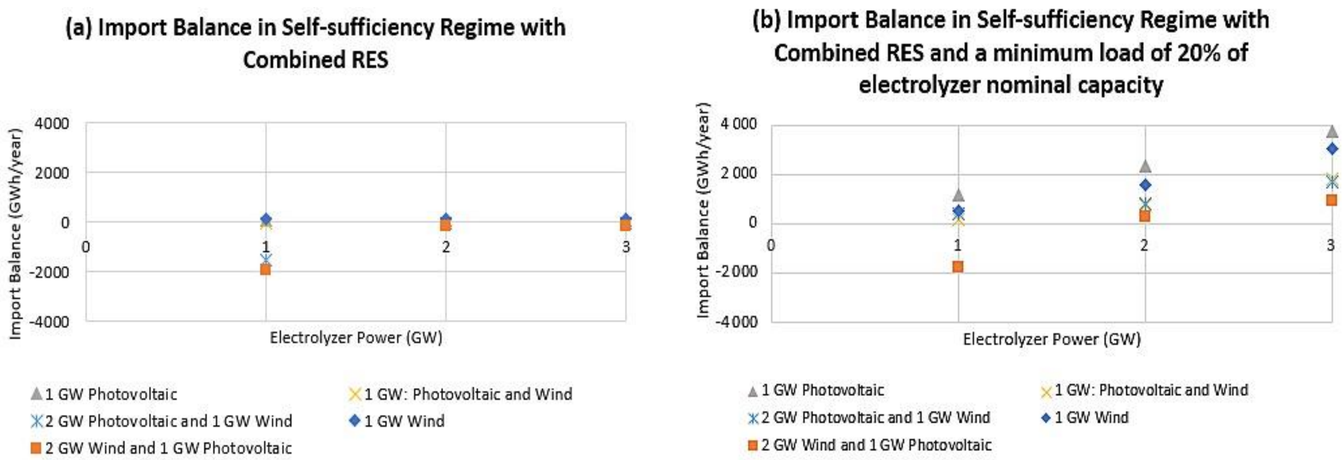

Figure 48: Import balance, in a sunny year, in: (a) Self-sufficiency Regime with Combined RES; (b): Self-sufficiency Regime with Combined RES and a minimum load of 20% of electrolyzer nominal capacity.

Considering the import balance of the previous scenarios, it is expected that scenario E (represented in Figure 48 - b) also presents some significant import values. These values are higher for a single RES, such as 1 GW of photovoltaic or 1 GW of wind. As the wind power presents itself as the most favorable for H_2 production, it is verified that a combination of 2 GW of wind with 1 GW of photovoltaic power requires the lower value of imports.

4.2 Discussion of Technical Analysis

Taking into consideration all the previously described scenarios and in order to compare them, the 12 most productive scenarios were selected, in which the productivity is higher than 90 ktH_2 per GWin (input power). For these combinations, a nomenclature was adopted to identify the scenario under study taking into account all its characteristics, such as: weather conditions, electrolyzer power and RES power (Figure 49).

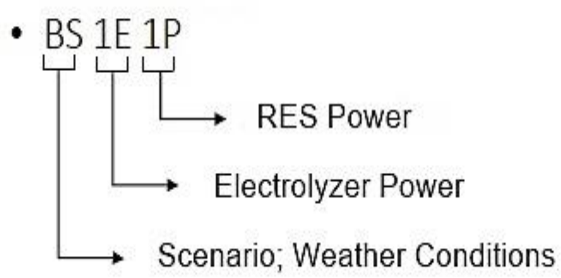

Figure 49: Example of a nomenclature.

Figure 49 presents an example of nomenclature which is referent to scenario B in a sunny year with 1 GW of electrolyzer and 1 GW of photovoltaic power. Another example could be **CW 2E**

2P1W, representing scenario C in a windy year with 2 GW of electrolyzer and 2 GW of photovoltaic power combined with 1 GW of wind power.

These 12 most productive scenarios are compared below from the point of view of the productions between the different regimes, the exchanges with the national electrical grid, the number of equivalent full load hours of the electrolyzers and the water consumption for the electrolysis reaction.

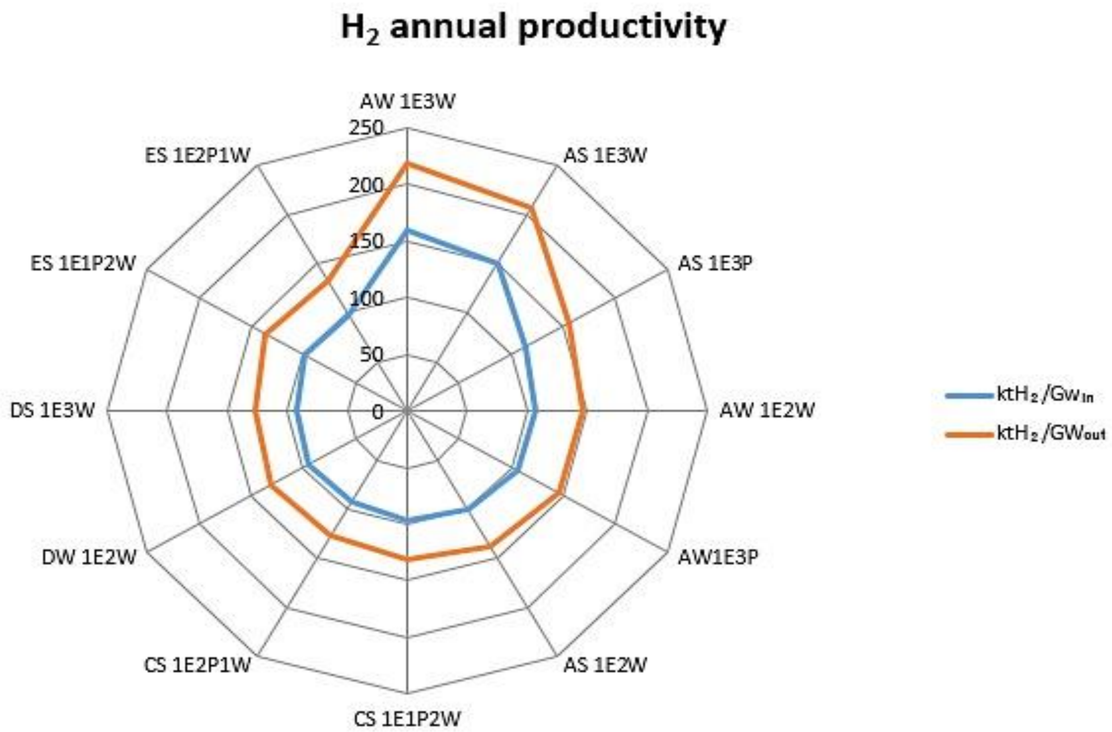

Figure 50: The 12 most productive scenarios of the plant with a production higher than 90 ktH2/year. The blue line is the production by electric input power. The orange line is the production by output power.

Figure 50 represents the productivity of the 12 most productive scenarios in terms of annual production of H_2 per unit of electrolyzer electric input capacity. Through this graphic, one can see that all of the scenarios are composed of just 1 GW of electrolyzer, 10 of them use wind power, and just 2 scenarios (AS 1E3P and AW 1E3P) use photovoltaic power as their only source of electricity. This further strengthens the power of renewable wind for this type of production. The scenario A presents 6 of the 12 scenarios, in which 3 of them have productions above the 110 ktH_2/year.

The Figure 51 presents the exchanges with the national grid, in which one can see that the scenarios using the renewable resources (isolated or combined) at their fullest, have very low values of imports and higher values of exports, namely the scenario DW 1E2W. The scenario

A that has H_2 productions above 100 kt/year presents itself as the regime with the largest electricity exchanges with the grid, reaching values of 3,12 TWh/year for scenario AS 1E3P.

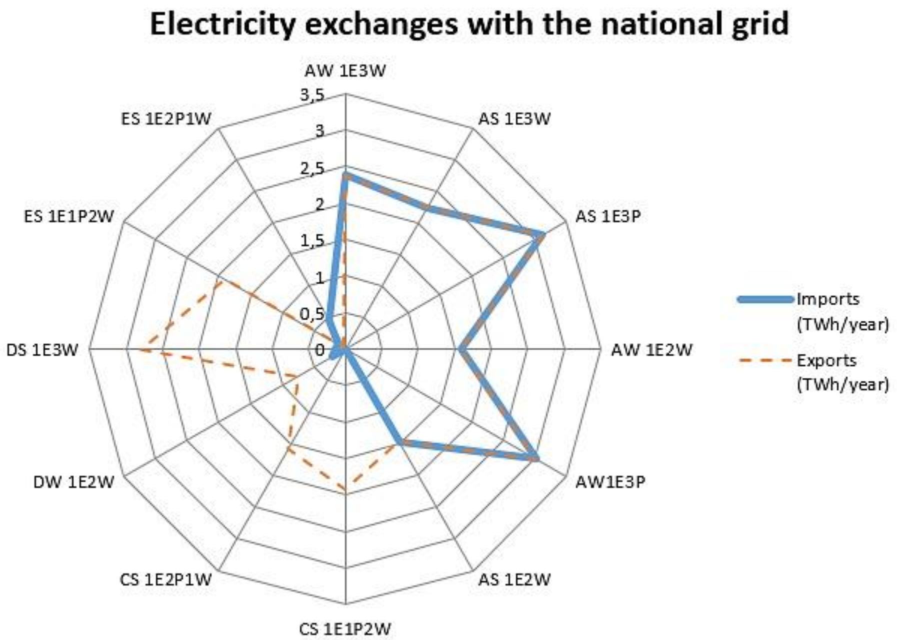

Figure 51: Electricity exchanges with the national electricity grid of the 12 technical most productive scenarios. The blue and orange line are the imports and exports, respectively.

The number of equivalent hours of electrolyzer production was also taken into consideration and can be evaluated in Figure 52. All the most productive scenarios have more than 4 thousand equivalent full load hours of electrolyzer production, above 50% of its nominal production.

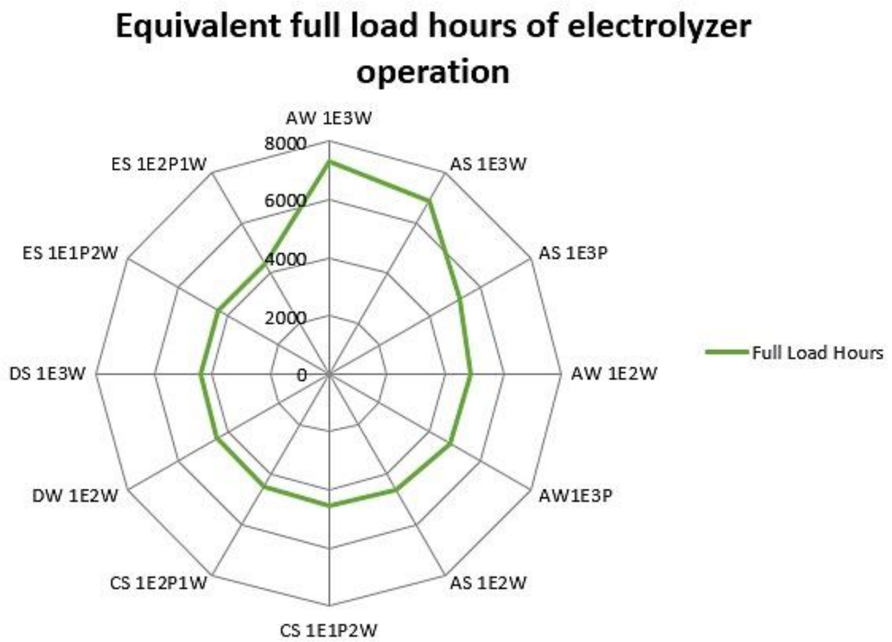

Figure 52: Equivalent full load hours of electrolyzer production in technical analysis.

Since water is the feedstock for H_2 production, Figure 53 presents the water consumption for the electrolysis reaction for the 12 most productive scenarios in comparison with the volumes of grid water distributed in the two municipalities in the Sines industrial area.

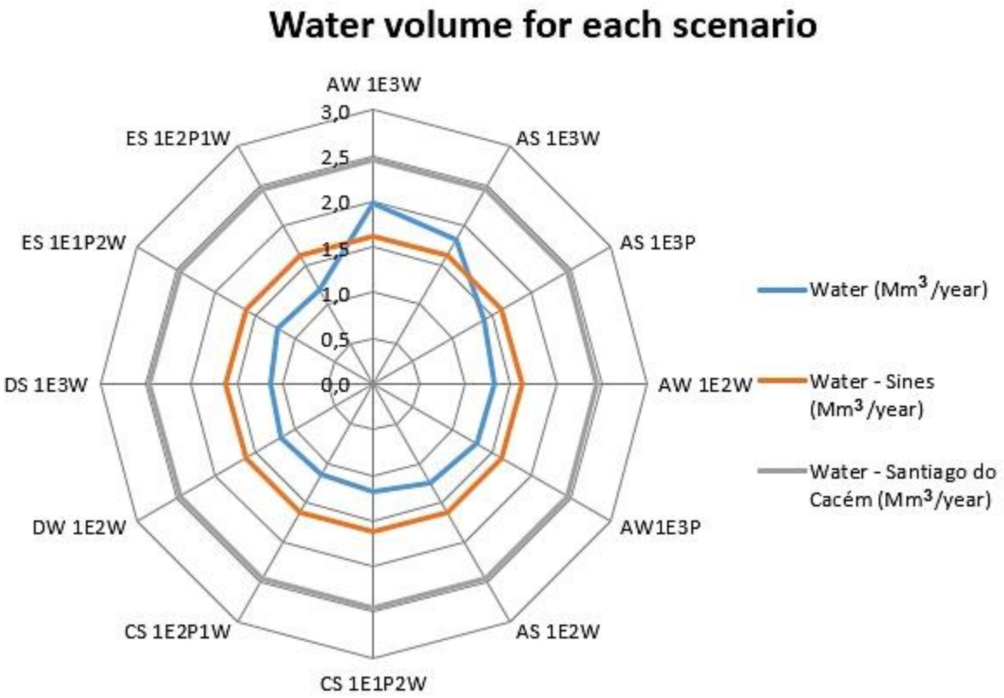

Figure 53: Volume of water consumed in the electrolysis reaction in each scenario in millions of m3/year. The grey line is the grid water distribution in the municipality of Santiago do Cacém in 2017. The orange line is the grid water distribution in the municipality of Sines in 2017.

The water consumed by the electrolyzer is represented with the blue color line Figure 53. To highlight the amount of water needed for these scenarios, data on the amount of water distributed by the public network in nearby municipalities were collected. Santiago do Cacém (grey line) had, in 2017, about 28.892 inhabitants consuming 2,456.000 m^3 of water. The Sines municipality (orange line) with 13.662 inhabitants consumed, also in 2017, 1,622.000 m^3 of water. Most of the scenarios in this graphic have water consumptions that are similar to the annual consumption of Sines, except the 2 most productive scenarios (AW 1E3W and AS 1E3W) that have a consumption between the Santiago do Cacém and Sines municipalities.

4.3 Economic analysis

The method for calculating annualized costs and the levelized cost of energy was described in section 3.2. Here we pass directly to the presentation of results derived from application of that method. A table of all relevant costs for each configuration of the H_2 plant is presented in Annex II.

The Total Annualized Costs of the plant in millions of euros are plotted as a function of the total annual H_2 production in the graph of Figure 54.

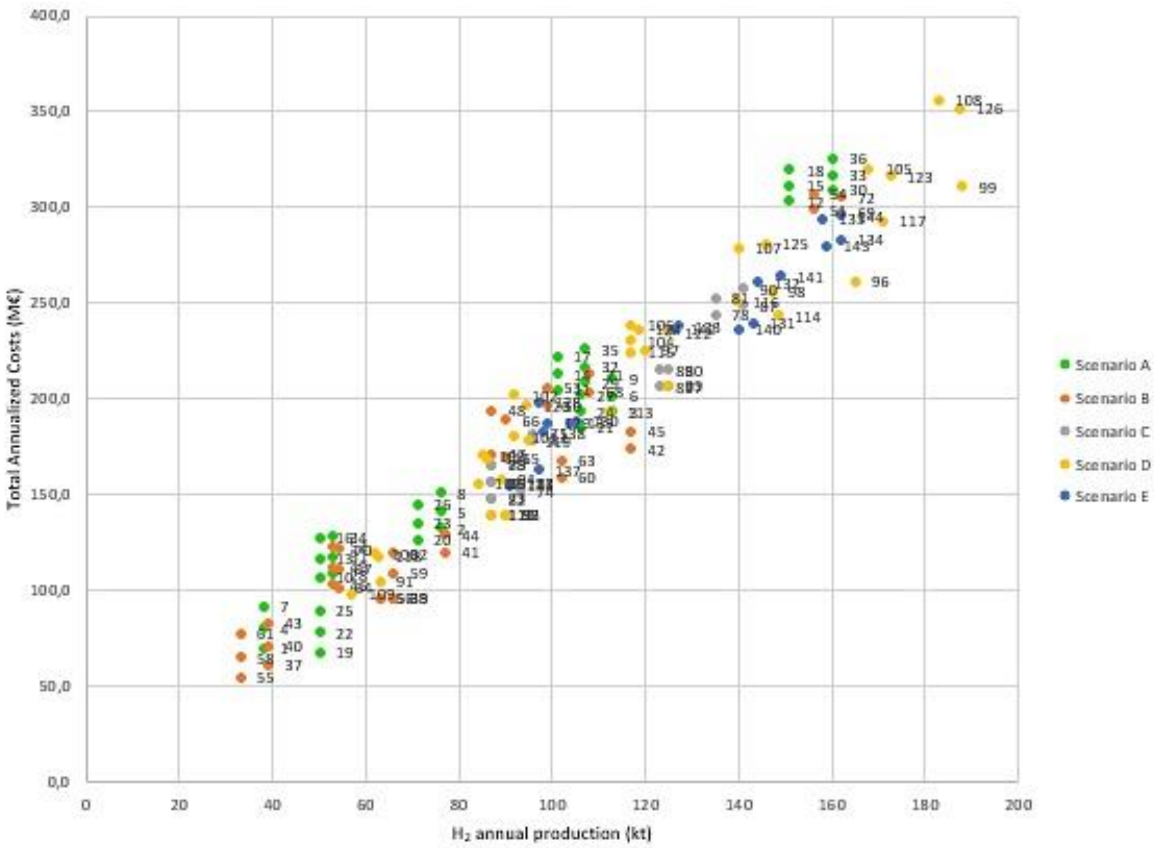

Figure 54: Total Annualized Costs of the plant for each scenario.

Through Figure 54, one can see that with the increase in the H_2 annual production it is also verified an increase in the total annualized costs of the plant.

The highest cost is achieved with the point 108 that belongs to scenario D and has 3 GW of electrolyzer and 3 GW of wind power. This cost it is justified with the electrolyzer investment and operation costs.

All the configurations above the 300 M€ are majorly composed with 3 GW of electrolyzer power however there are some configurations with 2 GW of electrolyzer, from scenario D an A, and two configurations with only 1 GW from scenario A (points 12 and 30). All of them are composed with the maximum capacity of renewable resources, 3 GW of power. This corroborates the fact that the electrolyzer capacity represents the main costs of investment.

The configuration 55, from scenario B with 1 GW of electrolyzer power and 1 GW of photovoltaic power, presents the lowest total annual costs although the H_2 annual production is only 33 kt/year. At the other extreme is point 51, belonging to scenario B with 2 GW of electrolyzer and 3 GW of wind power, that has a significantly higher total annual costs. This is justified with capacity of the electrolyzer, as previously said, although the operation also influences the annual costs. The electrolyzer of point 51 is fed by wind power and in this way, it works more hours per year achieving 50,000 operation hours in fewer years. Thereby as well as having a shorter duration, the annual costs are spread over fewer years leading to a higher cost of each year. The configuration 55 is just the opposite given the fact that the electrolyzer it is just fed with photovoltaic power that works a few hours per year and for that it has a longer duration with the total annual costs distributed for more years.

The LCOH, in €/kgH_2, is calculated through the division of the Total Annualized Costs by the H_2 annual production for each case study. Figure 55 presents the LCOH for each configuration.

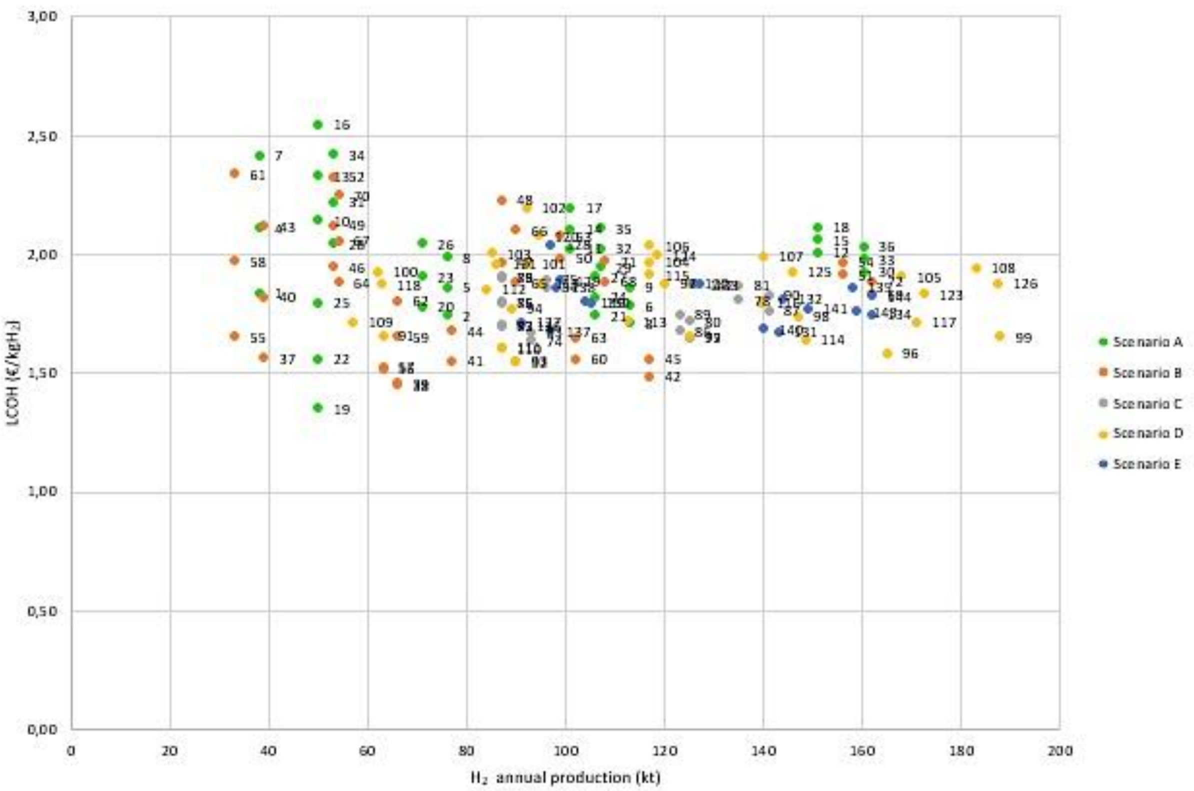

Figure 55: LCOH of each configuration. The numbers represent the 144 configurations belonging to the 5 scenarios under study.

As one can see from Figure 55, the 144 configurations have a fairly comprehensive dispersion.

The scenario A has a LCOH equal to or greater than 1.35 €/kgH_2 presenting different amounts of hydrogen produced.

The point 19 with the lowest LCOH (below 1.50 €/kgH_2) belongs to scenario A however it also records a lower H_2 production, around 50 ktH_2/year. This configuration it is also one of the points with lowest total annual costs.

The majority of data presents a H_2 production between 80 and 120 ktH_2/year and a LCOH between 1.50 and 2.50 €/kgH_2.

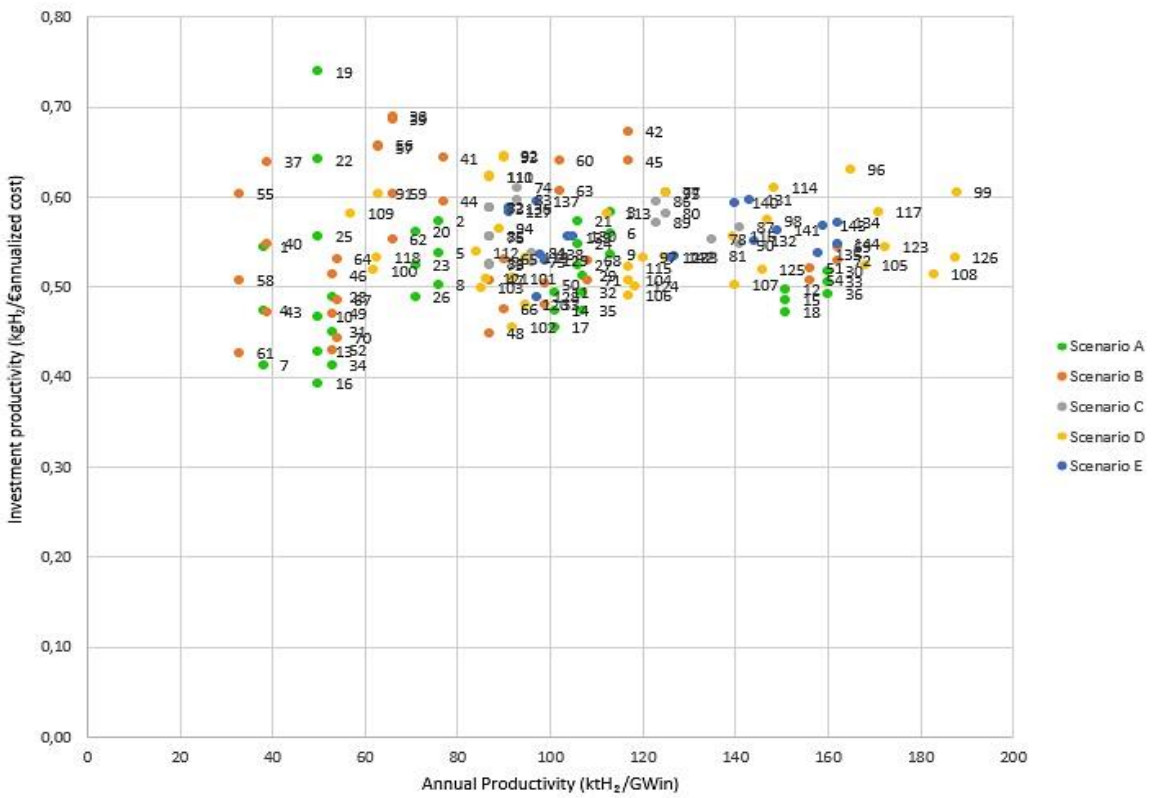

Figure 56: Investment productivity of each configuration.

Through Figure 56, one can see that most of the points of each scenario are located approximately, below the 0.60 kgH_2/€annualized costs, however covering different amounts of H_2 produced between 33 ktH_2/year and 188 ktH_2/year. Despite that the point 19, from scenario A with 1 GW of electrolyzer and 1 GW of photovoltaic power, can be a potential point given is high investment productivity it has a low H_2 annual production, about 50 ktH_2/year.

When trying to choose the best options from such a large number of data points it is useful to find variables that allow one to reduce the analysis to finding a Paretian optimum solution, i.e., a problem of maximization (or minimization) of utility. For that purpose we plot a graph of the investment productivity (simply the inverse of the LCOH, providing the amount of H_2 production for each euro of annualized costs) as a function of annual H_2 productivity (in terms of H_2 produced by unit electrolyzer input capacity) displayed in Figure 56. This plot allows the analysis of the problem as one of maximization of utility, as the investor will want to both maximize investment productivity and annual H_2 output. [60]

In order to choose the best economic performance of the investment, it was taken into consideration the Pareto Optimality, which in this case is evaluated from the product of investment productivity by annual H_2 productivity. The optimal solution is obtained for the maximum value of this product. Table 13 shows the twelve best economic configurations in terms of the product of investment productivity by ktH_2 per input power. It is clear that there is one clearly defined optimum configuration for the case of 1 GW electrolyzer fed by 3 GW wind power working in a constant regime (Scenario A).

Table 13: The 12 best economic configurations in terms of the product of investment productivity by H_2 output

Point	***Configuration***	***H_2 productivity*** *(ktH_2/GW_{in})*	***Investment productivity*** *(ktH_2/M€annualized costs)*	***Product value*** *(Investment productivity × ktH_2 per input power)*
30	AW 1E3W	160	0.52	83.01
12	AS 1E3W	151	0.50	75.19
3	AS 1E3P	113	0.58	65.97
21	AW 1E3P	106	0.57	60.72
92	DS 1E2P	90	0.65	58.12
93	DS 1E3P	90	0.64	57.92
137	EW 1E2P1W	97	0.60	57.77
74	CS 1E2P1W	93	0.61	56.79
83	CW 1E2P1W	93	0.60	55.52
29	AW 1E2W	107	0.51	54.87
110	DW 1E2P	87	0.62	54.19
111	DW 1E3P	87	0.62	54.11

Figure 57 presents the study of the productivity of the selected points, in which, each configuration displays the number of the associated point. This, and all subsequent radar graphics, are ordered by the descending order of the product (Investment productivity × H_2 productivity as shown in Table 13), in a clockwise direction.

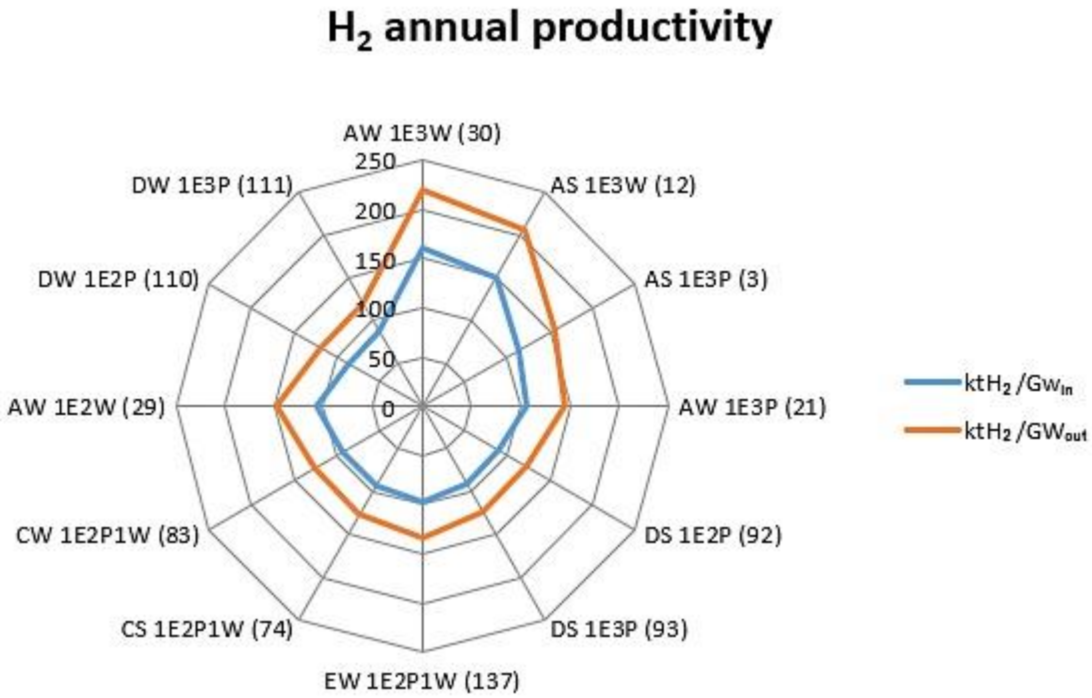

Figure 57: H_2 annual productivity of the 12 best economic configurations. The blue line is the productivity by GW of electric input power. The orange line is the productivity by GW of H_2 output power.

Through Figure 57 one can see in the economic analysis that there are 6 points in common with the technical analysis, which are all the configurations of scenario A and the point 137 from scenario E. Also, the options of Scenario A that top the list of optimal utility of Table *13* seem to be quite robust from the point of view of economic performance. The economic analysis presents 4 options of scenario D, although they have H_2 productions below or equal to 90 ktH_2/year. Six scenarios are based on wind power alone or in combination with solar PV, while 6 are composed with photovoltaic power alone, which are all configurations of scenario D and the configurations AS 1E3P and AW 1E3P. As in the technical evaluation all the 12 selected points are composed with just 1 GW of electrolyzer input capacity and with a RES capacity higher than 1 GW of power (individual or combined technologies).

The exchanges with the national grid can be evaluated through Figure 58.

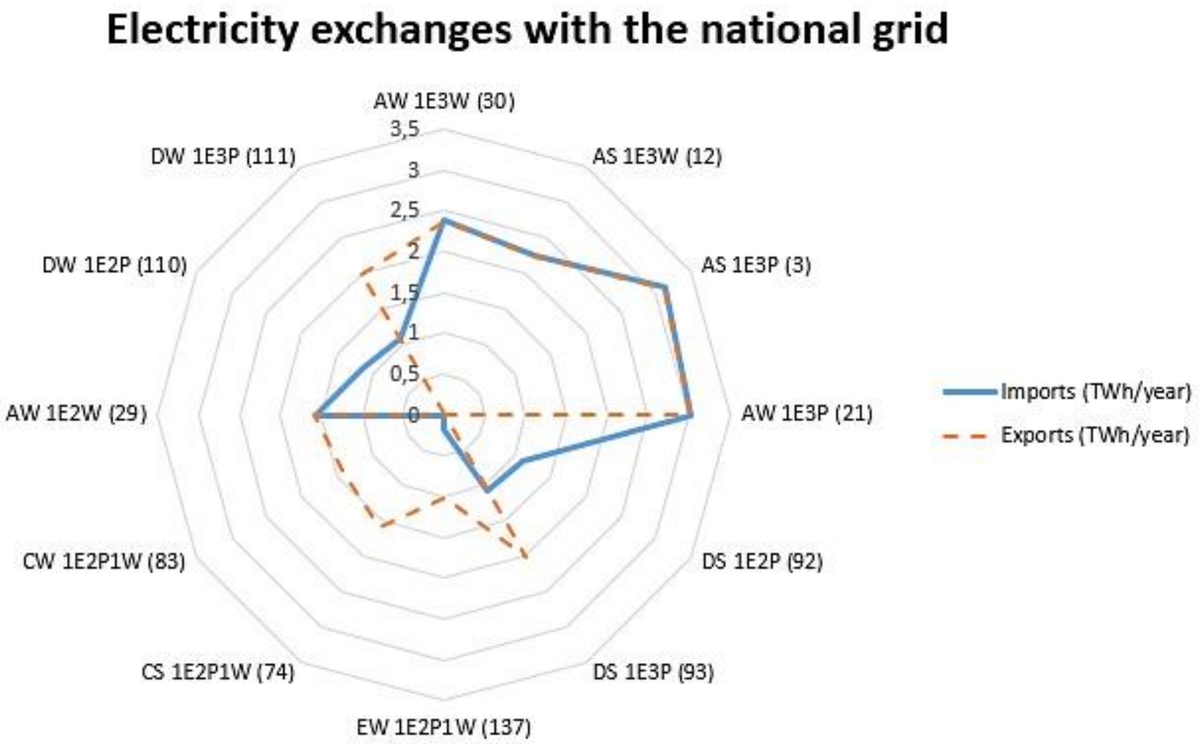

Figure 58: Electricity exchanges with the national grid of the 12 best economic configurations. The blue and orange lines are the imports and exports, respectively.

The analysis of Figure 58 shows the large quantities of imports and exports to the national electricity grid specially from scenario A, as expected. Comparatively, the other configurations require values below the 1.5 TWh/year of imports although exports some electricity to the national grid. It should be noted that the amounts of electricity exchanged with the national network are very substantial and of the same order of magnitude of electricity exchanges between Portugal and Spain. This raises a number of technical questions such as availability of electricity demand to absorb the excess production of the hydrogen plant. These problems are out of the scope of this work, but they will be a necessary concert requiring a deep evaluation before implementation of the project.

Figure 59 presents the equivalent hours of electrolyzer production.

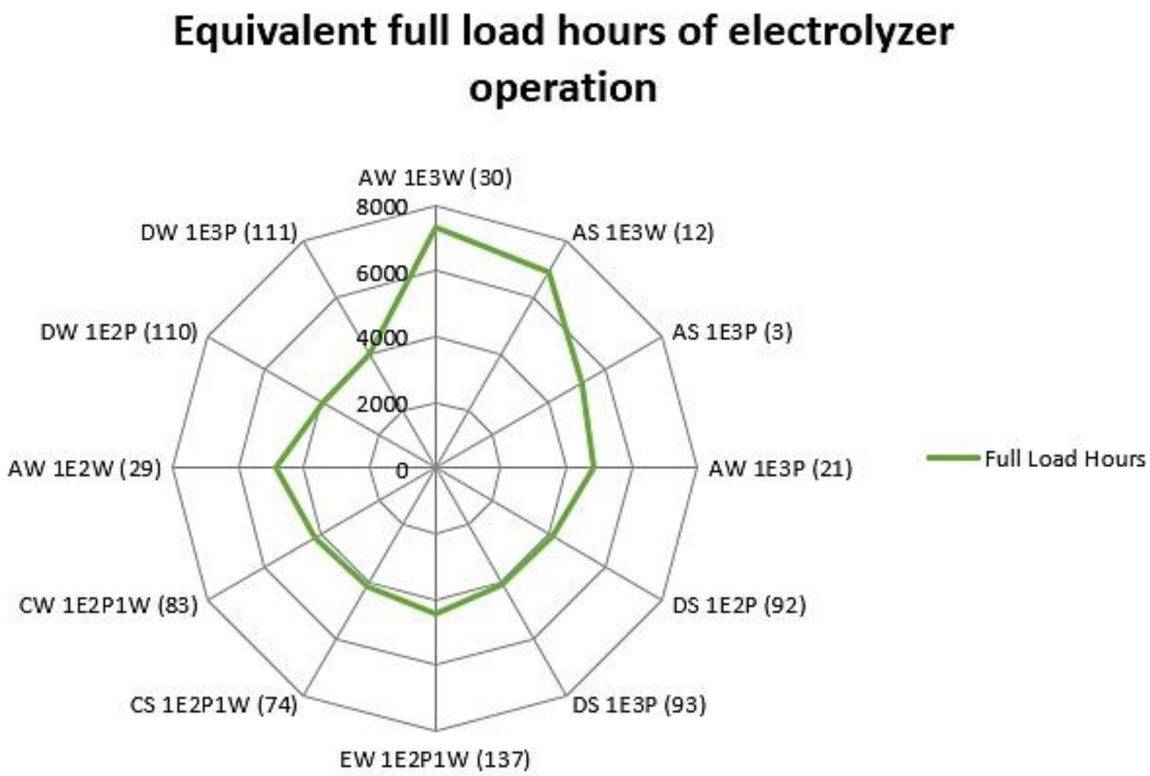

Figure 59: Equivalent full load hours of electrolyzer production of the 12 best economic configurations.

In the graphic above it is possible to see that like the technical analysis all the configurations have a production capacity approximately 50% above their nominal capacity. The scenario AW 1E3W is the only that have almost 8 thousand hours of electrolyzer production.

The water required for each configuration can be seen in Figure 60.

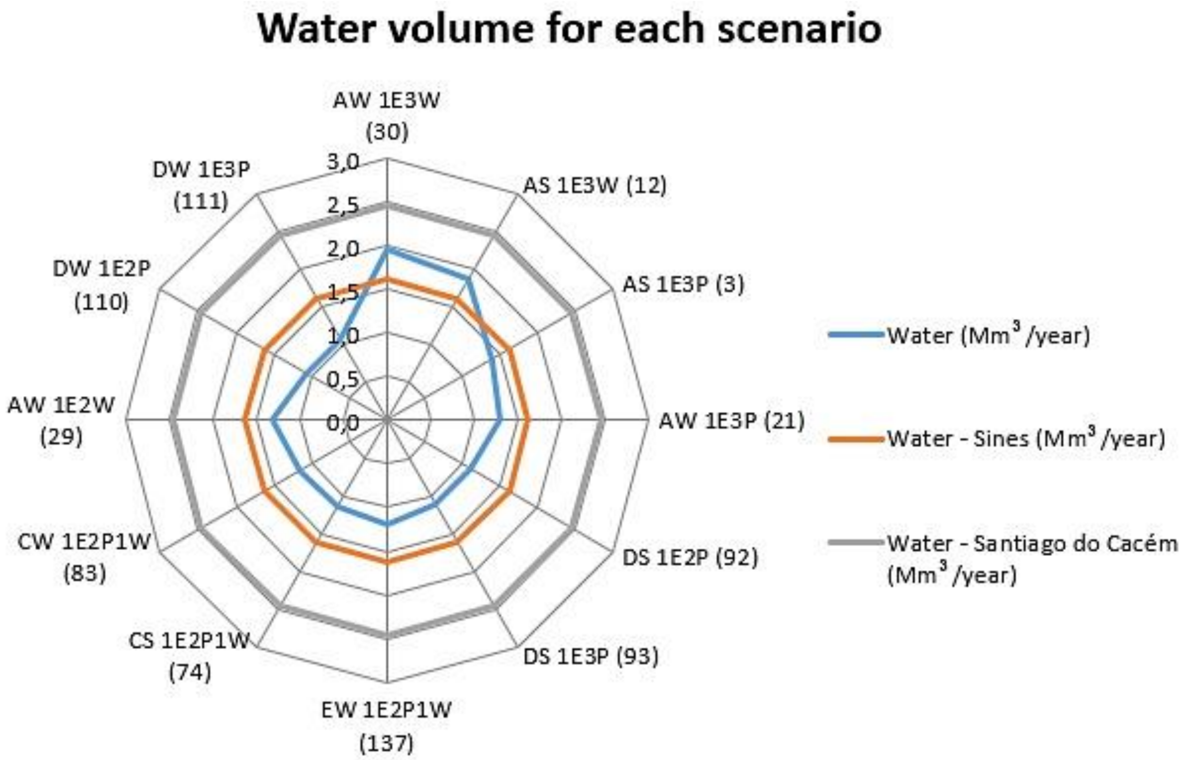

Figure 60: Volume of water consumed by the configurations selected in millions of m^3/year. The grey line is the water consumption of the municipality of Santiago do Cacém in 2017. The orange line is the water consumption by the municipality of Sines in 2017.

Figure 60 shows that 10 of the 12 configurations required a lower volume than that distributed in the Sines municipality. The volumes AW 1E3W and AS 1E3W require water volumes around the 2 million of m^3/year, between the volume of water distributed in the Santiago do Cacém and Sines municipalities.

Also, for the 12 selected scenarios were evaluated the Annualized Investment Costs, Total Annual Costs and LCOH.

The Annualized Investment Costs can be seen in Figure 61.

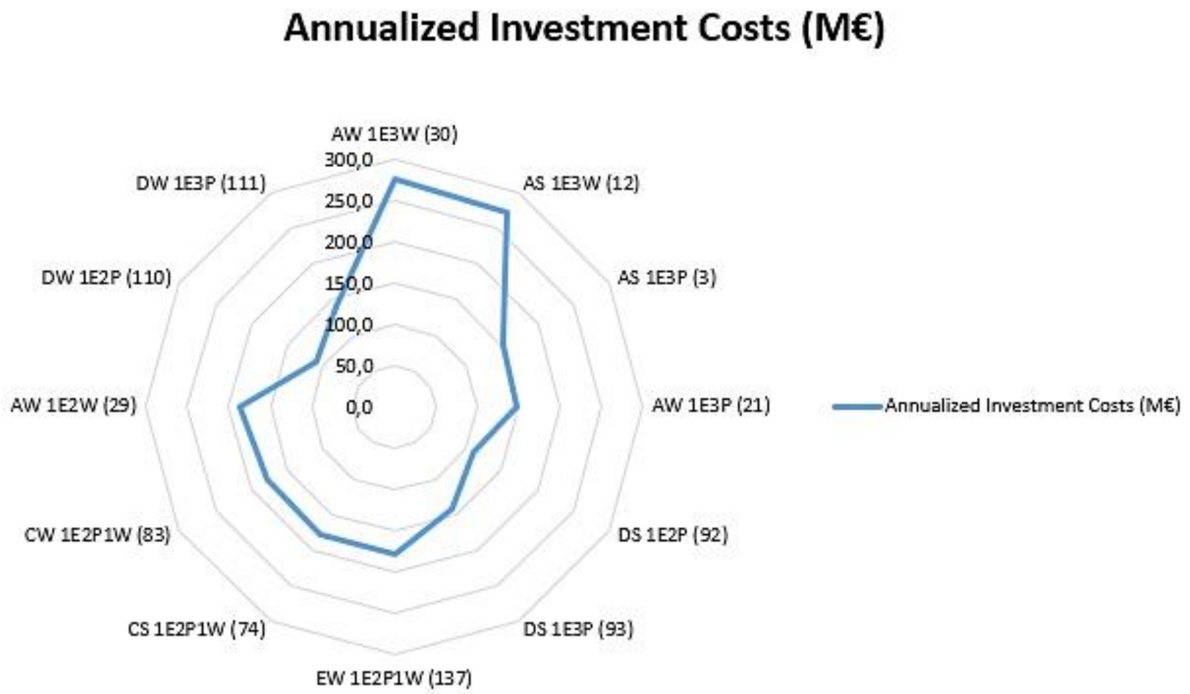

Figure 61: Annualized Investment Costs of the 12 selected configurations.

Analyzing Figure 61, one can see that 2 of the 12 scenarios have high investment costs, approximately 270 M€ per year. These 2 scenarios (point 30 and 12) are the ones composed with 3 GW of wind power and 1 GW of electrolyzer power and require large exchanges with the national grid which can be determinant for the costs of the project. The scenario D with the configurations DS 1E2P and DW 1E2P present the lowest values of Annualized Investment Costs. This is a scenario of minimum electrolyzer load of 20% capacity powered by solar PV and requiring electricity imports during night time. The use of solar PV contributes significantly for the lower cost.

The Total Annual Costs of the plant can be evaluated in Figure 62 and have in consideration all the parameters referred in chapter 3.2.

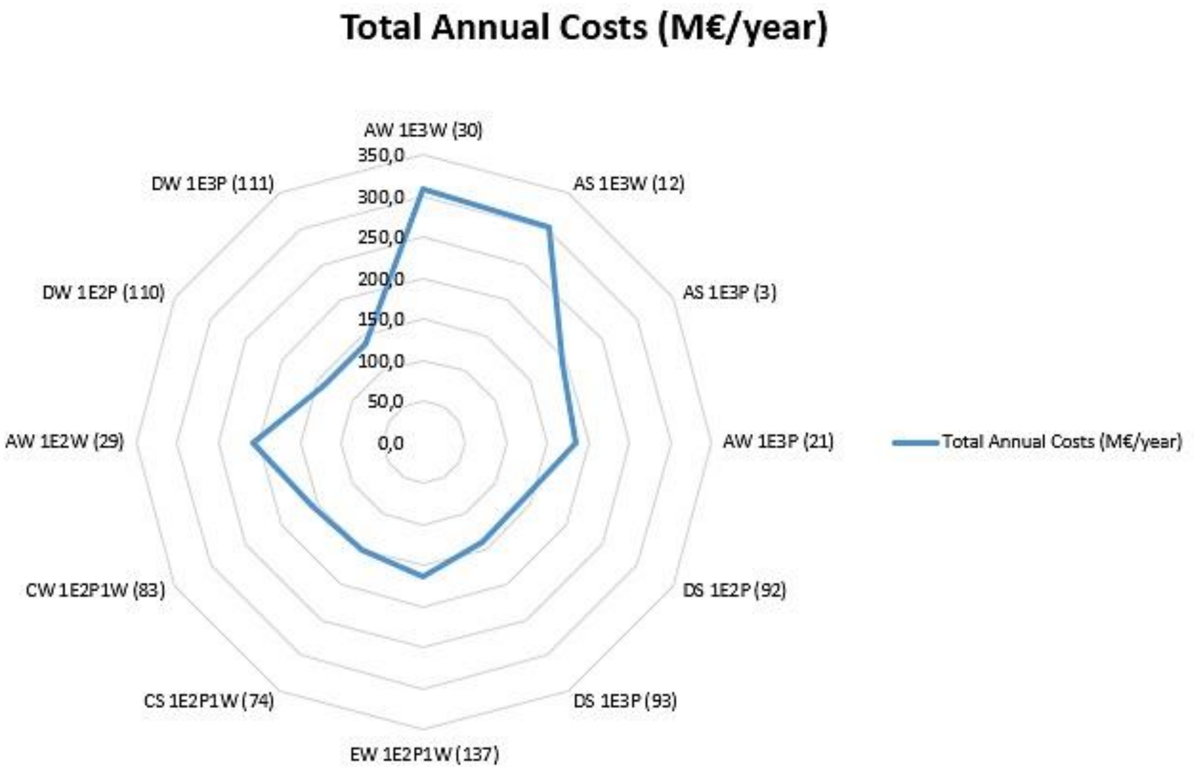

Figure 62: Total Annual Costs of the 12 selected configurations.

Figure 62 presents the annual costs of the plant in the year 2030, in which one can see that the scenarios that require high annual investments cost have the highest central costs, around the 300 M€/year. These scenarios are all composed of a 1 GW electrolyzer combined with 3 GW of wind power, and they also present the number of equivalent production hours between 6,800 and 7,300 hours. The remaining scenarios have costs approximately equal or less than 200 M€/year, with exception of scenario AW 1E2W that have 208 M€/year which is justified with the large quantities of imports necessary to fulfill the requirements of this operating regime.

The analysis of the LCOH for the 12 selected configurations can be seen in Figure 63.

Figure 63: LCOH of the 12 selected configurations.

Through Figure 63 it is possible to see that all 12 scenarios have a LCOH value between 1.5 and 2 €/kgH_2. The only cases where the LCOH is approximately 2 €/kgH_2 are with the scenario A.

According to IRENA, for green hydrogen to be competitive with the blue hydrogen, it must have a production cost below the 2.5 USD/kgH_2, approximately 2.15 €/kgH_2. [61] Therefore, it can be concluded that all present scenarios provide options that are competitive with H_2 production from fossil fuels. However, one should approach these results with caution as the discount rate used for this calculation is 3% and as it will be shown below, when performing a sensitivity analysis, the picture will change significantly with increasing discount rate.

Also, the LCOE (Levelized Cost of Electricity) was evaluated for the 12 selected scenarios (Figure 64). The LCOE is obtained from the ratio between the total annualized costs of producing electricity in the H_2 plant (in this case it consists of investment and O&M costs of the respective combination of solar and wind farms for each configuration) and the total annual electricity production at the H_2 plant.

For an optimization of H_2 production it is expected the lowest value of LCOE possible with a highest capacity of the electrolyzer. As claimed by IRENA, in 2030, the H_2 produced can reach a LCOE of 21 €/MWh with a LCOH of 2.46 €/kg. [61]

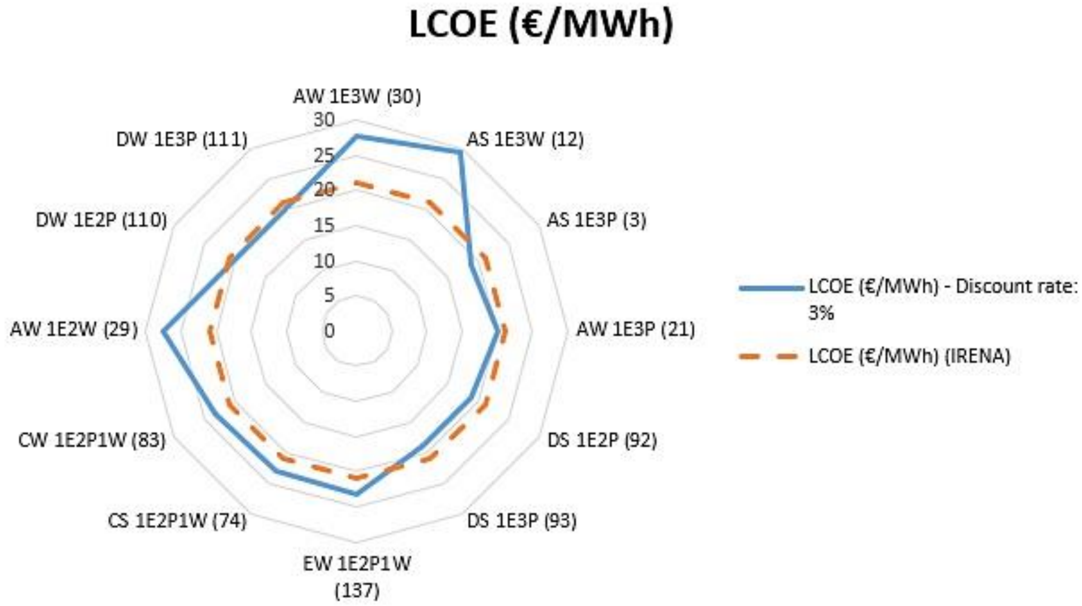

Figure 64: LCOE of the 12 selected configurations is represented with a blue line. According to IRENA, in 2030, electricity can have a LCOE of 21 €/MWh (orange line). [61] It was considered a discount rate of 3%.

As one can see through the figure above, only 50% of the 12 configurations present a LCOE below 21 €/MWh, being composed with just photovoltaic power (points 3, 21, 92, 93, 110 and 111). The other configurations present a LCOE between 20 and 30 €/MWh, being the maximum achieved with configuration AS 1E3W, that has a LCOE of 29.37 €/MWh. Thus, it is possible to state that in this context that for an LCOE value lower than that established by IRENA, only the configurations composed by solar PV are solution.

4.3.1 Sensitivity analysis

Given that the economic study contains parameters that can vary significantly and have a notorious impact in the evaluation, a sensitivity analysis was carried out.

a) Sensitivity to the discount rate

One parameter selected for evaluation was the discount rate. All results above have considered a discount rate of 3%, the standard value used in prospective studies at DGEG. However, the uncertainty faced by investors may be much higher, as there is not yet a mature market for hydrogen and there is no experience of production at such large scale as that envisaged in this project. The LCOH for the 12 best scenarios selected above is evaluated assuming the values of 3%, 9% and 15% for the discount rate (Figure 65).

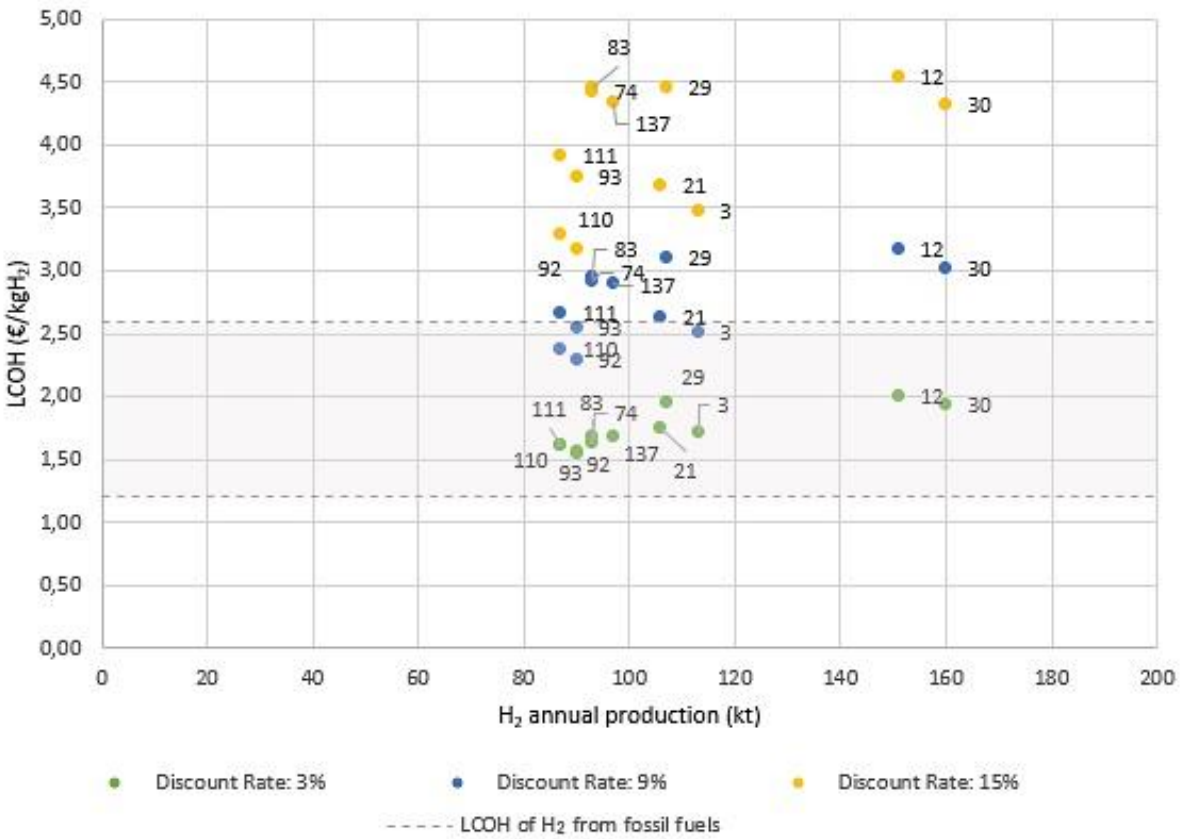

Figure 65: LCOH for different discount rates, being these: 3%, 9% and 15%, with green, blue and yellow color respectively. The dashed delimited section represents the LCOH range, in 2030, for H_2 produced from fossil fuels. [61]

As one can see through Figure 65, with the increase in the discount rate the LCOH tends to grow achieving a maximum of 4.53 €/kgH$_2$. This maximum is achieved with the point 12 that has the configuration AS 1E3W and produces 151 ktH$_2$/year. It is verified that with a discount rate of 15%, green hydrogen is no longer competitive when compared with the H_2 produced from fossil fuels. It should be noted that with a discount rate of 9% the only configurations capable of competing with the hydrogen produced by fossil fuels are configurations composed of photovoltaic power only, which are represented by the points 3, 92, 93 and 110.

Given the application of different discount rates, the 12 best scenarios for the 9% discount rate are not exactly the same as for the 3% discount rate, as shown in Figure 66. As before, the results are displayed in a clockwise decreasing order of utility value.

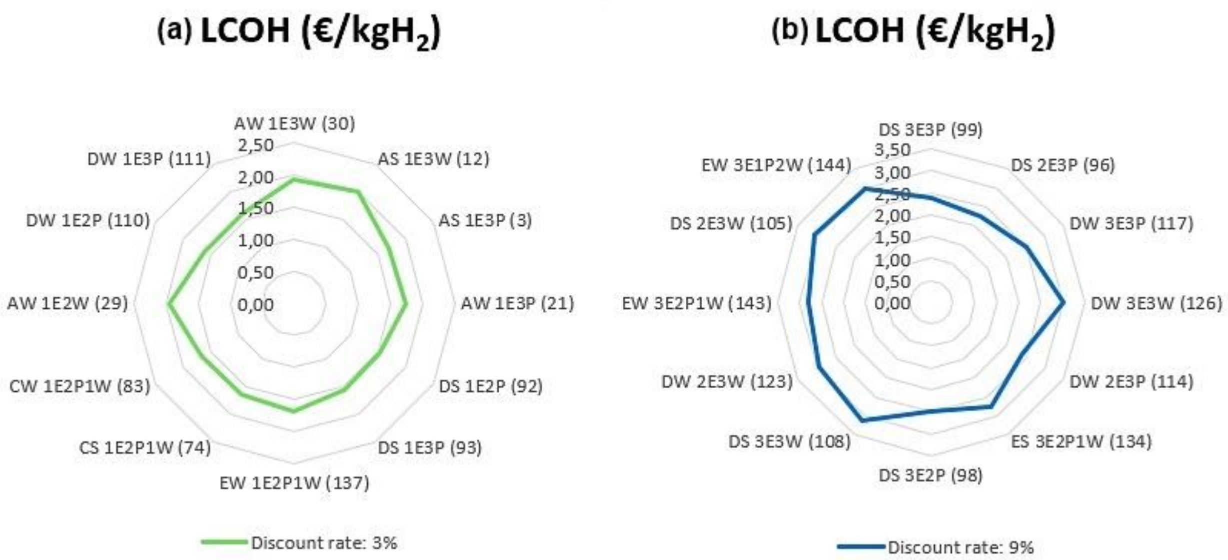

Figure 66: LCOH for a discount rate of: (a) 3% and (b) 9%.

As one can see through the figure above, for a discount rate of 9% the 12 best configurations are no longer the same as for the LCOH with a discount rate of 3%. Figure 66 – b presents a LCOH between 2.27 and 3.13 €/kgH_2, being the maximum achieved with point 108 belonging to scenario D. The majority of these configurations belong to scenario D and E (in both cases requiring a minimum operation electrolyzer load of 20%) with an electrolyzer capacity of 2 or 3 GW and a renewable power of 3 GW combined or individual, except point 98 that present only 2 GW of photovoltaic power.

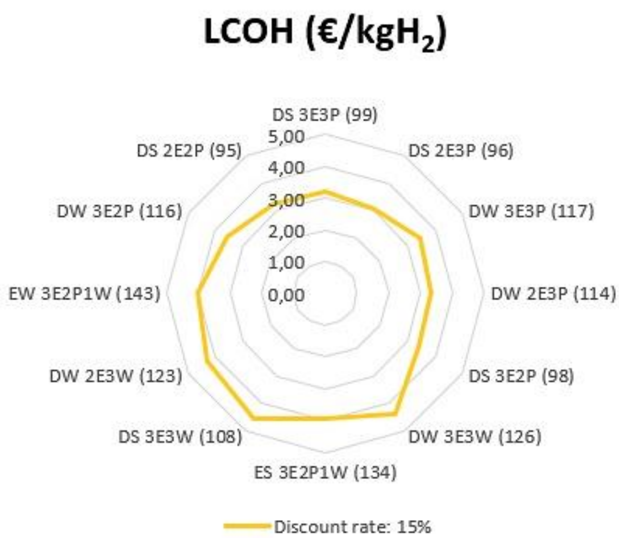

Figure 67: LCOH for a discount rate of 15%.

When a discount rate of 15% is considered (Figure 67), the majority of the points are equal to those of a discount rate of 9%, except the points 144 and 105 that are substituted by point 116 and 95. The LCOH for this case takes values between 3.08 and 4.53 €/kgH_2, being the maximum achieved with point 108. Once again, all the scenarios are composed with 2 or 3 GW of electrolyzer and 7 configurations are composed with photovoltaic power only. The points that require the combination of both renewable powers present a higher capacity of photovoltaic power.

b) Sensitivity to costs of wind technology

For the sensitivity analysis it is also calculated the LCOH when the costs of offshore wind energy are considered, which can be seen in Figure 68.

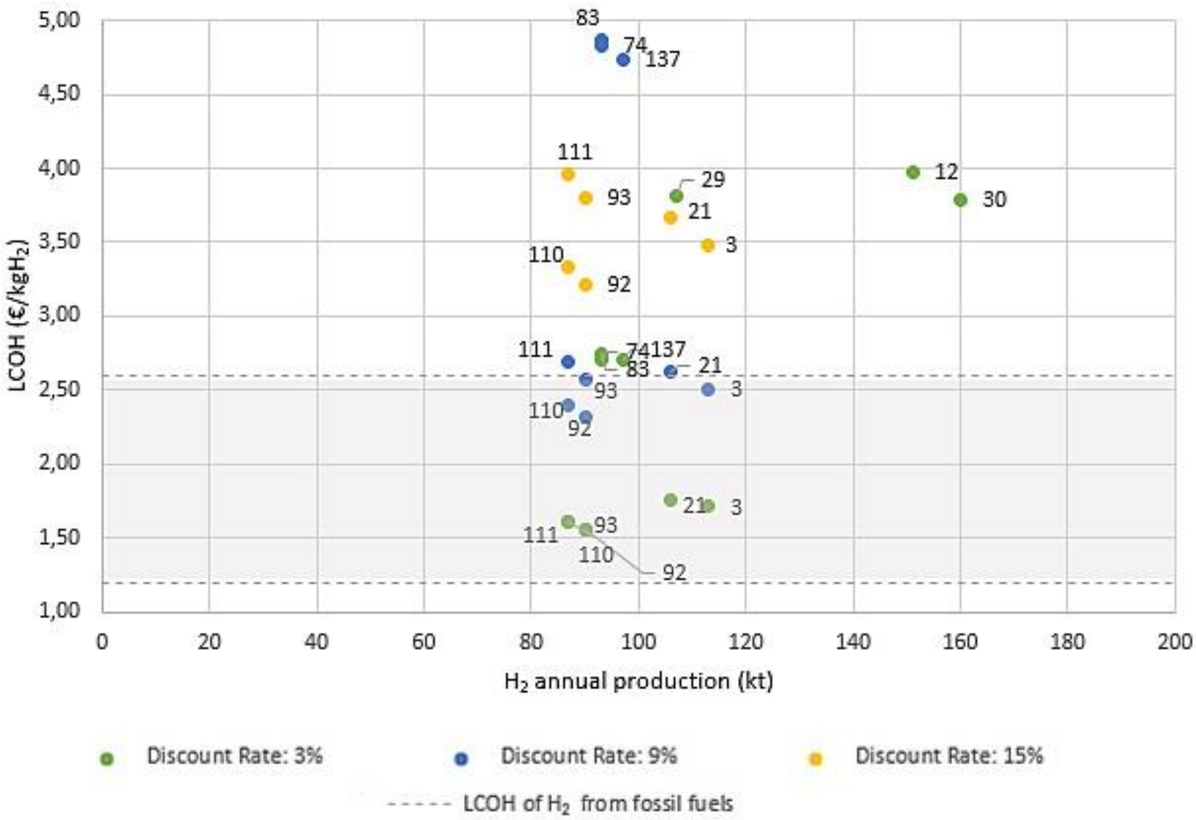

Figure 68: LCOH for different discount rates, being these: 3%, 9% and 15%, with green, blue and yellow color respectively. The dashed delimited section represents the LCOH range, in 2030, for H_2 produced from fossil fuels. [61] For this analysis it is considered the use of offshore wind energy.

Figure 68 shows that when the use of offshore wind energy is considered, instead of onshore wind, the LCOH increases significantly (Figure 65). The highest value of LCOH achieved is with the configuration AS 1E3W, reaching nearly 10 €/kgH_2. With a discount rate of 3% and 9% there are configurations for which green hydrogen is competitive with fossil hydrogen, but this advantage is totally lost for a discount rate of 15%. Once again with a discount rate of 9%

it is verified that only options composed with photovoltaic power are competitive with the H_2 from fossil fuels, being these the points 3, 92, 93 and 110.

One can see through the figure above that only 6 and 4 configurations with a discount rate of 3% and 9%, respectively, have capacity to be competitive with the H_2 produced from fossil fuels in 2030.

It should be noted that there is probably some inaccuracy in the estimation of the LCOH obtained from the use of offshore wind. This is because offshore wind generally provides higher equivalent full load hours and therefore a higher annual H_2 output but a shorter lifetime for the electrolyzer. As we have no data for offshore wind production it is not possible to estimate how these factors influence the LCOH.

c) Exchanges with electricity grid

One possibility that should be considered is that of unavailability of the electricity grid to receive the excess production from the solar/wind farms associated with the project. This could happen for technical or economic reasons, but from the point of view of the simulation the problem is approached by performing a sensitivity analysis based on the assumption that the selling price of the excess production is zero, which is equivalent to turning off the electricity generation equipment during periods when there is excess of production that is not used (curtailment). It is considered that all imports needs of the plant are still satisfied by the national grid. This assumption leads to an increase of the costs of the plant, as expected, reaching almost the 350 M€/year. The LCOH it is also affected with this assumption, and can be evaluate in Figure 69.

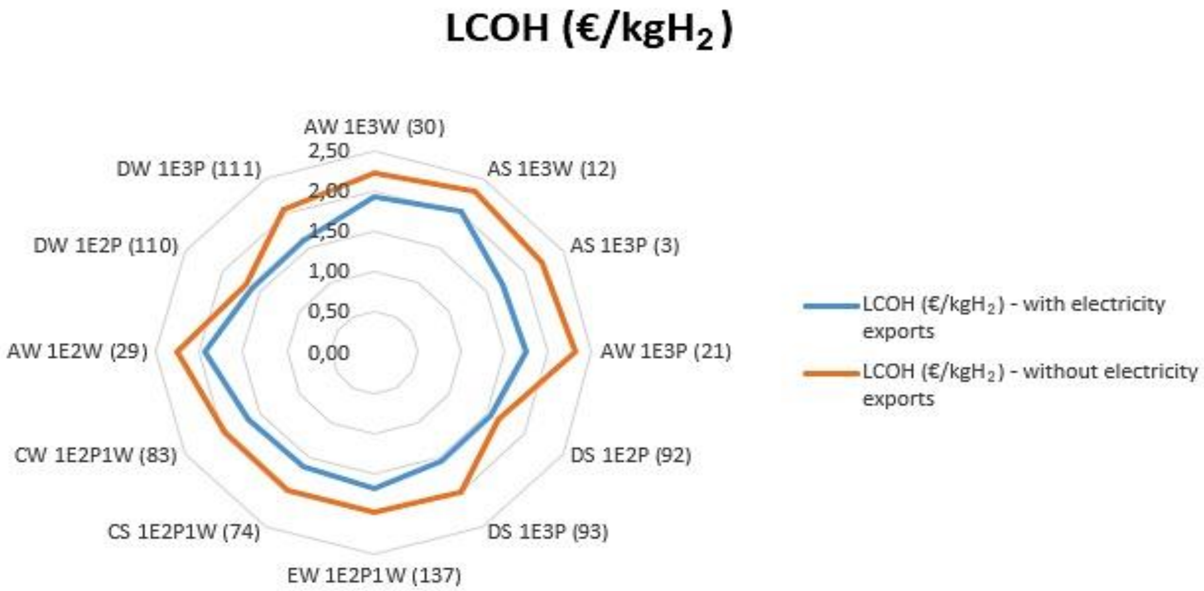

Figure 69: LCOH of the 12 selected configurations. The blue line is the LCOH that does not consider exports to the national grid. The orange line is the LCOH that consider exports to the national grid. It is considered a discount rate of 3%.

As one can see through the figure above, when exports to the national grid are not considered, the LCOH achieves a maximum of 2.31 €/kgH_2, increasing between 5.8% and 14.9% compared to the LCOH with the electricity exports. The lack of revenues from the export of excess electricity leads to an increase in production costs, as can be seen. Nevertheless, the LCOH is still within the band of values that allow green hydrogen to compete with blue hydrogen.

If this outcome is now analyzed with a discount rate of 9% (Figure 70). It is possible to see that the cost of electricity self-production is above 30 €/MWh, much higher than the expected LCOE for 2030 and therefore it would be economically advantageous to power the electrolyzers with grid electricity.

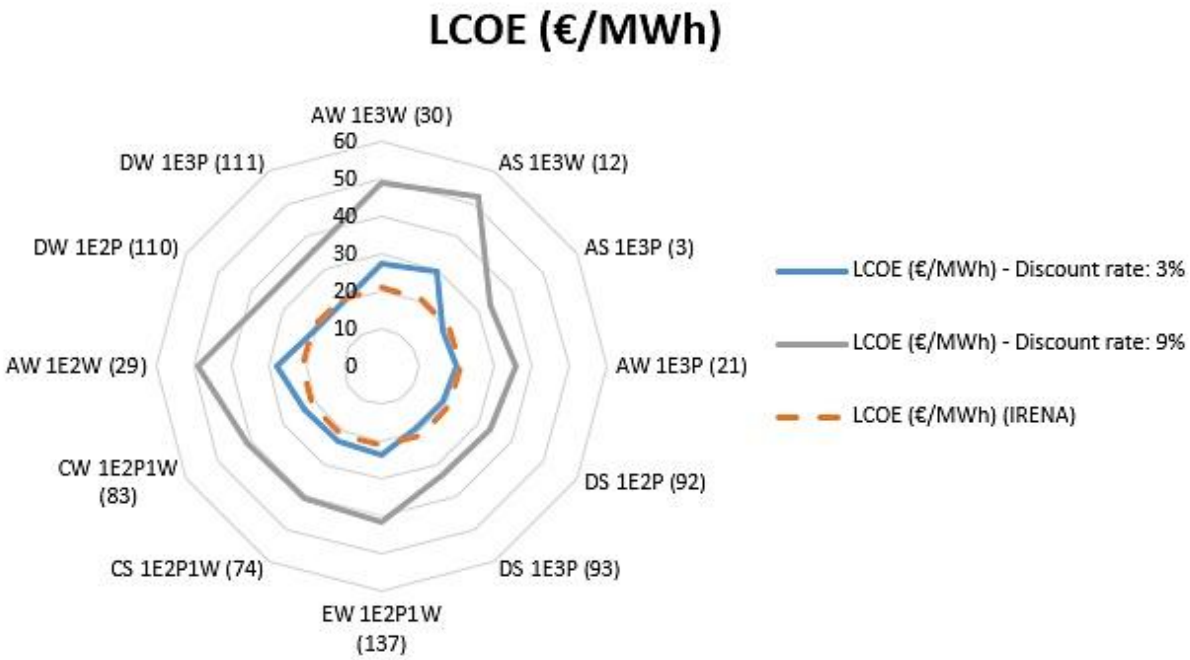

Figure 70: LCOE for different discount rates, being these: 3%, 9% and 15%, with blue, gray and yellow color respectively. According to IRENA, in 2030, the hydrogen can have a LCOE of 21 €/MWh (orange line).

Through the figure above one can see that with the increase in the discount rate, the LCOE increases a maximum of 77% for a discount rate of 9%. With a discount rate of 9% the LCOE varies between 33.21 to 52.07 €/MWh. As verified previously, only configurations composed of photovoltaic power and a discount rate of 3% are solutions when it is required a value below the 21 €/MWh defined by IRENA.

5. Conclusions and further work

This study developed an investigation about the scenarios for the centralized production of green hydrogen based on the electrolysis of water. The analysis focuses on the operation of the H_2 production plant announced for the Sines region, by modeling an electrical grid (balance between electricity production and consumption) that has H_2 as a by-product, using the energyPLAN software. The necessary electricity is provided by dedicated renewable energy sources, solar photovoltaic and onshore wind energy, and possible recourse to the national electricity grid. The technical and economic performances of 144 different configurations combining weather conditions, installed capacities for electrolysis and electricity production and operation regimes have been analyzed.

Weather conditions can have a significant impact on annual H_2 production. However, that impact is significantly smaller when the operation depends on electricity obtained from wind generation.

Access to the national electricity network can supplement the shortcomings of intermittent renewable production allowing a more continuous operation and a higher H_2 output. Wind generation also provides a more continuous operation of the electrolyzer, and generally a higher H_2 output, especially in the cases where the plant works in a self-sufficiency mode. The most productive technical solutions provide an annual H_2 output between 95 and 160 kton.

Through technical analysis it was possible to see that most of the scenarios selected are just composed with 1 GW of electrolyzer, in which the majorly uses wind power in an individual way or combined with photovoltaic power and uses electricity from the national grid. Wind power presents itself as a promising source for the production of H_2, given the higher number of equivalent hours of production when compared with the hours of photovoltaic power. The use of wind combined with photovoltaic power allows suppressing periods when there is no production from the dedicated renewable parks. In the scenario evaluation, the scenario A, which assumes a constant electrolyzer load, is the one which has the highest annual H_2 production, although it also requires large exchanges of electricity with the national grid, increasing the costs of the plant.

However, these most productive technical solutions are not necessarily the best economic options. The calculation of the total annualized costs allows the determination of the levelized cost of hydrogen for each technical solution and a very different picture emerges. The best economic solutions (from point of view of LCOH) include options from four of the five scenarios (except scenario B) in a variety of combinations of technologies and operation modes, but among them, the most outstanding options are generally obtained for an electrolyzer of 1 GW powered by either solar PV or wind. Their annual H_2 production varies between 87 and 160 kton.

The economic analysis evidenced that with the higher H_2 productions the associated costs will be higher too. Also, the use of larger electrolyzer capacities increases the investment and operations costs. The evaluation of the LCOH for all the scenarios shows that the 144 configurations have a fairly comprehensive dispersion, but the vast majority presents a LCOH between 1.50 and 2.50 €/kgH$_2$, when a discount rate of 3% is considered. It can also be concluded that the use of wind energy increases the total annualized costs not only because of higher capital costs, but due to the fact that this renewable source has a greater number of hours of work and consequently shortens the duration (in years) of the electrolyzer, leading to the associated expenses being spread over a smaller number of years. In a more detailed analysis of Pareto Optimality (3% discount rate), it is possible to highlight that scenario A still remains the principal scenario and once again all the configurations require an electrolyzer capacity of 1 GW of power. The 12 best selected configurations present a LCOH below 2.01 €/kgH$_2$ and according to IRENA, this value of green hydrogen is competitive with the fossil hydrogen. The LCOE for those 12 scenarios has values between 18.75 to 29.37 €/MWh. Taking in consideration the IRENA projections of LCOE for 2030, only the configurations composed with solar PV have competitive LCOE, when a discount rate of 3% is considered.

Sensitivity analysis shows that increasing discount rates increases the LCOH. More importantly it shows that the best configurations for a discount rate of 3% are not the same as for a discount rate of 9% and 15%. For a 9% discount rate, the profile of best options is composed by scenario D powered solar PV. The discount rate of 15% presents the highest values of these parameters failing to compete with the LCOH of H_2 from fossil fuels. This change in the best options with discount rate are justified with the fact that scenario D options have longer lifespan of the electrolyzer and therefore the annualized costs of higher electrolyzer and RES capacities are spread over longer periods.

The study with the use of offshore wind energy highlights that the LCOH and total costs are superior when compared with the onshore wind. In the LCOE parameter with different discount rates it was also verified as an increase. For both parameters LCOH and LCOE, the only configurations capable of competing with the IRENA standards are configurations composed with only photovoltaic power, highlighting that with a medium discount rate it is more advantageous to take electricity from the national grid than from the wind dedicated parks.

Is it necessary at this point to present a critical perspective of the results and set forth some directions for further development of this work.

In this analysis no assumptions were made regarding the technology of electrolysis used, such as alkaline or PEM electrolyzer, as each imposes different limitations on operation modes (for estimation of costs the PEM values were chosen for they are higher and therefore give a “worst case” cost). The energyPLAN software does not distinguish the type of electrolyzer and operation mode is defined by the user. However, with a more detailed analysis of the alkaline or PEM type, the results obtained, both technical and economic, could assume different values.

No assumptions were made regarding the origin and quality of the water used. There is a research and business interest in direct seawater electrolysis, although this is in its early stages of development. Alternatively, sea water desalination could be necessary, but it would also require a dedicated infrastructure. Each possibility would mean very different investment costs that could change the picture in terms of LCOH. However, for the economic study the costs of potable water or industrial water were used. The functioning of the electrolyzer in this H_2 production facility requires large amounts of water, turning this into a problem if fresh water, an increasingly scarce resource in the region, is to be used. The volumes required almost achieved the amount of water annually consumed by Sines municipality, a region with 13.662 inhabitants.

For the storage and dispatch of H_2 no assumptions were made, given the wide extent of these parameters.

The analysis was based on discrete values of installed capacities of both electrolyzer and RES. It is possible that a finer tuning of these values could lead to improved results.

The problem of using offshore wind would also require further analysis. We have made a sensitivity analysis on the introduction of this technology but from the point of view of cost only. It is evident that the production profile of offshore wind must be significantly different from the profile used here (the total national production of onshore wind). Offshore wind is generally more productive, with higher equivalent full load hours. The resulting increase in H_2 production could make the larger investment worthwhile.

Bibliography

[1] http://apambiente.pt/index.php?ref=16&subref=81&sub2ref=119&sub3ref=506. March 2020.

[2] Observatório da Energia, DGEG, ADENE. (2019). *Energia em Números – Edição 2019*. ADENE.

[3] https://rea.apambiente.pt/node/716?language=pt-pt. March 2020.

[4] DGEG. (2019). *Balanço Energético Sintético 2018*.

[5] DGEG. (2018). *O Hidrogénio no Sistema Energético Português: Desafios da integração.* 1ª edição.

[6] Data provided by DGEG.

[7] APREN. (2019). *Anuário.*

[8] https://rea.apambiente.pt/content/emiss%C3%B5es-de-gases-com-efeito-de-estufa?language=pt-pt. March 2020.

[9] https://ec.europa.eu/clima/policies/international/negotiations/paris_en. March de 2020.

[10] Roteiro para a neutralidade carbónica 2050 (RNC2050). Estratégia a longo prazo para a neutralidade carbónica da economia portuguesa em 2050. (2019).

[11] Decreto-Lei n.o 85/2019, Legislação do RNC2050. *Diário da República, 1.a série — N.o 123 — 1 de julho de 2019*

[12] https://ec.europa.eu/clima/policies/strategies/2030_en. March 2020.

[13] https://www.portugalenergia.pt/setor-energetico/bloco-3/. March 2020.

[14] Plano Nacional Energia e Clima 2021-2030 (PNEC 2030). (2019). Portugal.

[15] Estêvão, T. *O Hidrogénio como combustível*. Dissertação de mestrado, Faculdade de Engenharia da Universidade do Porto, 2008.

[16] DGEG. “Integração do Hidrogénio nas cadeias de valor – Sistemas energéticos integrados, mais limpos e inteligentes”. Direção-Geral da Energia e Geologia, Lisboa. 2019.

[17] https://www.britannica.com/science/hydrogen. March 2020.

[18] Orecchini, F. *The era of energy vectors*. International Journal of Hydrogen Energy, 27/06/2006, v. 31, p. 1951 – 1954.

[19] Fonseca, J., Camargo, M., Commenge, J., Falk, L., Gil, I. *Trends in design of distributed energy systems using hydrogen as energy vector: A systematic literature review.* International Journal of Hydrogen Energy, 12/04/2019, v. 44, p. 9486-9504.

[20] http://www.ap2h2.pt/sobre-h2.php. March 2020.

[21] Abad, Anthony & Steinberger-Wilckens, Robert & Radcliffe, Jonathan & Al-Mufachi, N.A. & Dodds, Paul & Jones, Owain & Kurban, Zeynep. (2017). The role of Hydrogen and Fuel Cells in delivering Energy Security for the UK.

[22] Felseghi, R., Carcadea, E., Raboaca, M., Trufin, C., Filote, C. *Hydrogen Fuel Cell Technology for the Sustainable Future of Stationary Applications.* Energies, 03/December/2019, p. 1-28.

[23] https://hydrogeneurope.eu/hydrogen-production-0. March 2020.

[24] Abdin, Z., Zafaranloo, A., Rafiee, A., Mérida, W., Lipiński, W., Khalilpour, K. *Hydrogen as an energy vector*. Renewable and Sustainable Energy, 20/11/2019, v. 120.

[25] https://www.energy.gov/eere/fuelcells/hydrogen-production-biomass-gasification. March 2020.

[26] Vezirglu, T., Barbir, F. *Hydrogen Energy Technologies*. Emerging Technology Series. 1998. Vienna.

[27] Keçebaş, A., Kayfeci, M., Bayat, M. Chapter 9 – Electrochemical hydrogen generation. *Solar Hydrogen Production: Processes, Systems and Technologies.* p. 299 – 317, 2019.

[28] Carmo, M., Fritz, D., Mergel, J., Stolten, D. *A comprehensive review on PEM water electrolysis.* International Journal of Hydrogen Energy, 22/04/2013, v. 38, p. 4901 – 4934.

[29] El-Shafie, M., Kambara, S., Hayakawa, Y. *Hidrogen Production Technologies Overview*. Journal of Power and Energy Engineering. 28/01/2019, v. 7, p. 107-154. DOI: 10.4236/jpee.2019.71007

[30] Dincer, I., Acar, C. *Review and Evaluation of Hydrogen production methods for better sustainability.* International Journal of Hydrogen Energy, 14/09/2015, v. 40, p. 11094 – 11111.

[31] https://www.popularmechanics.com/science/energy/a926/4199381/. March 2020.

[32] Yu, L., Zhu, Q., Song, S. *et al. Non-noble metal-nitride based electrocatalysts for high-performance alkaline seawater electrolysis*. Nat Commun **10,** 5106 (2019).

[33] https://news.stanford.edu/2019/03/18/new-way-generate-hydrogen-fuel-seawater/. March 2020.

[34] https://hydrogeneurope.eu/hydrogen-storage. March 2020.

[35] https://hydrogeneurope.eu/hydrogen-applications. March 2020.

[36] https://www.sines-tis.com/copia-termoelectrica-edp. March 2020.

[37] Marianito, Andreia. *Modelos Preditivos de desempenho da unidade de Hydrocracking*. Dissertação de Mestrado, Instituto Superior Técnico, 2015.

[38] https://www.maveng.com/index.php/business-streams/industrial/refining/hydrocrackers. March 2020.

[39] Refinaria de Sines. Data *Book* de Segurança, Saúde e Ambiente 2013. Galp energia. March 2020.

[40] https://www.edp.com/pt-pt/noticias/2019/12/11/edp-prepara-projeto-para-testar-hidrogenio-na-central-do-ribatejo. March 2020.

[41] Carvalho, Inês. *Central do Carregado e Central do Ribatejo: Avaliação Comparativa dos Efeitos na Qualidade do Ar.* Dissertação de Mestrado, Universidade de Aveiro, 2015.

[42] https://www.theportugalnews.com/news/edp-to-produce-hydrogen/52332. March 2020.

[43] https://expresso.pt/economia/2019-12-11-EDP-avanca-com-dois-projetos-inovadores-para-produzir-hidrogenio?fbclid=IwAR3EPTRFM7UsWQqrzPoXSAl-jtNzvzGQD-YY-TDStKn-QrRK_YbMXiZoClY. March 2020.

[44] EN-H_2 – Estratégia Nacional para o Hidrogénio. (2020). República Portuguesa.

[45] https://observador.pt/2019/11/19/governo-planeia-construcao-de-fabrica-de-hidrogenio-verde-em-sines-com-ajuda-da-holanda/. March 2020.

[46] https://jornaleconomico.sapo.pt/noticias/ministro-do-ambiente-construcao-da-central-de-hidrogenio-em-sines-arranca-no-inicio-de-2021-549625. March 2020.

[47] https://jornaleconomico.sapo.pt/noticias/central-de-hidrogenio-de-sines-implica-investimento-de-35-mil-milhoes-537147. March 2020.

[48] Cardoso, E. *Simulação de sistemas energéticos isolados. Ilha de Santiago.* Dissertação de Mestrado, Universidade de Aveiro, 2011.

[49] Nunes, R. *Planeamento de Sistemas de Energia 100% Renováveis*. Dissertação de Mestrado, Faculdade de Ciências e Tecnologia de Universidade de Coimbra, 2017.

[50] Pina, A. *Supply and Demand Dynamics in Energy Systems Modeling*. Dissertação de Doutoramento, Universidade Técnica de Lisboa – Instituto Superior Técnico, 2012.

[51] D. Connolly, H. Lund, B. V. Mathiesen, M. Leahy. "A review of computer tools for analysing the integration of renewable energy into various energy systems." Applied Energy, 2010: 1059-1082.

[52] Prina, M., Manzoli, G., Moser, D., Nastasi, B., Sparber, W. *Classification and challenges of bottom-up energy system models – A review.* Renewable and Sustainable Energy Reviews. v.129, 2020. DOI: https://doi.org/10.1016/j.rser.2020.109917

[53] Lund, T., Thellufsen, J. *EnergyPLAN – Advanced Energy Systems Analysis Computer Model*. 2019.

[54] D. Connolly, "Finding and Inputting Data into the EnergyPLAN Tool - version 4.5," Aalborg University (Denmark), 2013.

[55] Connolly, D. *Finding and Inputting Data into the EnergyPLAN Tool (The FIDE Guide)*. Department of Development and Planning, Aalborg University. Dinamarca, 2015.

[56] DGEG. *Combustíveis fósseis. Estatísticas rápidas – nº 175 – fevereiro de 2020.* República Portuguesa.

[57] https://www.omip.pt/pt/dados-mercado?date=2020-07-08&product=EL&zone=ES&instrument=FTB. July 2020.

[58] ERSE – Entidade Reguladora dos Serviços Energéticos. *Tarifas e Preços para a Energia Elétrica e outros serviços em 2020.* Dezembro, 2019. https://www.erse.pt/media/xcwb23n2/tarifaspre%C3%A7os2020.pdf. September 2020.

[59] http://www.adsa.pt/clientes-industriais/ . July 2020.

[60] Santos, J. *Economia Pública.* Instituto Superior de ciências Sociais e Políticas, 2012, p. 161-163.

[61] Hydrogen: a renewable energy perspective, International Renewable Energy Agency, Abu Dhabi, 2019

Annex I – Weather conditions

	Photovoltaic power										
	Year		**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
	Installed capacity:										
(a)	Photovoltaic	MW	175	244	299	418	454	519	585	673	914
(b)	Concentrated Photov.	MW	0	0	0	6	9	9	14	16	17
(c)	**Total Capacity** (a – b)	MW	175	244	299	412	445	510	571	657	897
(d)	**Production**	GWh	282	393	479	627	799	871	993	1006	1275
	Quotient (d / c)	GWh/MW	1.611	1.611	1.602	1.522	1.796	1.708	1.739	1.531	1.421
	Sunny year	**Average value =** 1.72 GWh/MW			**Correction factor =** - 0.56						
	Windy year	**Average value =** 1.55 GWh/MW			**Correction factor =** - 0.69						

	Onshore Wind power										
	Year		**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
(a)	**Installed Capacity**	MW	4378	4531	4731	4953	5034	5313	5313	5368	5437
(b)	**Production**	GWh	9162	10260	12015	12111	11608	12474	12248	12617	13738
	Quotient (b / a)	GWh/MW	2.093	2.264	2.540	2.445	2.306	2.348	2.305	2.350	2.527
	Sunny year	**Average value =** 2.29 GWh/MW			**Correction factor =** - 0.34						
	Windy year	**Average value =** 2.44 GWh/MW			**Correction factor =** - 0.26						

By comparing the productivity of each technology with general weather data, we have classified the years in the period 2011-2019 as windy or sunny. In order to estimate the annual productivity of each technology in the two weather conditions, an average productivity of the three last sunny (or windy) years was taken. That productivity was used to estimate the total production of each technology in 2030 for the different combinations of installed capacities and weather conditions. Typical profiles for wind and solar PV production were also chosen based on these data. The production profiles of year 2012 were chosen as characteristic profiles for a sunny year and those of year 2016 for a windy year.

Annex II – Summary of technical and economic results

Discount rate: 3%
Expressed in: €$_{2015}$.

Number	Scenario and Weather	Electrolyzer capacity (GW)	RES Capacity (GW)		H_2 produced (kt/year)	Equivalent full load hours of electrolyzer operation	Annualized Investment Costs (M€)	O&M (M€)	LCOH (€/kg)	LCOE (€/MW)	Total Annual Costs (onshore wind) (M€)	Total Annual Costs (offshore wind) (M€)
			Solar PV.	Wind								
1	AS	1	1		38	1722	55.85	1.50	1.84	18.79	69.85	69.85
2	AS	1	2		76	3452	103.31	2.74	1.75	18.73	132.67	132.67
3	AS	1	3		113	5165	150.94	3.98	1.71	18.75	193.54	193.54
4	AS	2	1		38	861	65.67	1.74	2.11	18.79	80.22	80.22
5	AS	2	2		76	1726	111.78	3.22	1.86	18.73	141.40	141.40
6	AS	2	3		113	2582	158.92	4.71	1.79	18.75	201.78	201.78
7	AS	3	1		38	574	76.98	1.47	2.40	18.79	91.89	91.89
8	AS	3	2		76	1151	121.16	2.67	1.98	18.73	151.09	151.09
9	AS	3	3		113	1722	167.55	3.87	1.86	18.75	210.69	210.69
10	AS	1		1	50	2301	96.06	1.74	2.14	29.41	107.20	206.55

Discount rate: 3%
Expressed in: €$_{2015.}$

Number	Scenario and Weather	Electrolyzer power (GW)	RES Power (GW)		H_2 produced (kt/year)	Equivalent full load hours of electrolyzer operation	Annual Investment Costs (M€)	O&M (M€)	LCOH (€/kg)	LCOE (€/MW)	Central costs (onshore wind) (M€)	Central costs (offshore wind) (M€)
			Solar PV.	Wind								
11	AS	1		2	101	4585	183.86	3.22	2.03	29.41	204.56	403.26
12	AS	1		3	151	6878	271.98	4.71	2.01	29.37	303.26	601.31
13	AS	2		1	50	1151	105.22	1.47	2.32	29.41	116.66	216.01
14	AS	2		2	101	2293	191.96	2.67	2.10	29.41	212.93	411.63
15	AS	2		3	151	3439	279.71	3.87	2.05	29.37	311.25	609.29
16	AS	3		1	50	767	115.65	1.78	2.54	29.41	127.42	226.77
17	AS	3		2	101	1528	200.79	3.31	2.19	29.41	222.04	420.73
18	AS	3		3	151	2293	287.94	4.84	2.11	29.37	319.74	617.79
19	AW	1	1		50	1616	54.91	1.47	1.35	20.07	67.64	67.64
20	AW	1	2		71	3215	101.10	2.67	1.78	20.07	126.63	126.63
21	AW	1	3		106	4822	147.72	3.87	1.75	20.07	185.04	185.04
22	AW	2	1		50	808	64.89	1.78	1.56	20.07	77.94	77.94
23	AW	2	2		71	1607	109.67	3.31	1.91	20.07	135.47	135.47

Discount rate: 3%
Expressed in: €$_{2015}$.

Number	Scenario and Weather	Electrolyzer power (GW)	RES Power (GW)		H_2 produced (kt/year)	Equivalent full load hours of electrolyzer operation	Annual Investment Costs (M€)	O&M (M€)	LCOH (€/kg)	LCOE (€/MW)	Central costs (onshore wind) (M€)	Central costs (offshore wind) (M€)
			Solar PV.	Wind								
24	AW	2	3		106	2411	155.77	4.84	1.83	20.07	193.35	193.35
25	AW	3	1		50	539	76.41	1.52	1.78	20.07	89.82	89.82
26	AW	3	2		71	1072	119.23	2.61	2.04	20.07	145.33	145.33
27	AW	3	3		106	1607	164.51	3.33	1.90	20.07	202.37	202.37
28	AW	1		1	53	2442	97.35	1.78	2.05	27.61	108.40	207.75
29	AW	1		2	107	4875	186.57	3.31	1.95	27.61	208.64	407.34
30	AW	1		3	160	7317	276.11	4.84	1.93	27.61	309.19	607.24
31	AW	2		1	53	1221	106.39	1.52	2.21	27.61	117.73	217.08
32	AW	2		2	107	2438	194.62	2.61	2.02	27.61	216.94	415.64
33	AW	2		3	160	3659	283.81	3.33	1.97	27.61	317.13	615.18
34	AW	3		1	53	814	116.65	1.83	2.41	27.61	128.32	227.66
35	AW	3		2	107	1625	203.34	3.02	2.10	27.61	225.94	424.64
36	AW	3		3	160	2439	291.96	4.28	2.03	27.61	325.54	623.59
37	BS	1	1		39	1781	56.37	1.52	1.57	18.79	61.05	61.05

Discount rate: 3%
Expressed in: €$_{2015.}$

Number	Scenario and Weather	Electrolyzer power (GW)	RES Power (GW)		H_2 produced (kt/year)	Equivalent full load hours of electrolyzer operation	Annual Investment Costs (M€)	O&M (M€)	LCOH (€/kg)	LCOE (€/MW)	Central costs (onshore wind) (M€)	Central costs (offshore wind) (M€)
			Solar PV.	Wind								
38	BS	1	2		66	3014	99.24	2.61	1.45	18.73	95.76	95.76
39	BS	1	3		66	3014	130.82	3.33	1.46	18.75	96.17	96.17
40	BS	2	1		39	890	66.11	2.31	1.84	18.79	71.10	71.10
41	BS	2	2		77	1747	112.14	4.05	1.57	18.73	119.72	119.72
42	BS	2	3		117	2671	160.55	5.88	1.50	18.75	174.03	174.03
43	BS	3	1		39	594	77.32	3.11	2.14	18.79	82.67	82.67
44	BS	3	2		77	1164	121.51	5.34	1.71	18.73	129.39	129.39
45	BS	3	3		117	1781	169.13	7.73	1.59	18.75	182.88	182.88
46	BS	1		1	53	2397	96.94	1.77	1.95	29.41	103.24	202.59
47	BS	1		2	87	3973	178.12	3.04	1.97	29.41	171.27	369.97
48	BS	1		3	87	3973	244.68	3.84	2.23	29.37	193.87	491.92
49	BS	2		1	53	1199	106.02	2.74	2.14	29.41	112.61	211.96
50	BS	2		2	99	2260	191.37	4.81	2.00	29.41	196.70	395.40
51	BS	2		3	156	3561	282.00	7.17	2.36	29.37	366.45	664.50

Discount rate: 3%
Expressed in: €$_{2015}$.

Number	Scenario and Weather	Electrolyzer power (GW)	RES Power (GW)		H_2 produced (kt/year)	Equivalent full load hours of electrolyzer operation	Annual Investment Costs (M€)	O&M (M€)	LCOH (€/kg)	LCOE (€/MW)	Central costs (onshore wind) (M€)	Central costs (offshore wind) (M€)
			Solar PV.	Wind								
52	BS	3		1	53	799	116.33	3.72	0.64	29.41	32.39	131.74
53	BS	3		2	99	1507	200.22	6.41	1.64	29.41	160.15	358.85
54	BS	3		3	156	2374	290.19	9.56	2.00	29.37	307.51	605.55
55	BW	1	1		33	1506	53.95	1.44	1.66	20.07	54.62	54.62
56	BW	1	2		63	2877	97.97	2.57	1.52	20.07	95.77	95.77
57	BW	1	3		63	2877	129.55	3.29	1.53	20.07	96.20	96.20
58	BW	2	1		33	753	64.12	2.16	1.98	20.07	65.11	65.11
59	BW	2	2		66	1507	107.91	3.76	1.67	20.07	109.25	109.25
60	BW	2	3		102	2329	154.26	5.47	1.57	20.07	159.05	159.05
61	BW	3	1		33	502	75.86	2.87	2.36	20.07	77.23	77.23
62	BW	3	2		66	1005	117.61	4.92	1.83	20.07	119.26	119.26
63	BW	3	3		102	1552	163.06	7.12	1.68	20.07	168.13	168.13
64	BW	1		1	54	2466	97.57	1.79	1.88	27.61	101.73	201.08
65	BW	1		2	90	4109	179.39	3.08	1.88	27.61	169.53	368.22

Discount rate: 3%
Expressed in: €$_{2015}$.

Number	Scenario and Weather	Electrolyzer power (GW)	RES Power (GW)		H_2 produced (kt/year)	Equivalent full load hours of electrolyzer operation	Annual Investment Costs (M€)	O&M (M€)	LCOH (€/kg)	LCOE (€/MW)	Central costs (onshore wind) (M€)	Central costs (offshore wind) (M€)
			Solar PV.	Wind								
66	BW	1		3	90	4109	245.95	3.88	2.10	27.61	189.19	487.24
67	BW	2		1	54	1233	106.59	2.78	2.07	27.61	111.04	210.39
68	BW	2		2	108	2466	195.13	5.05	1.90	27.61	203.95	402.65
69	BW	2		3	162	3699	284.55	7.34	1.85	27.61	297.28	595.33
70	BW	3		1	54	822	116.82	3.78	2.28	27.61	121.60	220.95
71	BW	3		2	108	1644	203.83	6.78	2.00	27.61	212.93	411.63
72	BW	3		3	162	2466	292.70	9.81	1.91	27.61	305.68	603.73
73	CS	1	1	1	87	3 973	143.15	2.97	1.70	24.86	148.09	247.44
74	CS	1	2	1	93	4178	176.65	3.75	1.64	22.99	152.29	251.64
75	CS	1	1	2	96	4383	213.55	3.89	1.90	26.51	182.15	380.85
76	CS	2	1	1	87	1987	151.42	4.41	1.81	24.86	156.63	255.98
77	CS	2	2	1	125	2843	198.69	6.16	1.66	22.99	206.34	305.69
78	CS	2	1	2	135	3082	238.11	6.52	1.82	26.51	244.23	442.93
79	CS	3	1	1	87	1324	160.52	5.85	1.93	24.86	166.02	265.37

Discount rate: 3%
Expressed in: €$_{2015}$.

Number	Scenario and Weather	Electrolyzer power (GW)	RES Power (GW)		H_2 produced (kt/year)	Equivalent full load hours of electrolyzer operation	Annual Investment Costs (M€)	O&M (M€)	LCOH (€/kg)	LCOE (€/MW)	Central costs (onshore wind) (M€)	Central costs (offshore wind) (M€)
			Solar PV.	Wind								
80	CS	3	2	1	125	1895	207.17	8.11	1.75	22.99	215.09	314.44
81	CS	3	1	2	135	2055	246.48	8.62	1.90	26.51	252.86	451.56
82	CW	1	1	1	87	3973	143.15	2.97	1.70	24.61	147.70	247.05
83	CW	1	2	1	93	4246	177.29	3.77	1.68	23.32	155.78	255.13
84	CW	1	1	2	96	4383	213.55	3.89	1.86	25.74	178.63	377.33
85	CW	2	1	1	87	1987	151.42	4.41	1.81	24.61	156.24	255.59
86	CW	2	2	1	123	2808	198.06	6.12	1.69	23.32	206.53	305.88
87	CW	2	1	2	141	3219	240.65	6.69	1.78	25.74	249.16	447.86
88	CW	3	1	1	87	1324	160.52	5.85	1.93	24.61	165.63	264.98
89	CW	3	2	1	123	1872	206.56	8.05	1.78	23.32	215.30	314.65
90	CW	3	1	2	141	2146	248.97	8.87	1.86	25.74	257.74	456.44
91	DS	1	1		63	2877	66.38	1.84	1.66	18.79	104.46	104.46
92	DS	1	2		90	4108	109.44	2.93	1.55	18.73	139.37	139.37
93	DS	1	3		90	4108	141.02	3.66	1.55	18.75	139.85	139.85

Discount rate: 3%
Expressed in: €$_{2015.}$

Number	Scenario and Weather	Electrolyzer power (GW)	RES Power (GW)		H_2 produced (kt/year)	Equivalent full load hours of electrolyzer operation	Annual Investment Costs (M€)	O&M (M€)	LCOH (€/kg)	LCOE (€/MW)	Central costs (onshore wind) (M€)	Central costs (offshore wind) (M€)
			Solar PV.	Wind								
94	DS	2	1		89	1918	83.64	3.53	1.79	18.79	157.78	157.78
95	DS	2	2		125	2842	132.12	5.36	1.67	18.73	206.80	206.80
96	DS	2	3		165	3767	180.91	7.20	1.60	18.75	261.50	261.50
97	DS	3	1		120	1826	107.17	6.40	1.91	18.79	225.46	225.46
98	DS	3	2		147	2237	149.91	8.24	1.77	18.73	256.11	256.11
99	DS	3	3		188	2854	198.51	10.64	1.68	18.75	310.92	310.92
100	DS	1		1	62	2808	100.72	1.89	1.93	29.41	119.59	218.94
101	DS	1		2	92	4206	180.30	3.11	1.96	29.41	180.39	379.09
102	DS	1		3	92	4206	246.86	3.91	2.20	29.37	202.17	500.22
103	DS	2		1	85	1932	118.85	3.61	2.02	29.41	170.45	269.80
104	DS	2		2	117	2678	199.04	5.31	1.98	29.41	230.40	429.10
105	DS	2		3	168	3829	286.99	7.49	1.92	29.37	320.30	618.35
106	DS	3		1	117	1781	140.93	6.35	2.06	29.41	238.34	337.69
107	DS	3		2	140	2123	216.76	8.08	2.02	29.41	279.05	477.75

Discount rate: 3%
Expressed in: $€_{2015.}$

Number	Scenario and Weather	Electrolyzer power (GW)	RES Power (GW)		H_2 produced (kt/year)	Equivalent full load hours of electrolyzer operation	Annual Investment Costs (M€)	O&M (M€)	LCOH (€/kg)	LCOE (€/MW)	Central costs (onshore wind) (M€)	Central costs (offshore wind) (M€)
			Solar PV.	Wind								
108	DS	3		3	183	2781	301.41	10.66	1.97	29.37	356.11	654.16
109	DW	1	1		57	2604	63.86	1.76	1.72	20.07	97.93	97.93
110	DW	1	2		87	3971	108.16	2.89	1.61	20.07	139.67	139.67
111	DW	1	3		87	3971	139.74	3.62	1.61	20.07	139.89	139.89
112	DW	2	1		84	1918	83.64	3.53	1.87	20.07	155.96	155.96
113	DW	2	2		113	2569	127.09	5.03	1.73	20.07	193.38	193.38
114	DW	2	3		149	3390	173.88	6.75	1.65	20.07	243.63	243.63
115	DW	3	1		117	1781	105.96	6.28	1.94	20.07	224.21	224.21
116	DW	3	2		140	2124	146.82	7.94	1.83	20.07	251.07	251.07
117	DW	3	3		171	2602	191.55	9.96	1.74	20.07	293.12	293.12
118	DW	1		1	63	2863	101.23	1.91	1.88	27.61	117.64	216.99
119	DW	1		2	95	4330	181.46	3.14	1.88	27.61	178.13	376.83
120	DW	1		3	95	4315	247.88	3.94	2.08	27.61	196.72	494.77
121	DW	2		1	86	1966	119.46	3.65	1.98	27.61	168.94	268.29

Discount rate: 3%
Expressed in: €$_{2015.}$

Number	Scenario and Weather	Electrolyzer power (GW)	RES Power (GW)		H_2 produced (kt/year)	Equivalent full load hours of electrolyzer operation	Annual Investment Costs (M€)	O&M (M€)	LCOH (€/kg)	LCOE (€/MW)	Central costs (onshore wind) (M€)	Central costs (offshore wind) (M€)
			Solar PV.	Wind								
122	DW	2		2	125	2850	202.21	5.51	1.89	27.61	234.62	433.32
123	DW	2		3	173	3938	289.03	7.63	1.85	27.61	316.47	614.52
124	DW	3		1	119	1804	141.54	6.41	2.02	27.61	236.53	335.88
125	DW	3		2	146	2219	219.37	8.34	1.96	27.61	281.17	479.87
126	DW	3		3	188	2854	303.44	10.86	1.90	27.61	351.97	650.02
127	ES	1	1	1	91	4 164	144.94	3.02	1.71	24.86	156.00	255.35
128	ES	1	2	1	97	4439	179.09	3.83	2.04	22.99	198.13	297.48
129	ES	1	1	2	99	4520	214.83	3.93	1.89	26.51	187.22	385.92
130	ES	2	1	1	105	2390	158.77	4.89	1.81	24.86	188.81	288.15
131	ES	2	2	1	143	3260	206.44	6.66	1.69	22.99	239.40	338.75
132	ES	2	1	2	144	3294	242.05	6.78	1.83	26.51	261.04	459.73
133	ES	3	1	1	127	1932	176.58	7.49	1.90	24.86	238.03	337.38
134	ES	3	2	1	162	2470	222.88	9.67	1.78	22.99	283.26	382.61
135	ES	3	1	2	158	2402	255.97	9.56	1.89	26.51	294.22	492.92

Discount rate: 3%
Expressed in: €2015.

Number	Scenario and Weather	Electrolyzer power (GW)	RES Power (GW)		H_2 produced (kt/year)	Equivalent full load hours of electrolyzer operation	Annual Investment Costs (M€)	O&M (M€)	LCOH (€/kg)	LCOE (€/MW)	Central costs (onshore wind) (M€)	Central costs (offshore wind) (M€)
			Solar PV.	Wind								
136	ES	1	1	1	91	4150	144.81	3.02	1.70	24.61	154.88	254.23
137	EW	1	2	1	97	4425	178.96	3.83	1.68	23.32	162.86	262.21
138	EW	1	1	2	98	4493	214.58	3.92	1.86	25.74	182.71	381.41
139	EW	2	1	1	104	2377	158.52	4.87	1.81	24.61	187.24	286.59
140	EW	2	2	1	140	3185	205.04	6.57	1.70	23.32	236.21	335.56
141	EW	2	1	2	149	3411	244.22	6.92	1.79	25.74	264.36	463.06
142	EW	3	1	1	126	1922	176.32	7.46	1.90	24.61	236.25	335.60
143	EW	3	2	1	159	2420	221.49	9.54	1.79	23.32	280.18	379.53
144	EW	3	1	2	162	2466	257.72	9.73	1.85	25.74	295.91	494.61