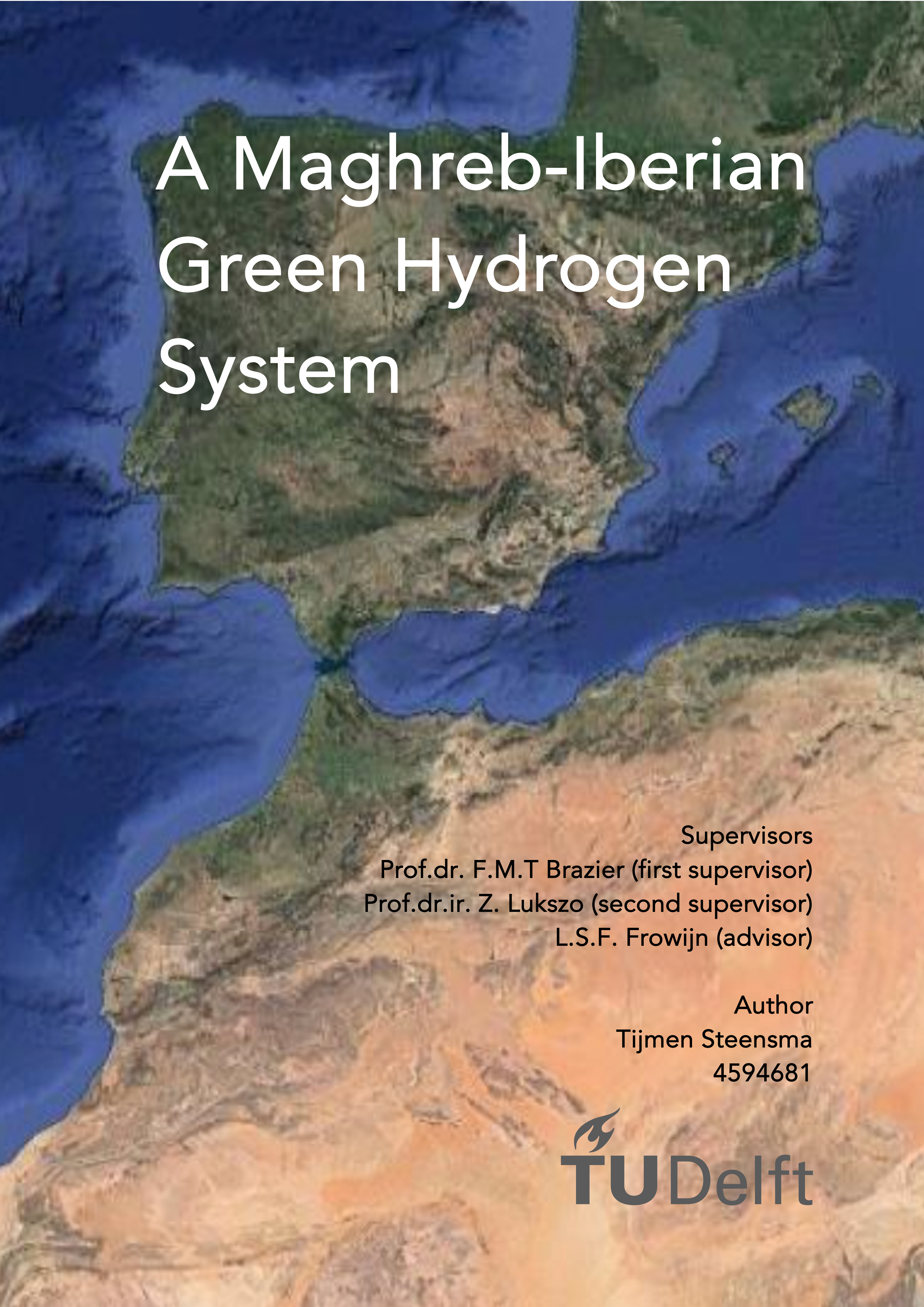


A Maghreb-Iberian Green Hydrogen System

Supervisors
Prof.dr. F.M.T Brazier (first supervisor)
Prof.dr.ir. Z. Lukszo (second supervisor)
L.S.F. Frowijn (advisor)

Author
Tijmen Steensma
4594681

TU Delft

Preface

The world stands at a pivotal juncture, where the quest for sustainable energy solutions has become more urgent than ever. In this pursuit, the realm of green hydrogen has emerged as a promising avenue towards a cleaner and greener future. As I delved into the intricate interplay of energy systems, green hydrogen and energy security, I embarked on a transformative journey of research and exploration.

This thesis encapsulates my passion for sustainable energy and my ardent commitment to understanding the intricacies of possible technologies in the energy transition. During my master's degree Complex Systems Engineering & Management at the TU Delft the energy transition – and hydrogen especially – has been a silver lining. Adding onto this last year as board member for the energy-transition ambassador's program, this thesis forms a fitting end to my academic career.

Focused on the geographical regions of Portugal, Spain, Morocco, and Algeria, this study delves into the unique opportunities and challenges presented by these nations in adopting green hydrogen as a viable energy alternative. The interest in this geographical area was sparked by a semester abroad in Portugal, immersing myself in its culture, people, and energy landscape. Additionally, I had the privilege of exploring the vibrant energy scene of Morocco during a two-week sojourn. These on-the-ground experiences not only shaped my perspective but also provided invaluable insights that shaped the trajectory of this research.

A special thanks goes out to Laurens Frowijn, whose exceptional guidance and unwavering support helped me throughout the completion of this thesis. Without his feedback, tips and support this thesis would definitely not have the form that it has today. Working with Laurens has been a great experience and his way of supervising was a great match to my way of working. A lot of gratitude also goes to my supervisors Frances Brazier and Zofia Lukszo, who were willing to form a thesis committee, despite their overflowing professional and personal commitments. Another word of thanks goes out to my parents, who helped me by proofreading the thesis and who tried very hard to understand it partially. Finally, I want to thank my friend and study companion Timo Maassen for the times we worked on our theses together and for peer reviewing this thesis in the final weekend before delivery.

As I present this thesis, I hope that it serves as a steppingstone in the ongoing quest for a sustainable energy future. May it spark new ideas, inspire collaboration, and contribute to the collective effort of creating a world powered by the boundless potential of green hydrogen. What I can guarantee is that I will proudly take the insights, skills, mentality and enthusiasm developed in my years at the TU Delft with me during the traineeship at the Dutch Ministry of Economic Affairs and Climate.

Executive summary

The Green Deal (Fetting, 2020), initiated by the European Commission, aims to reduce greenhouse gas emissions within the EU to limit global warming to 1.5 degrees Celsius compared to pre-industrial levels (International Panel of Climate Change, 2022). The EU focuses on energy that is acceptable, applicable, available, and affordable – referring to sustainability, technological readiness, energy security, and cost-effectiveness. Energy security involves meeting energy needs using domestic sources to avoid reliance on imported energy, which could pose threats to energy security due to the political power of supplying countries (Asia Pacific Energy Research Centre, 2007). A potential proposed by researchers is the Desertec project (Van Wijk & Wouters, 2021).

In this idea the strong solar radiation in African countries is used to supply Europe with hydrogen The Desertec project, despite its promising potential, never materialized. Studies examining the reasons for its non-realization concur that the primary hindrance was not technological limitations but rather the complexities arising from multi-country politics (Schmitt, 2018; Scheer, 2012; Lilliestam & Ellenbeck, 2011). Scheer (2012) aptly described the plan as "practically impossible for obvious political, economic, and sociological reasons" (Schmitt, 2018). He emphasized that coordinating an energy system involving over forty different goverments, each with their own energy grids and territories for power transmission, inevitably led to unrealistic expectations.

In response, this research presents a system that addresses key barriers that impeded the Desertec project's success. By focusing on a specific geographical area with fewer national governments involved, integrated energy grids, and no energy transport crossing other countries' territories, the research proposes a solution to the challenges identified by Scheer (2012) and Schmitt (2018). Portugal and Spain, with an integrated energy grid and limited European energy grid connection, are considered, while Spain's existing natural gas pipelines to Algeria offer a paved path for hydrogen transport. With this more manageable consortium of four national governments and fewer complexities, the research seeks to evaluate various technological design options using a cost model to test their feasibility and impact on energy security. The aim of this research is to provide an answer to: *How does a technologically feasible Maghreb-Iberian green hydrogen system (MIGHS) impact the Iberian energy cost and energy security?*

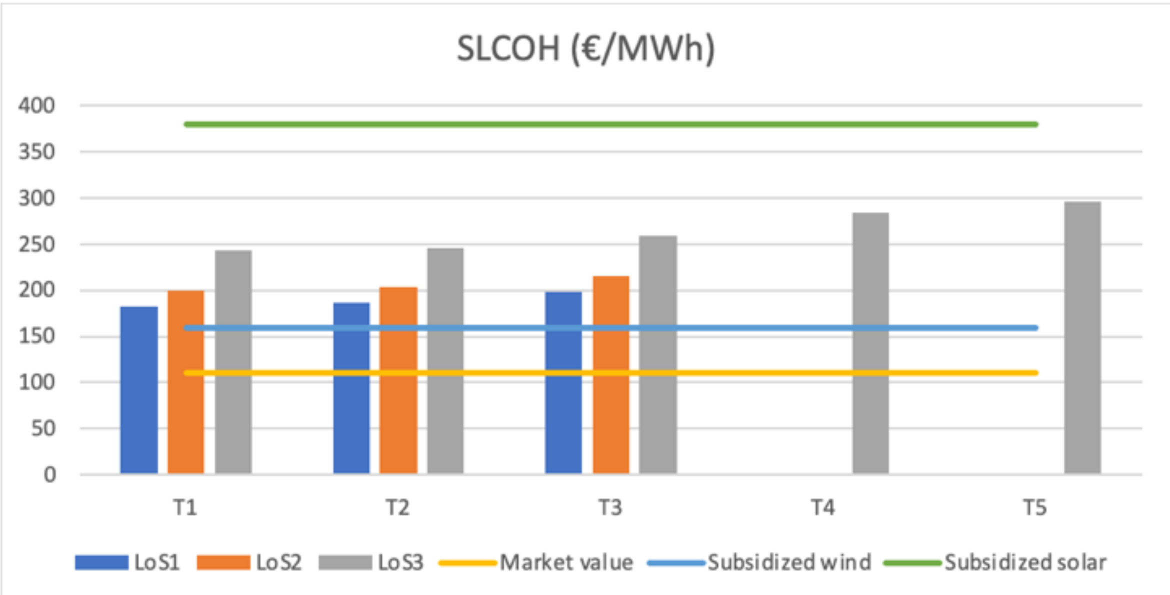
To estimate the system levelized cost of the hydrogen system, this research employs a linear cost model - a common approach for scenarios with multiple codable inputs relevant to policy decisions (Dawes & Corrigan, 1974). The model aims to support the policy decision of implementing the Desertec principle in the Maghreb-Iberian area, with technologically feasible options as codable inputs. The costs will be calculated using the minimum flow cost algorithm with the network simplex method (Könen et al., 2022; Thulasiraman et al., 2016).

The model offers possibility to experiment with three design options that influence the energy cost en energy security. The hydrogen s*ystem size* is the amount of hydrogen that the Iberian Peninsula imports from the MIGHS. This is divided in a scenario where only the industry is supplied with the imported hydrogen (D1) and a scenario in which all energy imports come from the MIGHS (D2). The hydrogen import dependence is a way to measure how much of the total Iberian energy consumption is affected when one of the supplying countries shuts down supply. Finally, also the effects of changing the means of hydrogen transport is tested. The three options of retrofitting the existing pipelines, building new pipelines and using hydrogen vessels are tested, of which the two latter options include a low-cost and high-cost scenario. The table below offers an overview of the design options.

System size	Hydrogen import dependence	Means of transport
D1: 80 TWh/year	LoS1: 14 % (D1), 35 % (D2)	T1: Retrofitting existing pipelines
D2: 200 TWh/year	LoS2: 10 %	T2: New pipelines (low-cost scenario)
	LoS3: 0 %	T3: New pipelines (high-cost scenaro)
		T4: Hydrogen shipping (low-cost scenario)
		T5: Hydrogen shipping (high-cost scenario)

1 The different design options that have been tested in this research regarding system size, hydrogen import dependence and means of hydrogen transport.

The resulting costs that the model produces are shown in the figure below. They are compared to the current energy cost in Portugal and the costs of wind and solar energy including the current subsidies for those energy sources.



2 System levelized cost of hydrogen for the different design options as calculated by this research.

Regarding the difference in system size, the most important outcome is the investment costs resulting from the model. Opting for the smaller system size implies investment costs between 15 to 24 billion euros, the larger system results in 37 to 59 billion euros.

The choice of transport has large impact on both the costs and hydrogen import dependency. Shipping for example opens the system up to other suppliers, whereas pipelines are less expensive.

The energy security can be increased, but it increases the costs. In the first system size scenario, decreasing the hydrogen import dependency (HID) from 14 percent to 10 percent incurs a 10 percent additional cost, while eliminating the HID entirely leads to a substantial 30 to 50 percent increase in system levelized cost of hydrogen (SLCOH). Similarly, in the second scenario, reducing the HID from 35 percent to 10 percent results in a significant 24 percent increase in SLCOH. These findings highlight the crucial trade-offs between energy security levels and cost-effectiveness in the Maghreb-Iberian Green Hydrogen System. Decision-makers must carefully consider the economic and strategic implications when determining the optimal HID for the system.

To test for the validity of the outcomes of the model it has been compared to previous research. All values from the model are in the same order of magnitude as similar research.

This master thesis makes a significant contribution to existing literature by addressing key knowledge gaps through the development of a novel model for evaluating design options in the Maghreb-Iberian Green Hydrogen System. The study's uniqueness lies in its focus on this specific geographical area, which had not been extensively researched before, allowing for a thorough examination of complex political implications in a multinational energy system. The deliberate selection of the area overcomes barriers identified in previous research, as it already possesses an integrated energy market and established energy transport routes.

Moreover, the thesis enhances earlier model studies by incorporating the crucial factor of energy security, which has gained prominence due to geopolitical events. The introduction of the hydrogen import dependency approach adds a significant political dimension, bridging technology and sociology.

With this expanded scope, the thesis offers valuable insights and opens avenues for future research. Among the recommended future research directions are exploring financing options for the multinational project to ensure fair cost-benefit distribution and investigating the applicability of the model and frameworks to regions with integrated energy grids. Additionally, refining the model to address limitations and uncertainties is crucial for more robust results.

Despite some omissions due to constraints, the master thesis sets the stage for further investigations, ultimately contributing to the advancement of sustainable energy systems in the Maghreb-Iberian area and stimulating future research in green hydrogen and energy security.

Key words: Green hydrogen, Energy security, System levelized cost of hydrogen, Net import dependency, Network simplex method, Desertec

Important abbreviations
MIGHS: Maghreb-Iberian Green Hydrogen System
SLCOH: System Levelized Cost Of Hydrogen
HID: Hydrogen Import Dependency

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1 Introduction

The *Green Deal* (Fetting, 2020) is a mission from the European Commission with ambitious goals for the European Union (EU) to reduce greenhouse gas emissions. The targets of an EU energy system with heavily reduced emissions by 2030 is set to limit global warming to 1.5 degree Celsius compared to pre-industrial temperature levels. This temperature rise is widely accepted as the value at which the effects of global warming can be limited (Livingston & Rummukainen, 2020; International Panel of Climate Change, 2022)

To limit global warming resposibly, the EU aims for energy that is acceptable, applicable, available and affordable. These *four A's* are respectively used to describe: the sustainability of energy, technological readiness, energy security and the cost of energy (Kruyt et al., 2009; Ainou et al., 2022; Tongsopit et al., 2016).

Energy security refers to a country's ability to meet its energy needs using domestic sources, without relying on imports from other countries (Asia Pacific Energy Research Centre, 2007). Imported energy can be a threat to energy security because the supplying country has the political power of (threatening to) stop the supply (Milov, 2023). Currently the European Commission (2022) has put extra focus on energy security with the RePower EU policy to phase out energy dependency on Russia on the short term (Lambert et al., 2022; Surwillo et al., 2022).

Kutscher et al. (2018) classifies energy as sustainable when it "meets the needs of the present without compromising the ability of future generations to meet their own needs." Since fossil fuels are not fitting the definition of sustainable, renewable energy sources should be used to provide EU countries with energy.

1.1 Renewable energy and hydrogen

Wind and solar energy are the two main used renewable energy sources (Brodny & Brodny, 2020; Bórawski et al., 2019). However, there are some problems with using those energy sources that generate electricity. Firstly, electricity transport over long distance is not very efficient because of transport losses (Jovcic & Ahmed, 2015; Alassi et al., 2019). Secondly, electricity is difficult to store seasonally on a large-scale (Kebede et al., 2022; Fan et al., 2020). Thirdly, certain heavy industry processes require a very high temperature, which is difficult to reach using electricity (Nadel, 2019; Bühler et al., 2019).

A potential solution to these three complications, is the energy carrier hydrogen. Similar to electricity, hydrogen is not a source of energy, but a means to transport, store and use energy. Compared to electricity, hydrogen (i) is more suitable to transport over long distances (Reddi et al., 2016; Melaina et al., 2013; Brändle et al., 2021), (ii) is more suitable to be stored for the long-term (Hydrogen TCP-Task 42, 2023; Linssen et al., 2020) and (iii) is more suitable for industrial processes that require high temperatures (Karakaya et al., 2018; Nadel, 2019; Oliveira et al., 2021).

There are different ways to produce hydrogen. For hydrogen to be considered sustainable, it should be produced using renewable energy sources (Oliveira et al., 2021). Hydrogen that is produced using renewable energy sources is called *green* hydrogen.

1.2 The Desertec project

Because of these practical advantages that hydrogen offers, researchers came up with the *Desertec* project (Abdelli et al., 2022; Van Wijk & Wouters, 2021). In this idea the strong solar radiation in African countries is used to supply Europe with sustainable energy. Over the course of 12 years, Desertec industrial initiative (Dii) Desert Energy has evolved from a basic vision of harnessing power from deserts for Europe (Desertec 1.0) to focusing on local renewable energy markets (Desertec 2.0), and now stands as a recognized facilitator of "green electrons" and "green molecules" from African countries, serving its population and the Arab world to become a significant player in global energy markets, referred to as 'Desertec 3.0' (*DII Desert Energy*, n.d.). Dii Desert Energy's current approach encompasses the entire energy system, including various forms of renewable power generation, conversion to green molecules and transmission grids.

However, the project never became a reality. Studies on why the plans were never realized agree that it was not the technology that was lacking, but that the multi-country politics complicated the feasibility of the plan (Schmitt, 2018; Scheer, 2012; Lilliestam & Ellenbeck, 2011). Scheer (2012) captured this adequately by stating that the plan was ‘practically impossible for obvious political, economic and sociological reasons’ (Schmitt, 2018). To amplify his statements, he summed up that an energy system including over forty different governments - each with their own energy grids and territories through which the power should be transmitted - was bound to be unrealistic.

1.3 The Desertec principle on a different scale

The project failed, but the principle is promising. Therefore, this research proposes a system that takes away a lot of barriers that stopped the Desertec project. Since in literature the Desertec principle has already been marked as technologically feasible, this research discusses a system that offers a solution to the three biggest barriers that Scheer (2012) and Schmitt (2018) identified: the enormous number of different governments having to work together, the different governments with different energy grids and the energy transport crossing territories of other countries. This research focuses on a geographical area in which fewer national governments are included, where the energy grid of the countries is already integrated and where no transport crossing other country’s territory is required.
Two European countries that have an integrated energy grid are Portugal and Spain (Mibel, 2023). Besides, the Iberian Peninsula has a relatively low connection to the European energy grid (European Commission, 2018), meaning that they cannot rely on European energy supply.

In addition, Spain is already connected to Algeria by natural gas pipelines (Timmerberg & Kaltschmitt, 2019; Van Wijk & Wouters, 2021). These pipelines do not cross the territory of other countries, taking away another political barrier. Moreover, natural gas pipelines could even be converted to transport hydrogen (Timmerberg & Kaltschmitt, 2019). The countries to which the Iberian countries are currently connected are the Maghreb countries Morocco and Algeria. Therefore, this thesis considers those two African countries as the producers of green hydrogen. This new geographical area including Portugal, Spain, Morocco and Algeria includes four - instead of forty - national governments, has no energy transport crossing other country’s territories and the hydrogen-consuming countries already have an integrated energy grid. To test the impact of the different technological design options a cost model is proposed in this thesis.

1.4 Shortcomings of other model studies

Backhaus et al. (2015) compared four existing models studying the Desertec project. Those four models had three main shortcomings in common. Backhaus et al. (2015) criticizes the approach of those three articles for neglecting to incorporate the political risks that come with such large- scale projects (Williges et al., 2010; Dii GmbH, 2009; Ummel & Wheeler, 2008; German Aerospace Center 2006).

Besides, all models date from at least 13 years ago. This greatly impacts the assumptions that have been made. For example, (obviously) none of the articles predicted the current Russia-Ukraine war and the resulting energy crisis. This results in the assumptions of energy costs being far from reality.

Also, the political situation between Europe and Russia has led to a different starting situation and different opinions towards political (energy) dependencies.

Lastly, all previous research is focused on the whole of Northern Africa working together with the whole of Europe. There is no model yet on a system that only includes the Iberian Peninsula with Morocco and Algeria.

1.5 Research questions and modelling approach

The model proposed in this thesis is created especially for the discussed geographical Maghreb-Iberian area. Also, it is based on data and assumptions from recent years. Finally, this model includes political aspects, addressing the critique from Scheer (2012) that the Desertec project is a "technology without sociology".

The political aspects are on the one hand included by the carefully selected geographical area (as discussed in §1.3: not crossing territories, integrated energy grid and limited number of governments). On the other hand, also energy security will be incorporated into this new model.

The aim of the model is to answer the question: *How does a technologically feasible Maghreb-Iberian green hydrogen system impact the Iberian energy cost and energy security?* This research question is built-up from a few important concepts, that need to be defined clearly. This system, limited to the Maghreb countries Morocco and Algeria supplying Iberian countries Portugal and Spain with green hydrogen, is being discussed using four sub-questions.

Firstly, *technologically feasible* means that this research only includes technological options of which existing literature states that it is implementable by the EU's first deadline of 2030. This assures the <u>applicability</u> dimension of energy and introduces the first sub-question: *Which technologically feasible options are there for a Maghreb-Iberian green hydrogen system by 2030?*

Secondly, energy security is an important requirement for any energy system to adhere to the <u>availability</u> aspect of energy. Aiming to answer the question from literature research: *Which measures can be taken to support energy security?*

Thirdly, the *Iberian energy cost* is the cost per megawatt hour of energy that is delivered to the Iberian countries. To come to an appropriate way of estimating <u>affordability</u> of energy, the question that will be answered is: *Which factors influence the system levelized cost of hydrogen?*

These three questions will form the basis for the linear cost model that estimates the system levelized cost of the hydrogen system that is created especially for this thesis. Linear models are commonly employed in scenarios where policy decisions rely on multiple codable inputs (Dawes & Corrigan, 1974). In this case the model should support the policy decision of realising the Desertec principle in the Maghreb-Iberian area, with the technologically feasible options as codable inputs.

The costs will be calculated by the minimum flow cost algorithm with the network simplex method, which will be further explained in §2.4. Experimenting with different technologically feasible design options and the different means to support energy security, this research explores the impact of those different design options on the Iberian energy cost and energy security. By including the political factor of energy security to the model, this research differentiates itself from the existing literature.

Ultimately, to assess how the system performs in comparison to alternative sources of energy, the question will be answered: *What are the appropriate performance metrics for the hydrogen system design?*

The theoretical concepts and definitions for this research will next be discussed in the theoretical framework. The theoretical findings will then be applied to the specific conditions from the delineated area and enriched with empirical data in chapter three. This combination of theoretical and empirical findings forms the basis for the model described in chapter four, which estimates the effects on energy cost and on Iberian energy security of different design options. The results will then be discussed in chapter five and the research is concluded by the final conclusions and recommendations for future research in chapter six.

2 Theoretical framework

The four sub-questions as defined in chapter one start with a broad, theoretical overview of a potential Maghreb-Iberian Green Hydrogen System (MIGHS) including Morocco, Algeria, Portugal and Spain. Figure 1 shows that sub-questions one and two explore the options that theoretically possible for the hydrogen system and its impact on energy security. The options found from those sub-questions will be input to the third sub-question that defines the factors that influence the system levelized cost of energy. In its turn the findings from the third sub-question, including the findings from the previous sub-questions, will be the input for the cost model. This model calculates the costs of the hydrogen system under different design options from sub-question one and two that will be tested. To put the outcomes of the model into perspective, the outcomes will be tested against appropriate performance metrics. The findings of the model as opposed to those metrics will ultimately form the basis to answer the main research question.

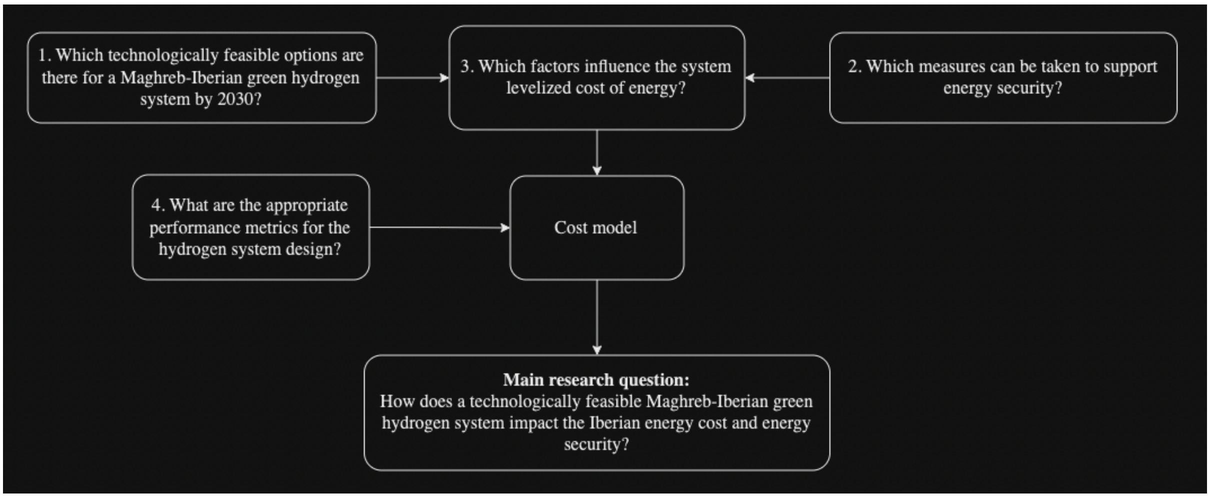

Figure 1 Subquestions one and two form the input for subquestion three, which is answered by the proposed cost model. The outcomes of the model are tested against the performance metrics that follow from subquestion four to eventually answer the main research question.

This chapter sets the theoretical framework for the research. It further delineates the system and defines the core concepts that are used in this research. Firstly, starting with the geographical and technical delineation in §2.1 in which the technologically feasible options for the green hydrogen supply chain are described. §2.2 continues by defining energy security and how it is relevant to this research. In §2.3 the concept of system levelized cost is defined and its calculation is explained. §2.4 introduces the algorithm on which the linear cost model is based, after which in §2.5 a framework for policy models is set out. Finally, in §2.6 the framework for assessing the performance of an energy system is clarified.

2.1 The green hydrogen supply chain

Hydrogen, the lightest and most abundant element in the universe, holds immense potential as a clean and versatile energy carrier (Oliveira et al., 2021). With its high energy content of 33,33 MWh per ton and ability to be produced through renewable sources, hydrogen offers promising solutions for decarbonizing various sectors, including transportation, industry, and energy storage. This research focuses solely on green hydrogen. Green hydrogen is hydrogen that is produced using renewable energy sources (Rezaei et al., 2020; Al-Sharafi et al., 2017; Nasser et al., 2020).

The research considers the whole hydrogen supply chain. A supply chain is a network of interconnected entities, including manufacturers, suppliers, distributors, and retailers, collaborating to ensure the smooth flow of goods and services from raw materials to the end consumer (Reuß et al., 2017; Balakotaiah et al., 2021; Li et al., 2019; Almansoori & Shah, 2006). Therefore, the system is considered from the production of renewable energy in the Northern African countries to the conversion of that energy towards hydrogen, which will then be transported and stored, to finally the hydrogen demand in the Iberian Peninsula (Figure 2). This paragraph shows which technologies are considered technologically viable by 2030 for each step. Technologies with a clear economic disadvantage and no significant other advantage will not be included in further chapters.

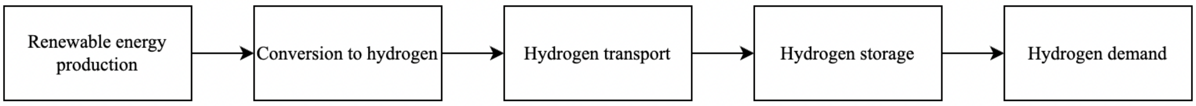

Figure 2 the five steps in the green hydrogen supply chain (Reuß et al., 2017; Balakotaiah et al., 2021; Li et al., 2019).

2.1.1 Renewable energy production from wind and solar

The Desertec principle is based on renewable energy from wind and solar power (Van Wijk & Wouters, 2021; Abdelli et al., 2022; Trieb, 2021). However, both wind and solar energy are *intermittent*. Intermittency refers to the unpredictable and irregular nature of energy sources, resulting in fluctuations in availability and output as shown in Figure 3 (Heide et al., 2010; Rezaei et al., 2020; Al-Sharafi et al., 2017). Therefore, wind and solar are often used in combination with each other to produce hydrogen (Rezaei et al., 2020; Al-Sharafi et al., 2017). According to Heide et al. (2010) wind and solar power complement each other, balancing seasonal variations. The optimal mix for seasonal load requires 55% wind and 45% solar power. To use them together and even further balance out the intermittency over the day, Al-Sharafi et al. (2017) and Rezaei et al. (2020) suggest using batteries to store renewable energy in the short term, to create a more consistent supply of electricity for the production of hydrogen. This battery is being charged when there is more renewable energy produced and it discharges when there is less than average wind and solar power.

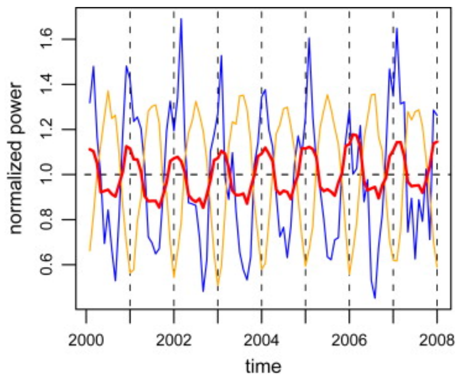

Figure 3 the intermittency of wind and solar energy Heide et al. (2010)

2.1.1.1 Solar energy production

A popular scientific method to calculate the potential for solar energy was proposed by Angstrom (1924) and later added to by Prescott (1940). Equation 1 shows Angstrom's formula used for calculating the solar energy potential.

$$H = H_o\alpha + \beta nD \tag{1}$$

$H = daily\ global\ radiation\ (MJm^{-2}d^{-1})$
$H_o\alpha = daily\ extraterrestrial\ radiation\ (MJm^{-2}d^{-1})$
$n = daily\ sunshine\ duration\ (h)$
$D = astronomial\ daylength\ (h)$
$\alpha, \beta = empirical\ constants$

This old Angstrom-Prescott model was later improved and modified to be more precise, but it is still being used to calculate production over a longer time (Supit & Van Kappel, 1998; Zhou et al., 2021). This formula leads to a value in kilowatt hours per installed watt peak to calculate the solar energy potential in a specific area. Online available dataset Solargis (*Solar Irradiance Data*, n.d.) also makes use of this Angstrom-Prescott model (Mboumboue et al., 2016; Iradukunda & Chiteka, 2023) to calculate yearly solar energy production in different areas.

2.1.1.2 Wind energy production

To calculate the wind energy production, the Weibull distribution as shown in equation 2 is commonly used (Shoaib et al., 2017; Hulio et al., 2019; Genç et al., 2005). An online dataset that gives local wind potential - global wind atlas - also uses the Weibull distribution (*Global Wind Atlas*, n.d.).

$$f(x) = \frac{k}{\lambda} * \frac{x^{(k-1)}}{\lambda} * e^{-\left(\frac{x}{\lambda}\right)^k} \tag{2}$$

k = shape parameter
λ = scale parameter

The Weibull distribution is used in wind power to model the distribution of wind speeds at a given location. By analysing wind speed data and fitting it to the Weibull distribution, the shape and scale parameters can be estimated. The shape parameter determines the skewness of the wind speed distribution, indicating the energy level of the wind resource, while the scale parameter represents the average wind speed. This information helps in designing wind

turbines, estimating energy production, and evaluating the feasibility of wind power projects (Shoaib et al., 2017).
The Weibull distribution can then be used to calculate wind power. The wind speeds found in the Global Wind Atlas can be used in equation 3 (Blok & Nieuwlaar, 2020).

$$P = 0.5 * \rho * A * v^3 \tag{3}$$

$P = \text{Power (W)}$
$\rho = \text{air density } \left(\frac{kg}{m^3}\right)$
$A = \text{cross sectional area of the wind blades } (m^2)$
$v = wind\ speed\ \left(\frac{m}{s}\right)$

2.1.1.3 Battery bank
A battery bank can be used to balance out wind and solar intermittency (Runzhao et al., 2023; Al-Sharafi et al., 2017); Rezaei et al., 2020). Runzhao et al. (2023) suggest a 20-megawatt battery bank for 60 megawatts of electrolysis is sufficient. Therefore, per 3 megawatts of installed electrolysis capacity, 1 megawatt of battery capacity will be considered.

2.1.2 From renewables to hydrogen

Overall, the most common and commercially viable method of producing hydrogen from wind and solar power is through the electrolysis of water (Rezaei et al., 2020; Al-Sharafi et al., 2017; Nasser et al., 2020). However, research is ongoing to explore other methods of producing hydrogen and to improve the efficiency and cost-effectiveness of existing methods. But even though there are multiple ways to produce hydrogen, electrolysis is currently the most viable and will thus be considered for this research (Nasser et al., 2022). Electrolysis is a chemical process in which electricity is used to convert water into oxygen and hydrogen:

$$\text{Overall chemical reaction: } 2H_2O \rightarrow O_2 + 2H_2$$

A very important characteristic of electrolysis is the efficiency of the process (Rezaei et al., 2020; Al-Sharafi et al., 2017; Nasser et al., 2020). The efficiency determines how much of the energy that is produced can be converted to hydrogen, according to equation 4 (Blok & Nieuwlaar, 2020).

$$\eta_{electrolysis} = \frac{E_{H_2}}{E_{in}} \tag{4}$$

$\eta_{electrolysis} = the\ efficiency\ of\ the\ electrolysis\ (\%)$
$E_{H_2} = the\ amount\ of\ hydrogen\ that\ is\ delivered\ after\ the\ electrolysis\ (MWh)$
$E_{in} = the\ electricity\ that\ enters\ the\ electrolysis\ (MWh)$

The two forms of electrolysis that have already passed the research and development stage are Alkaline and proton exchange membrane (PEM) according to Kumar & Lim (2022). These methods are already being commercially used, even though there is still research going on to improve both methods. Also, an analysis of the hydrogen roadmaps of 25 countries showed that Alkaline and PEM are the most used forms of electrolysis worldwide (Wappler et al., 2022; IREA, 2020; Kuckshinrichs et al., 2017). The most important characteristics are shown in Table 1.

Table 1 Alkaline and PEM electrolysis

	Alkaline	PEM
Efficiency (%)	50 - 78	50 - 83
Development status	Mature	Commercialized
Lifetime (h)	60.000	50.000 - 80.000
Capital costs (for minimum 10 MW, €/kW)	500 - 1.000	700 - 1.400

The alkaline water hydrogen production technology has reached a mature development stage with low manufacturing costs (Kumar & Lim, 2022; Kuckshinrichs et al., 2017; Guo et al., 2019). It is currently capable of achieving a hydrogen production rate of 1000 m^3 per hour, making it suitable for large-scale hydrogenation stations. However, this technology does have drawbacks including slow start-up, corrosion, complex maintenance, and a high number of components.

On the other hand, PEM hydrogen production technology offers advantages such as fast start-up, no corrosion, simple maintenance, and fewer components. The most advanced PEM equipment available can currently produce hydrogen at a rate of 400 m^3 per hour. However, the main obstacle for the widespread adoption of PEM technology is its high manufacturing costs, which hinder its further development.

This research focuses on applicable technology that is ready to be applied on a large scale. Moreover, the affordability of the system is an important performance metric. Thus, this research will take Alkaline electrolysis as the method to convert renewable electricity into hydrogen. Alkaline electrolysis has an efficiency of 60 percent and a capital cost of 1.000 million euros per gigawatt (Chi & Yu, 2018; IREA, 2020; Kuckshinrichs et al., 2017). Over four hunderd Alkaline electrolysis installations had already been successfully installed in 2020 (Grigoriev et al., 2020). The chemical anode and cathode reactions for Alkaline electrolysis are (Kumar & Lim, 2022):

$$\text{Anode: } 4OH^- \rightarrow O_2 + 2\mathrm{H_2O} + 4e^-$$
$$\text{Cathode: } 4H^+ + 4e^- \rightarrow 2H_2$$

2.1.3 Hydrogen transport

Hydrogen can be transported using various methods depending on the specific needs and infrastructure available. The main ways to transport hydrogen (Faye et al., 2022; Reddi et al., 2016; Melaina et al., 2013; Brändle et al., 2021):

1. Pipeline Transport: Similar to natural gas, hydrogen can be transported via pipelines (Cheng & Cheng, 2023). This method is efficient, cost-effective, and already used for transporting hydrogen in some regions (Reddi et al., 2016). However, hydrogen pipeline transport requires a specific pipeline network as hydrogen can embrittle some metals, requiring specialized materials and technologies.
2. Liquid Hydrogen Transport: Hydrogen can also be cooled to very low temperatures (-253°C) to become a liquid and transported in cryogenic tanks (Melaina et al., 2013). Liquid hydrogen has a higher energy density than compressed gas, but it requires more energy to liquefy and keep at low temperatures. Liquid hydrogen transport is often used for space applications or supplying large-scale industrial customers (Brändle et al. 2021).

3. Chemical Carrier Transport (Niermann et al., 2021): Hydrogen can be chemically bound to other molecules and transported in a liquid or solid form, such as ammonia (NH3), methylcyclohexane (MCH), or liquid organic hydrogen carriers (LOHCs). These molecules can be produced using renewable electricity, and the hydrogen can be released upon demand by a chemical reaction or a catalyst. Chemical carrier transport is still in the early stages of development but offers potential for long-distance hydrogen transport without the need for a dedicated pipeline network (Niermann et al., 2019). Since this technology is still in the early stages of development, it will not be considered applicable for 2030 in this research

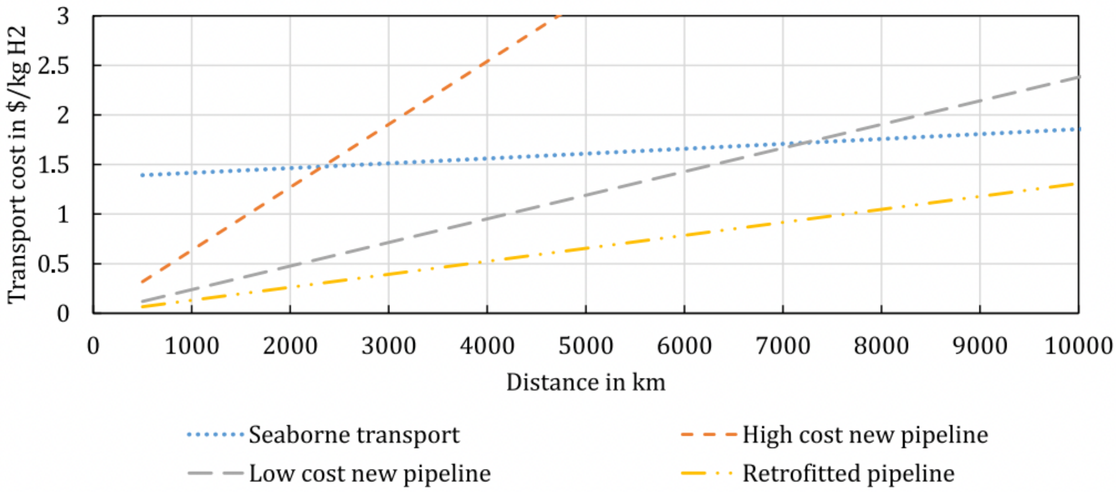

Figure 4 the costs of four means of hydrogen transport (Brändle et al., 2021)

That leaves pipeline transport and liquified hydrogen transport as the two categories considered in this research. Brändle et al. (2021) identify the same two options, but splits the pipelines into new low-cost, new high-cost and retrofit pipelines to deal with the uncertainty of new pipeline costs (Figure 4). Furthermore, since pipeline transport has been in use for a long time no significant cost reductions are expected (Brändle et al., 2021). For overland transport, Di Lullo et al. (2022) state that pipeline transport has the most potential regarding greenhouse gas emissions and cost, out of 32 assessed hydrogen transport technologies. Therefore, onshore only pipeline transport is considered in this research. Offshore pipelines are 25 percent more costly than onshore pipelines (Van Gerwen et al., 2019), but also shipping will be considered as an option.

2.1.4 Hydrogen storage

One of the main advantages of hydrogen is that it can be seasonally stored. There are several ways to store hydrogen on a large scale that are available right now, which are all forms of underground hydrogen storage in natural resources (Van Gessel & Hajibeygi, 2023). Important is that hydrogen storage in liquid form or chemical form is also possible. However, due to their high costs they cannot compete with underground hydrogen storage. Underground hydrogen storage can be done in salt caverns, depleted oil and gas reservoirs, aquifers and hard rock caverns (Van Gessel & Hajibeygi, 2023; Thiyagarajan et al. 2022).

Out of those options Linssen et al. (2020) identified salt caverns as the most accessible form of underground hydrogen storage, which is supported by Van Gessel & Hajibeygi (2023). Figure 5 shows that there are four main areas on the Iberian Peninsula where underground hydrogen storage in salt caverns could take place. In Portugal the area around Óbidos is most suitable, whereas in Spain the Barcelona, Valencia and Bilbao area have the most potential.

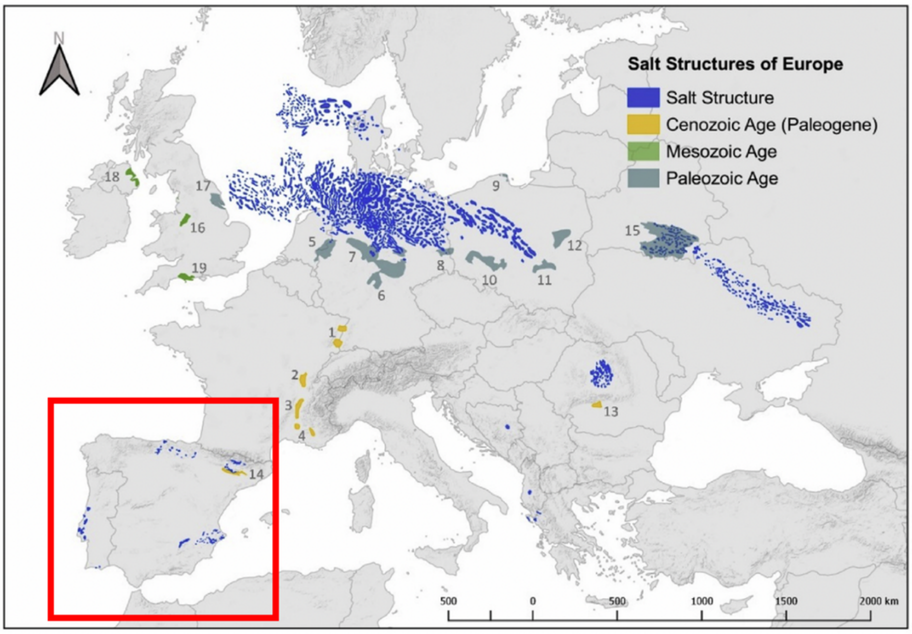

Figure 5 salt structures of Europe (Linssen et al., 2020)

2.1.5 Hydrogen demand

Ultimately, the potential hydrogen demand determines the size of the hydrogen system. However, it is uncertain which processes could potentially be converted to hydrogen. Heavy industry is seen as more likely to be using hydrogen than for example transport by car (De Tommasi & Lyons, 2022; Karakaya et al., 2018), even though transport in general is also seen as an attractive sector for hydrogen by others (Acar & Dincer, 2020; Andrews & Shabani, 2012; Guillén-Gosálbez et al., 2009). Next to (heavy) industry and transportation, there are also prospects for hydrogen use in power generation and heating (Brandon & Kurban, 2017; Elmer et al., 2015; Dodds et al., 2015; Jones et al., 2018). Since energy use is generally divided over industry, transportation, domestic and commercial, hydrogen theoretically has the potential to provide for each of these sectors (Ren et al., 2020). All in all, the industry sector is most likely to be using hydrogen in the short term, but potentially all sectors could switch to hydrogen.

2.2 Energy security

The situation with Russia as the main energy supplier for the European Union has shown in 2022 that this has led to a politically complicated situation (Milov, 2023; Cifuentes-Faura, 2022). In 2022 Russia started a war with Ukraine and European countries still depended on Russian natural gas. For example, Germany wanted to boycott Russia but could not function without Russian gas (Bunde, 2022). Besides, the Russia-Ukraine War had a big impact on energy prices in Europe (Chen et al., 2023; Borowski, 2022). Germany's energy security was dependent on Russian gas. Therefore, energy security is an important, political performance indicator for the green hydrogen system. Energy security refers to a country's ability to meet its energy needs using domestic sources, without relying on imports from other countries (Asia Pacific Energy Research Centre, 2007) This means that a country can produce enough energy from its resources to meet its energy demand without having to rely on foreign suppliers.

2.2.1 Means to support energy security

To increase independent energy security, there are three measures a country can take without scaling down **energy use** (Gasser, 2020; Halser & Paraschiv, 2022):

1. Increase their domestic alternative energy **production**.
2. Increase the volume of seasonal **energy storage**.
3. Increase possibilities for hydrogen **transport** from alternative energy suppliers.

Since this thesis focuses on a scenario in which an alternative for domestic energy production is proposed, the first measure will not be considered. Therefore, Portugal and Spain can either increase their energy storage or increase the possibilities for the transport of alternative hydrogen suppliers. However, when hydrogen is transported by pipeline there is no possibility to switch suppliers without building new infrastructure. When shipping is chosen for hydrogen transport on the other hand, suppliers can be switched without extra infrastructure investment, since the infrastructure is open to any supplier that can supply hydrogen by ship.

2.2.2 Net import dependency (NID)

Besides, for this thesis only the impact on the energy security of this hydrogen system will be considered. The impact on the energy security of Portugal and Spain regarding this hydrogen system will be defined as the percentage of energy that the country needs from this hydrogen system for one year. Kolosok & Kovalenko (2022) introduced the term *net import dependency* to measure the dependency of a country on imports. The net import dependency of a country is the share of energy that it imports from foreign countries compared to a country's energy use.

2.2.3 Net import dependency and energy security

This thesis is interested in the impact of the described MIGHS on energy security. Therefore, this thesis introduces the term *hydrogen import dependency*. This term uses the concept of the net import dependency from Kolosok & Kovalenko (2022) but adds to it by incorporating the two methods of increasing energy security found in §2.2.1. The hydrogen import dependency (HID) is the percentage of hydrogen import that a country cannot replace by their installed storage capacity or their possibility to switch to another supplier (equation 5). The HID should be calculated for each individual hydrogen supplier, meaning there will be a HID from Morocco and one from Algeria.

$$HID_s = \frac{H2_{imported} - H2_{storage} - H2_{switchable}}{E_{use}} * 100\% \tag{5}$$

$HID_s = Hydrogen\ import\ dependency\ from\ supplier\ s\ (\%)$

$H2_{imported} = Net\ imported\ hydrogen\ \left(\frac{TWh}{year}\right)$

$H2_{storage} = Hydrogen\ storage\ capacity\ \left(\frac{TWh}{year}\right)$

$H2_{switchable} = Possibility\ to\ switch\ supplier\ (\frac{TWh}{year})$

$E_{use} = Total\ energy\ use\ (\frac{TWh}{year})$

To minimize the hydrogen import dependency, the minimax method can be used. This method from game theory chooses the most favorable option by minimizing the losses in the worst-case scenario (Fan, 1953). Applied to this research that would mean the minimal hydrogen import dependency on one country. In this case, the minimax method points out that the energy production should be divided 50/50 between Morocco and Algeria since any other ratio would include a percentage over 50 percent and thus a higher hydrogen import dependency.

2.3 System levelized cost of hydrogen

The concept of the levelized cost of hydrogen (LCOH) is similar to the concept of the more widely known levelized cost of energy (LCOE) (Farhat & Reichelstein, 2016). The LCOE is the costs over the lifetime of the energy production per unit of energy produced (Blok & Nieuwlaar, 2020). The LCOH is defined as the costs over the lifetime of hydrogen production per unit of hydrogen produced (Viktorsson et al., 2017). To calculate the LCOH the capital expenditure (CAPEX), operational expenditure (OPEX) and lifetime of the hydrogen production are used (Vartiainen et al., 2021; Berrada & Laasmi, 2021). The CAPEX is the investment costs (€) that are made in energy production and electrolysis, whereas the OPEX are the yearly costs (€/year) to operate those systems. The lifetime (years) is the number of years that the energy production and electrolysis are operational. The LCOH is then calculated according to equation 6.

$$LCOH = \frac{\frac{C_{investment}}{l} + C_{operational}}{H_2} \tag{6}$$

$LCOH = Levelized\ cost\ of\ hydrogen\ \left(\frac{€}{MWh}\right)$
$C_{investment} = Capital\ expenditure\ (CAPEX)\ (€)$
$C_{operational} = Operational\ expenditure\ (OPEX)\left(\frac{€}{year}\right)$
$l = lifetime\ (years)$
$H_2 = Produced\ hydrogen\ \left(\frac{MWh}{year}\right)$

However, neither the LCOE nor the LCOH consider the costs for storage and transport. Therefore, this thesis uses the term *system levelized cost of hydrogen (SLCOH)*. The SLCOH works the same as the LCOH but adds to it by incorporating the costs of hydrogen transport and hydrogen storage.. The SLCOH is calculated by equation 7.

$$SLCOH = \sum_{s \in S} \frac{\frac{C_{investment}}{l} + C_{operational}}{H_2} \tag{7}$$

$SLCOH = System\ levelized\ cost\ of\ hydrogen\ \left(\frac{€}{MWh}\right)$
$s = Step\ in\ the\ hydrogen\ supply\ chain$
$S \in \{Renewable\ energy\ production, electrolysis, transport, storage\}$

The parts of the hydrogen supply chain that both LCOH and SLCOH cover can be seen in Figure 6.

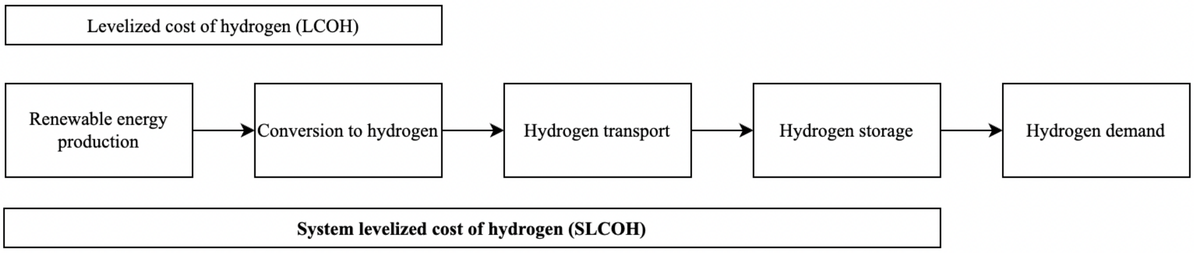

Figure 6 the difference between LCOH and SLCOH

2.4 Linear cost model to calculate minimum flow cost

The costs for production, electrolysis and storage all depend on the capacity of each process that will be installed. However, the costs for the hydrogen transport system are dependent on both the capacity and distances that the hydrogen network covers (§2.1.3). To calculate these costs under different situations, a linear economic cost model will be used. To calculate the cost of hydrogen transport, the *minimum flow cost* should be calculated (Könen et al., 2022; Thulasiraman et al., 2016). The minimum flow cost is the lowest cost of a network while fulfilling the performance metrics. The minimum flow cost is calculated according to equation 8.

$$Minimise \sum_{(i,j)} c_{ij} f_{ij} \tag{8}$$

$c_{ij} = transport\ cost\ from\ node\ i\ to\ node\ j\ \left(\frac{€}{MWh}\right)$

$f_{ij} = hydrogen\ flow\ from\ node\ i\ to\ node\ j\ \left(\frac{MWh}{year}\right)$

2.4.1 Network Simplex Method optimization

A widely used algorithm to calculate the minimum flow cost is the *network simplex method (NSM)* (Cunningham, 1976; Kovács, 2014: Thulasiraman et al., 2016). The Network Simplex Method has been used in different studies for similar calculations. For example, De Wolf & Smeers (2000) used it to calculate the transport costs for a natural gas network. Abdollahi et al. (2016) and (Barras et al., 1987) used the algorithm to calculate the minimum cost flow of an electricity transmission network.

The NSM can be applied to networks according to the graph theory. In graph theory networks are schematically represented as a network of *nodes* and *edges* (Heijnen et al., 2019). In figure 7 the nodes are the circles numbered one to four, symbolizing network connection points that can either be a *source* (in this case hydrogen producer) or a *sink* (in this case a hydrogen user). Nodes are connected by edges, which in this thesis are the hydrogen transport routes. Edges are the lines connecting the nodes (figure 7). The *flow* is the amount of hydrogen that is transported from the source to the sink. Edges have a weight, which in this research is the cost (dependent on distance and capacity). The NSM algorithm calculates the flow through each edge, minimising costs. The output of the NSM is the costs.

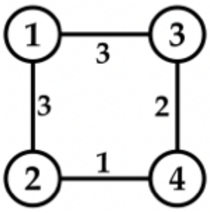

Figure 7 Display of nodes (circles) and edges (lines) according to graph theory (Heijnen et al., 2019).

2.4.2 Degrees of freedom

The degrees of freedom of a model represent the number of independent variables or parameters that can be varied. The model will vary the topology of the hydrogen system, determine the hydrogen production areas and the capacity of hydrogen that flows through each pipeline.

2.5 XLRM modelling framework

The main research question is based on the XLRM framework proposed by Lempert et al. (2003). The XLRM abbreviation describes the four aspects of a policy model that are shown in figure X: e**X**ternal factors, policy **L**evers, **R**elationships in the system and performance **M**etrics (Nikolic et al., 2019).

Policy Levers represent the actions within control of the policy making party and the various alternative decisions they can make. They encompass the range of policy options available to them. *System Relations* refers to the system model that explicitly defines the relationships between elements within the system, confined by the system boundary. *External Factors* encompass all the influences on the system that lie outside of control. They include events, circumstances, and developments that can, could, or will occur. *Performance Metrics* are the key outcomes of interest. They allow to gauge the impact of actions, determining what will be measured and how it is measured.

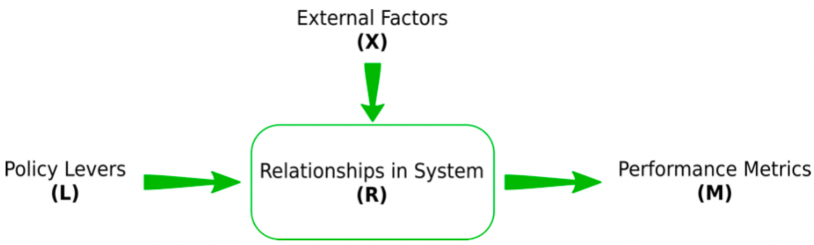

Figure 8 the XLRM framework (Lempert et al., 2003)

2.6 Framework for assessing energy system performance

A common way of assessing energy systems is the framework of the four A's: affordability, applicability, acceptability and availability (Kruyt et al., 2009; Ainou et al., 2022; Tongsopit et al., 2016; Vera & Langlois, 2007).

Acceptability refers to the social acceptability of the energy system. That means that the energy should be environmentally friendly and safe. *Applicability* embodies the technological readiness of the energy system; the technology used in the design should be ready-to-use. *Availability* is the term that represents energy security. Energy should be available for everyone and at every time. *Affordability*, finally, refers to the costs of energy that the energy system delivers.

This research explores which **applicable** technological options can form an **acceptable** energy system and which effects this has on the **availability** and **affordability** of energy.

3 Methodology

This research aims to compare the effects that different design options of the Maghreb-Iberian Hydrogen System (MIGHS) have on energy cost and energy security. To estimate these effects, a linear cost model will be used. Different design options will be tested to see the differences in costs and energy security.
Chapter two provided an overview of accessible technologies that are ready to be used by 2030, this chapter continues by selecting the technologies that would fit the geographical area and by providing the characteristics of those technologies and areas.

3.1 Maghreb-Iberian hydrogen supply chain

This paragraph explains how the local characteristics of Morocco, Algeria, Portugal and Spain influence the technological possibilities for 2030. The different technological options will be input for the model and will be tested to be compared to each other.

The goal of the MIGHS is to supply Portugal and Spain with green hydrogen. Therefore, its size is determined by the hydrogen demand in those countries.

The amount of renewable energy that is needed to create enough hydrogen to supply the demand, is calculated using the efficiency of electrolysis. Even though there are some efficiency losses during hydrogen transport as well, those losses are insignificant on a large scale and will therefore not be considered in this research (Müller & Arlt, 2013; Melaina et al., 2013; Brändle et al., 2021).

The paragraph elaborates also on the possibilities regarding hydrogen storage and transport and is concluded by setting metrics that will determine the performance of the hydrogen system under different designs.

3.1.1 Iberian hydrogen demand

The hydrogen demand will be the energy demand for Portugal and Spain together. The energy demand in Algeria and Morocco itself will not be considered. The predicted energy demand in Portugal and Spain will be divided in types of energy use to determine different scenarios for hydrogen use. For example, heavy industry is seen as more likely to be using hydrogen than transport by car (De Tommasi & Lyons, 2022). The energy use, energy use by the industry and the domestic energy production are shown in Table 2 as depicted by the online database on energy statistics Enerdata.net (2021).

*Table 2 energy statistics from enerdata.net *scenario 1, ** scenario 2*

	Portugal		Spain		Total	
	TWh/year	%	TWh/year	%	TWh/year	%
Energy consumption	49	100	235	100	284	100
Industry energy use	16	33	63	27	79*	28
Domestic energy production	15	31	71	3	86	30
Energy import	34	69	164	70	198**	70

In this research the potential hydrogen demand will be different per scenario. In one scenario only the industry will be supplied with this hydrogen system (79 TWh/year) since the industry is most likely to be using hydrogen in the short term. The second scenario will replace the full energy import with hydrogen (198 TWh/year). Therefore, the size of the system is 80 TWh/year in the first design option and taken as 200 TWh/year in the second design option. Determining the size of the system is a policy lever and will impact the performance metrics.

3.1.2 Alkaline electrolysis

Alkaline electrolysis has an efficiency of 60 percent (Chi & Yu, 2018; IREA, 2020; Kuckshinrichs et al., 2017) and a capital cost of €1.000/kW. Rewriting the electrolysis-efficiency formula from 2.1.2 the amount of energy input that is needed to fulfill the demand in the two scenarios where the demand is 80 TWh/year and 200 TWh/year (equation 9).

$$E_{in} = \frac{E_{H_2}}{\eta_{electrolysis}} \tag{9}$$

This leads to a necessary energy production of 134 TWh/year and 334 TWh/year in scenario one and two respectively. The characteristics of Alkaline electrolysis and the battery pack to balance out wind and solar intermittency can be found in Table 3.

Table 3 Alkaline and battery costs

	Alkaline	Battery	unit
CAPEX	1,0	2,3	bln€/GW
lifetime	7	10	years
Opex	2,5	1,0	%CAPEX/year

3.1.3 Wind and solar in Morocco and Algeria

The energy used for the electrolysis comes from wind and solar power in Morocco and Algeria. A ratio of 55 percent wind and 45 percent solar energy is assumed to be optimal to balance out the intermittency of the renewable energy sources (§2.1.1). Therefore, areas need to be found with both high wind and solar power potential. Using data from the online database Solargis (n.d.) that uses Angstrom's method to calculate solar power potential and Global Wind Atlas (n.d.) that uses the Weibull distribution to calculate wind power potential, Figure 9 shows the areas with the most potential for hydrogen production in Morocco.

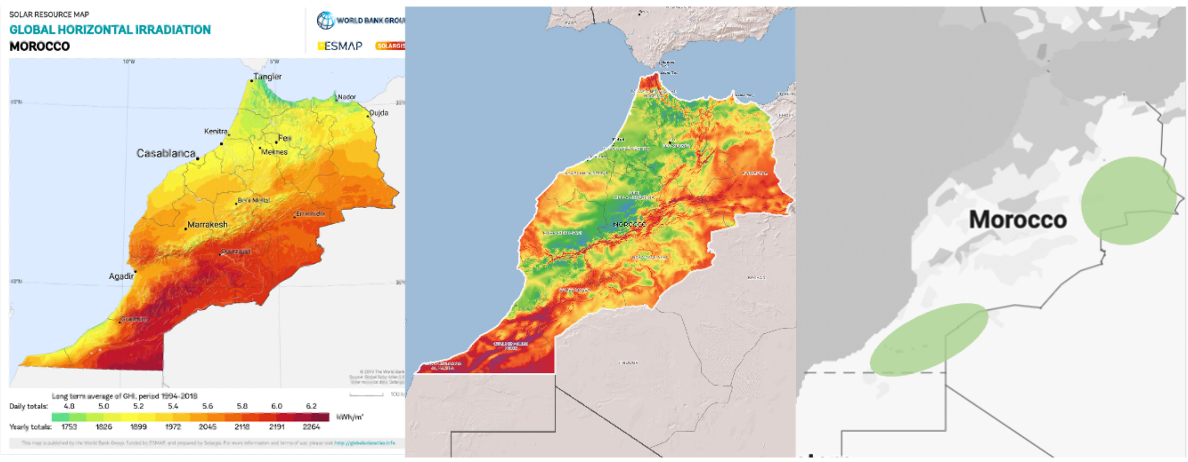

Figure 9 solar (left) and wind (middle) potential and areas with a combined high wind and solar potential (right) in Morocco

Figure 10 shows that Southern- and North-Eastern Morocco have the most potential. For Algeria, the Centre and South-Eastern region have the most potential with regards to wind and solar power (figure Y).

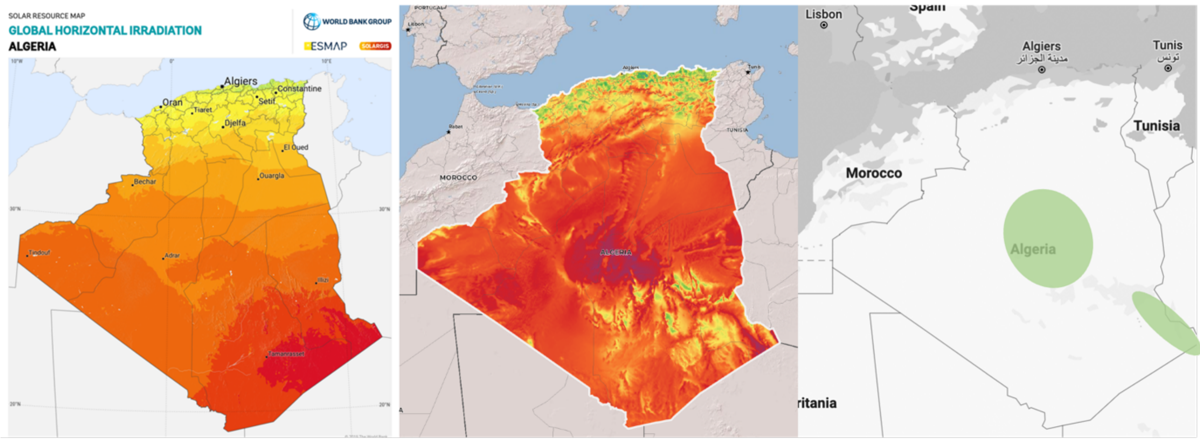

Figure 10 solar (left) and wind (middle) potential and areas with a combined high wind and solar potential (right) in Algeria

Two different scenarios determine the amount of hydrogen production: 80 TWh/year and 200 TWh/year. The renewable energy production needed to supply that demand including electrolysis efficiency losses is 134 TWh/year and 334 TWh/year respectively (§3.1.2). To minimize the hydrogen import dependency on a single country, production is split equally between Morocco and Algeria (§2.2.3), meaning both countries should produce 67 TWh/year and 167 TWh/year each in both scenarios. Each production location will have 55 percent wind power and 45 percent solar power (Table 4).

Table 4 Required power per location calculated from the demand and the ratio as indicated in §2.1.1

	D1	D2	Unit
Power needed per location	67	167	TWh/year
Wind (55%)	37	92	TWh/year
Solar (45%)	30	75	TWh/year

The areas with the highest combined wind and solar power potential are shown in figure 11.

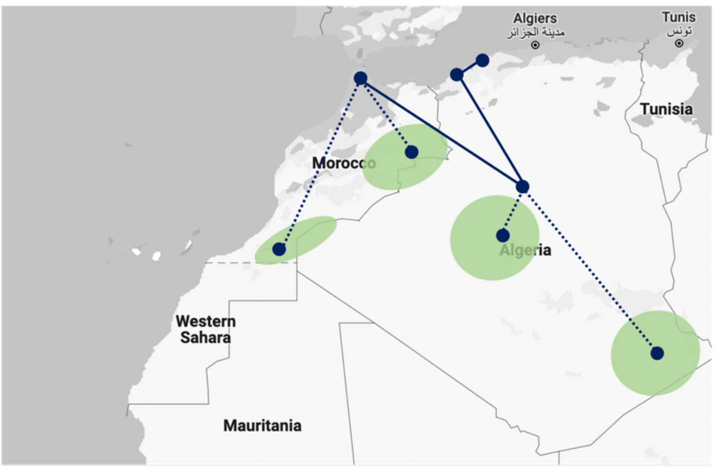

Figure 11 Areas with the highest combined wind and solar power potential

The mean power density for both energy sources in all four areas is converted to the needed installed power in Table 5. Even though the Southernmost areas seem to be the most interesting regarding required installed power, it does not consider the transport costs that will be higher, since those locations are further from the Iberian Peninsula.

Table 5 Required installed power capacity per energy source and location to match demand (own calculations)

Installed capacity	Capacity	Morocco		Algeria		Unit
	TWh/year	Bouarfa	Zag	El Menia	Djanet	
Installed solar power	30	15,5	14,7	14,4	12,9	GW
Installed wind power	37	13,2	9,6	14	11,7	GW
Installed solar power	75	38,8	36,7	36	32,3	GW
Installed wind power	92	32,8	23,9	34,7	29,1	GW

Research on wind and solar farms showed that solar farms cost 0,64 million euros per installed megawatt and wind farms cost 1,33 million euros per installed megawatt (Al-Dousari et al., 2019; Sens et al., 2022; Kaltschmitt et al., 2013; Kaltschmitt et al., 2020). The costs for wind and solar farms can be found in Table 6.

Table 6 Costs for wind and solar farms(Al-Dousari et al., 2019; Sens et al., 2022; Kaltschmitt et al., 2020).

	Solar farm	Unit	Wind farm	Unit
Lifetime	30	Years	20	Years
CAPEX	0,64	bln €/GW	1,33	bln €/GW
OPEX	1,3	%CAPEX/year	1,1	%CAPEX/year

With these figures, the investment costs (CAPEX) for the solar and wind plants can be calculated. Since also the lifetime and OPEX of both ways of energy production are shown in table 7, the contribution of the power production to the SLCOH can be calculated.

Table 7 CAPEX of power installations in billion euros calculated from capacity with the costs of Table 6.

Capex	Capacity	Morocco		Algeria		Unit
	TWh/year	Bouarfa	Zag	El Menia	Djanet	
Installed solar power	30	9,9	9,4	9,2	8,3	bln€
Installed wind power	37	17,6	12,8	18,6	15,6	bln€
Total	67	27,5	22,2	27,8	23,8	bln€
Installed solar power	75	24,8	23,5	23,0	20,7	bln€
Installed wind power	92	43,6	31,8	46,2	38,7	bln€
Total	167	68,5	55,3	69,2	59,4	bln€

As could be expected, the areas in the South – Zag in Morocco and Djanet in Algeria - with higher wind speeds and solar power density, are the cheapest in terms of investment; per invested euro more power can be generated. However, no conclusion can be made yet on which location would be economically most attractive. To determine this, the transport costs need to be included.

3.1.4 Hydrogen transport from Africa to Europe

The hydrogen needs to be transported from both Morocco and Algeria to the Iberian Peninsula. This paragraph first discusses which technically possible options are included in this research and their advantages. Subsequently, the routes of the transport system are explained.

3.1.4.1 Characteristics of hydrogen transport methods

There currently are multiple energy connections between Europe and North African nations (Figure 12). Presently, Europe relies on North Africa for 13 percent of its gas consumption and 10 percent of its oil consumption. Furthermore, Europe is the recipient of over 60 percent of North Africa's oil and gas exports, as reported by Eurostatgas (2019). In other words, importing energy from Africa is nothing new for Europe.

Converting the existing pipelines to transport hydrogen would be more cost-efficient than building new pipelines or transporting the hydrogen by ship (Melaina et al., 2013; Van Wijk & Wouters, 2021). However, using these pipelines would imply that they can no longer be used for the transport of natural gas at the same time. Also, using pipelines limits the possibility of switching energy suppliers, which results in a higher dependency from the consuming countries on this system.

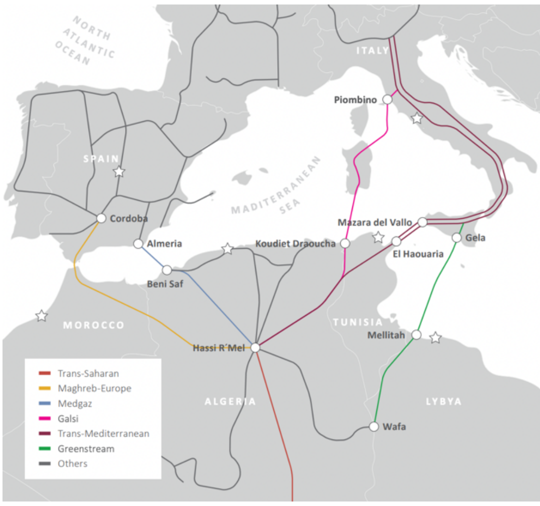

Figure 12 natural gas pipelines between Africa and Europe

This research considers only the current energy routes between Morocco, Algeria, Portugal and Spain for pipelines. These routes are assumed to be technically and politically feasible, since there is already energy transport taking place on those routes. However, three means of overseas transport will be considered, listed in Table 8 from most economically efficient to least (with two different cost-scenarios for the new pipelines). An important note is that some research sees natural gas as a *bridge fuel* that can help keep the energy prices low during the energy transition (Safari et al., 2019). Because it has relatively low greenhouse gas emissions and has a relatively low price. Therefore, it is seen as preferable over other fossil fuels, even though it is not a sustainable energy source.

Table 8 (dis)advantages of hydrogen shipping methods

Scenario	Advantages	Disadvantages
T1 Converting existing pipelines	Most economically efficient	Limited possibilities to switch supplier The current natural gas supply will no longer be possible
T2 Low-cost new pipelines T3 High-cost new pipelines	Natural gas can still be transported	More expensive than the first option Limited possibilities to switch supplier
T4, T5 Hydrogen shipping	Open to switching suppliers worldwide	High investment costs More expensive for relatively short distances

The costs of the four transportation methods (in which the high-cost and low-cost new pipelines are considered as different options) can be found in Table 9 (Brändle et al., 2021). These costs will later be used to calculate the SLCOH.

Table 9 costs of hydrogen transport

		High cost	Low cost	Retrofit
Pipeline	Lifetime (years)	40	40	40
	CAPEX (€/tpa/km)	3,56	1,33	0,73
	OPEX (%CAPEX/year)	5	5	5
	Cost (€/1000km/kgH2)	0,64	0,24	0,13
Ship	Lifetime (years)	30		
	CAPEX (€/tpa)	33.709		
	OPEX (%CAPEX/year)	4		
Export terminal	CAPEX (€/tpa)	672		
	OPEX (%CAPEX/year)	4		
Import terminal	CAPEX (€/tpa)	4.939		
	OPEX (%CAPEX/year)	4		
Liquefaction	CAPEX (€/tpa)	5.385		
	OPEX (%CAPEX/year)	4		

3.1.4.2 Hydrogen routes

Routes over land will follow the same infrastructure as shown in Figure 12. These routes are already being used, implying that the physical and political circumstances allow pipeline transport.

For the overseas routes, current routes will be considered in this research. That is, the pipeline between Beni Saf (Algeria) and Almeria (Spain) and the pipeline between Tangier (Morocco) and Tarifa (Spain). These pipelines can be either converted to hydrogen use, or new pipelines could be built next to them to ensure the natural gas supply.

For seaborn transport to the Iberian Peninsula, Sines (Portugal) and Barcelona (Spain) already have a Liquified Natural Gas terminal (Yafimava, 2020). In this research, those ports will also be considered for hydrogen shipping since the existing LNG infrastructure can be used.

The Tangier Med Port (Morocco) is already designed to transport LNG (Tanchum, 2020), making it the best location in Morocco for hydrogen shipping to Sines, Portugal. The other route would be between Arzew (Algeria) and Barcelona (Spain), for Arzew has all the LNG terminals of Algeria (Kacimi et al., 2021). The potential overseas routing options can be seen in Figure 13.

Figure 13 offshore hydrogen transport routes

3.1.5 Hydrogen storage in salt caverns

The most economical way of hydrogen storage is in salt caverns (§2.1.4). Linssen et al. (2020) and Carneiro et al. (2019) show that Spain has a total cavern storage capacity of a little over 1.000 TWh and Portugal has a total cavern storage capacity of even 5.000 TWh – half of which offshore (Figure 14). Reminding from chapter §3.1.1 that the yearly energy use of Portugal and Spain combined is 284 TWh/year, there is sufficient capacity for hydrogen storage to supply the Peninsula for over 20 years. The costs of hydrogen storage in salt caverns are €1,61 per kilogram, which translates to roughly €54.000.000 per gigawatt hour (Linssen et al., 2020).

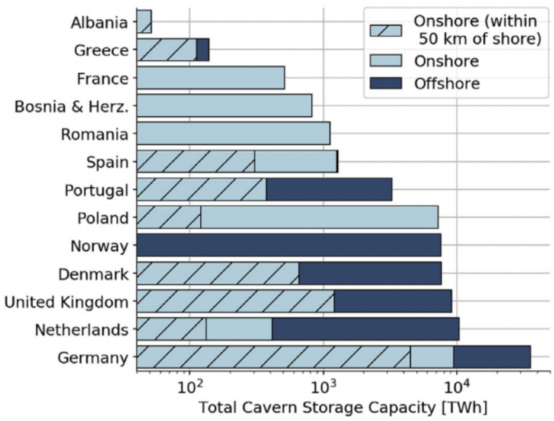

Figure 14 underground salt cavern storage capacity Carneiro et al. (2019)

3.1.6 Measures for energy security

The first measure that will be taken to support energy security is to split the energy production equally over Morocco and Algeria following the minimax method to minimize the consequences when problems occur with one of the hydrogen suppliers.

The other measures that were identified in §2.2.1 are an increase in hydrogen storage or the possibility to switch hydrogen suppliers. When pipelines are used for hydrogen transport, the supplier cannot be switched. The investments made are literally connected to the mentioned suppliers. However, hydrogen storage could be increased. This will add to the cost. When the choice is made to invest in shipping, the possibility to switch hydrogen supplier is fully open. Hydrogen can be imported from anywhere in the world. But investment costs of hydrogen shipping are higher. Even though shipping brings other risks like the unavailability of other suppliers or natural disasters, these risks are not considered in this research.

The experiments in the model should show the differences in costs and energy security under the different design options.

3.1.7 System performance metrics

An energy system should be acceptable, applicable, available and affordable. By opting for green hydrogen only, the energy system is assumed to be sustainable. Choosing only technologies that are ready to be used and applicable in the area, the system is also assumed to be applicable. Furthermore, applicable technologies are assumed to be safe.

However, regarding availability and affordability no conclusions can be drawn yet. The model should show what effects the different design options have on energy security (availability) and the system levelized cost of hydrogen (affordability). To estimate concrete benchmarks for both metrics, reference cases with similar situations are used.

3.1.7.1 Energy security performance metrics

The metric regarding energy security, as defined in §2.2.3, will be split into three categories. As a reference, the energy dependency from Germany on Russia will be taken, because that has recently shown the complications of the impact of breached energy security in Europe (Milov, 2023; Cifuentes-Faura, 2022; Bunde, 2022). Since Germany has always been a large consumer of Russian energy, their dependency on a single energy supplier will be taken as the reference point for a situation in which Spain and Portugal would be as dependent on African hydrogen as Germany was on Russian fossil fuels. Until the year of 2020 Germany imported 30 percent of their energy from Russia (Centre for Economic Policy Research, 2022). They had no option to replace this energy demand, causing them to be unable to cut off the Russian energy supply as a political measure against the war. Therefore, 20-30 percent hydrogen import dependence (HID) will be seen as an undesirable value. Little to no HID would be ideal, being 0-10 percent, leaving 10-20 percent HID to be as the acceptable range.

3.1.7.2 System levelized cost of hydrogen performance metrics

The metrics regarding the system levelized cost of hydrogen, as defined in 2.3, will be set in line with current energy costs. The current electricity price in Portugal and Spain (without taxes and charges) are respectively €0,11/kWh and €0,12/kWh (*Electricity Price in Portugal and Europe*, n.d.). Including taxes and charges they go up to €0,22/kWh for Spain and €0,21/kWh for Portugal. Preferably the SLCOH of this system will stay below the energy prices before taxes, because then it is comparable to the current energy costs.

But since the system delivers sustainable energy, subsidies could be applied. In Spain and Portugal, the government uses feed-in tariffs or feed-in premiums to support renewable

energy (Marques et al., 2019; Klessmann et al., 2011). Since those are already in use in the studied area, those subsidies will be further discussed.
Feed-in tariffs reward renewable energy producers with a fixed payment per delivered unit of energy (Figure 15). They have proven to be effective and provide a very low risk to the renewable energy producer according to a report from the European Commission (EC) (Manjola et al., 2017).

Feed-in premiums awarded renewable energy producers with a fixed extra amount of money per unit of energy delivered on top of the market price. This way of stimulating renewable energy lowers the risk for the producer on the one hand by guaranteeing a minimum price (the premium). On the other hand, it also lowers the risk for the government against *windfall* (Manjola et al., 2017). Windfall is when the feed-in tariff is set so high compared to the actual market price that the renewable energy producers make an unreasonable profit from the subsidy.

Data from the EC report (Manjola et al., 2017) shows that Portugal uses a feed-in tariff for most renewable energy technologies. The range in average support for those technologies goes from roughly €50 per megawatt hour for wind and hydropower all the way up to €270 per megawatt hour for solar PV according to that same report. Therefore, the benchmarks for the SLCOH will be divided into three categories: (1) competitive with electricity, (2) competitive with subsidized wind power and (3) competitive with subsidized solar power.

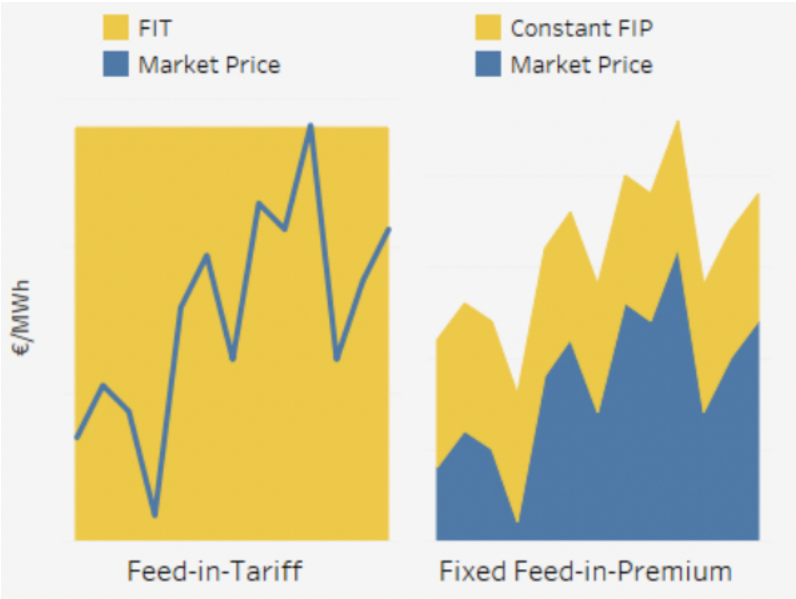

Figure 15 feed-in tariffs and feed-in-premiums (Manjola et al., 2017)

3.1.7.3 Performance metrics and benchmarks
The performance metrics regarding the hydrogen energy dependence (HID) and the system levelized cost of hydrogen (SLCOH) can be found in Table 10.

Table 10 performance metrics

`	Valuation	Benchmark	Unit
SID	Desired HID	0	%
	Acceptable HID	10	%
	Undesired HID	>30	%
sLCOH	Market value competitive sLCOH	110	€/MWh
	Subsidised wind competitive sLCOH	160	€/MWh

Subsidised solar competitive sLCOH	380	€/MWh

3.1.7 Geopolitical situation in the Maghreb-Iberian area

An important advantage of this research is that it includes fewer political barriers than were identified in literature. There are three important geopolitical situations that impact the selected area. Firstly, the integrated Iberian energy market, secondly the current relationship between Morocco and Algeria and thirdly the situation with Morocco and the Western Sahara.

3.1.7.1 Integrated Iberian energy market

The Integrated Iberian Energy Market (MIBEL, 2023) stands as a remarkable milestone in the energy landscape, uniting the electricity markets of Spain and Portugal into a seamless, cross-border entity. This collaborative initiative aims to foster efficient energy exchange, optimize resource allocation, and enhance the overall reliability of the Iberian Peninsula's energy supply. MIBEL enables the free flow of electricity between these neighboring countries, promoting competition and price convergence, while also facilitating the integration of renewable energy sources. By eliminating previous barriers and streamlining regulatory frameworks, MIBEL creates a dynamic marketplace that not only enhances energy security but also encourages sustainable development in the region. This integration should also be followed in the proposed MIGHS.

3.1.7.2 Political situation between Morocco and Algeria

The political relationship between Morocco and Algeria has been marked by historical complexities and regional dynamics (Lefèvre, 2016; Miller, 2013; McDougall, 2017). While sharing a geographic proximity and historical ties, the two countries have experienced periods of strained diplomatic relations and unresolved conflicts. Disputes over issues such as territory, historical claims, and competing interests have contributed to an enduring state of tension. The Western Sahara conflict, in particular, has been a longstanding point of contention, with both nations holding differing positions on the issue. These political challenges have at times hindered cooperation and hindered efforts towards regional integration. Despite these challenges, there have been sporadic attempts at dialogue and cooperation, reflecting the shared interests and potential for collaboration in areas such as energy, security, and economic development. The political situation between Morocco and Algeria remains intricate and multifaceted, influenced by both domestic considerations and broader regional dynamics. For this reason, it is important that both hydrogen supplying countries are able to operate independently from each other. Additionally, the difficult situation between Morocco and Algeria makes it less likely that the countries would cooperate and stop hydrogen supply at the same time.

3.1.7.3 Political situation between Morocco and the Western Sahara

The political situation between Morocco and the Western Sahara is characterized by decades of complexity and unresolved disputes (Lefèvre, 2016; Miller, 2013; McDougall, 2017). The region's status has been a focal point of contention, with Morocco asserting sovereignty over the territory, while the indigenous Sahrawi population seeks self-determination through the establishment of an independent state. This issue has led to conflict and tension, including armed clashes and diplomatic standoffs. International efforts, including those by the United Nations, have aimed at finding a peaceful and mutually agreeable resolution to the Western Sahara question. However, differing interpretations of historical and legal factors, as well as competing interests, have impeded a comprehensive settlement. The political landscape is further complicated by the presence of multiple actors and the region's strategic importance. The Western Sahara remains a sensitive and intricate matter, reflecting the broader complexities of self-determination, territorial integrity, and regional stability. Therefore, the Western Sahara region is not included in this research.

3.2 Model implementation details

The theoretical framework showed that a few aspects of the system design are open to experiment with. This research will experiment with the different system capacities, means of hydrogen transport and levels of energy security, which can be seen as policy levers. The different possible combinations of levels for the policy levers are shown in Table 11.

Table 11 policy levers and scenarios

System capacity	D1: 80 TWh			D2: 200 TWh		
Level of security	LoS1	LoS2	LoS3	LoS1	LoS2	LoS3
T1: Existing pipelines	S1	S2	S3	S11	S12	S13
T2: New low-cost pipelines	S4	S5	S6	S14	S15	S16
T3: New high-cost pipelines	S7	S8	S9	S17	S18	S19
T4: Shipping (low-cost)	-	-	S10	-	-	S20
T5: Shipping (high-cost)			S21			S22

As stated in §3.1.1, the system could either supply the Iberian industry with hydrogen or it could supply all Iberian energy imports. The system capacity in both cases respectfully would be 80 TWh/year and 200 TWh/year.

Paragraph §2.1.3 showed that there are five options for hydrogen transport: (i) using existing pipelines, (ii) using high-cost new pipelines, (iii) using low-cost new pipelines, (iv) using hydrogen vessels in combination with high-cost new pipelines or (v) using hydrogen vessels in combination with low-cost new pipelines. Despite large differences in cost all options will be researched, since the more expensive options have advantages regarding the continuity of existing natural gas supply and specific energy dependence.

Lastly, the effect of three levels of hydrogen energy dependence as described in §2.1.7.3 will be researched. In the first level of security (LoS1) no extra measures will be taken to guarantee energy security which will function as a base-case. The second level (LoS2) will be a situation with enough storage and/or capacity to switch suppliers to guarantee an HID of 10% and the third level of security (LoS3) entails the situation in which full measures are taken to guarantee a level of HID of 0%. In the third level of security, the Iberian Peninsula is prepared to continue a year without a decrease in energy use if Morocco or Algeria stops the hydrogen supply. In the case of hydrogen shipping, this (LoS3 scenario) will be the only relevant scenario since the shipping option allows for a switch of supplier to fill up potential shortages. The hydrogen import dependency and storage (calculated with the formula from §2.2.3) are shown in Table 12.

Table 12 hydrogen import dependency and corresponding storage capacities

	D1		D2	
	HID (%)	Storage (TWh)	HID (%)	Storage (TWh)
LoS1	14	0	35	0
LoS2	10	12	10	72
LoS3	0	40	0	100

4 Model and experiments

The Network Simplex Method will calculate the minimum cost flow of the MIGHS under different system designs. To do that, the MIGHS must be conceptualized into a network model. This paragraph shows how the described hydrogen system is conceptualized into the network model for the network simplex method. Each step of the hydrogen chain as shown in Figure 13 is conceptualized in the MIGHS model; this paragraph explains how each step is modeled to ultimately calculate the SLCOH.

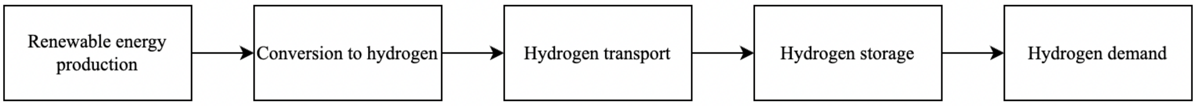

Figure 16 hydrogen supply chain

The layout of the model consists of nodes and edges (§2.4). The nodes are the cities through which the current natural gas pipelines cross. The edges follow the route of the current gas network. Cities are selected when they are: producing hydrogen, connecting the infrastructure or if they are cities where hydrogen will be demanded (Figure 17). The coordinates of each city that is included are retrieved from online database latlong.net (n.d.).

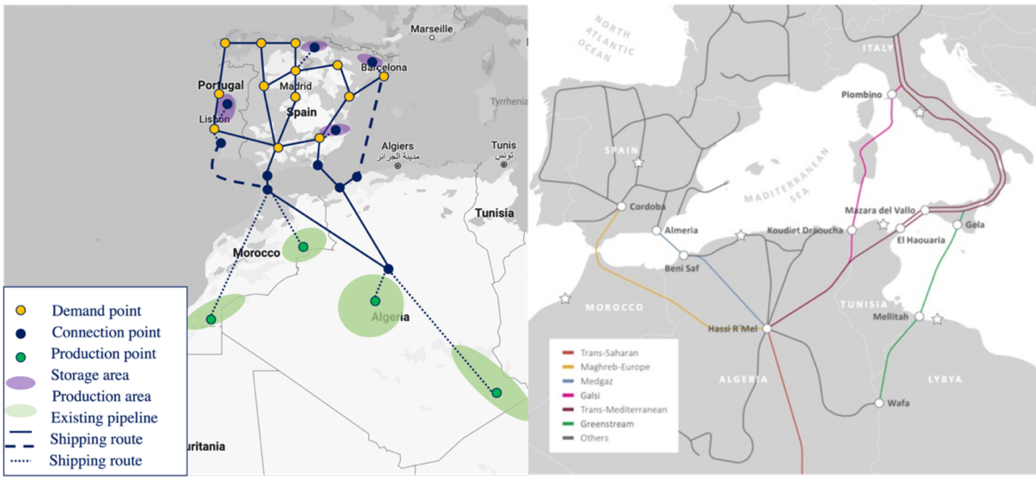

Figure 17 conceptual model (left) and current gas pipeline infrastructure (right)

4.1.1 Renewable energy production

The production areas are modeled as nodes with a negative demand (simulating supply), reflecting the scenarios D1 and D2 as discussed in §3.1.3. The production area used for each transport scenario will be determined through an experiment (§3.5).

The costs attributed to the production locations will be a combination of the CAPEX, lifetime and OPEX. This value is added as the 'weight' of those nodes.

Table 13 installed capacity per production location and energy source

Installed capacity	Capacity	Morocco		Algeria		Unit
	TWh/year	Bouarfa	Zag	El Menia	Djanet	
Installed solar power	30	15,5	14,7	14,4	12,9	GW
Installed wind power	37	13,2	9,6	14	11,7	GW
Installed solar power	75	38,8	36,7	36	32,3	GW
Installed wind power	92	32,8	23,9	34,7	29,1	GW

These capacities can be converted to the costs using the values from Table 14 using equation 10.

Table 14 costs of solar farms and wind farms

	Solar farm	Unit	Wind farm	Unit
Lifetime	30	Years	20	Years
CAPEX	0,64	mln €/MW	1,33	mln €/MW
OPEX	1,3	%CAPEX/year	1,1	%CAPEX/year

$$CAPEX_{REP} = \sum_{a,s} P_{as} * C_s \quad (10)$$

$CAPEX_{REP} = Capital\ expenditure\ of\ renewable\ energy\ production$ (€)
$P_{as} = installed\ capacity\ of\ energy\ source\ s\ on\ production\ area\ a$ (GW)
$a \in \{Bouarzat, Zag, El\ Menia, Djanet\}$
$s \in \{wind, solar\}$
$C_{as} = cost\ of\ energy\ source\ s\ \left(\frac{€}{GW}\right)$

4.1.2 Electrolysis cost calculations

The impact of the electrolysis is calculated using the values in Table 15 and equations 11.

Table 15 costs of alkaline electrolysis and battery packs

	Alkaline	Battery pack	unit
CAPEX	1	2,3	bln€/GW
lifetime	7	10	years
Opex	2,5	1,0	%CAPEX/year

$$CAPEX_e = P_e * C_e \quad (11)$$

$CAPEX_e = Capital\ expenditure\ for\ electrolysis$ (€)
$P_{installed} = installed\ electrolysis\ capacity\ (GW)$
$C_e = CAPEX\ per\ installed\ capacity\ (\frac{€}{GW})$

4.1.3 Hydrogen transport

In the model edges are added according to the current natural gas network. For the scenario in which shipping is considered, the shipping routes Tangier-Sines and Arzew-Barcelona are added and the routes Tangier-Tarifa and Beni Saf-Almeria are removed. The costs used for each scenario are shown in Table 16.

Table 16 hydrogen transport costs

	Pipelines				Shipping	
Scenario	T1 Retrofit	T2 Low cost	T3 High cost	Unit	T4 – T5 Shipping	Unit
Lifetime	40	40	40	years	30	years
CAPEX	0,73	1,33	3,56	€/tpa/km	44.705	€/tpa
OPEX	5	5	5	%CAPEX/year	4	%CAPEX/year

Costs for pipelines are measured in costs per distance per capacity. Capacity will be calculated using the network simplex method (§3.5). The distance is calculated as the *Euclidean* distance between the different connection points. The Euclidean distance is the straight-line distance between two points in a two- or three-dimensional space. Converting the distance in degrees to the distance in meters goes according to equation 12 (Stewart, 2018).

$$L = \frac{2\pi r A}{360} \tag{12}$$

$L = Length$
$r = radius$
$A = number\ of\ degrees$

The Euclidean distance is multiplied by the costs from table 16 (equation 13). When using the network simplex method it is important to use integer values (Király, 2012), so for that reason the cost-distance value is transformed into an integer.

$$CAPEX_T = \sum_{i,j} c_T L_{ij}\, x_{ij} \tag{13}$$

$CAPEX_T = Transport\ capital\ expenditure\ for\ transport\ mode\ T\ (€)$
$for\ T\ \in \{T1, T2, T3, T4\}$

$c_T = costs\ for\ transport\ mode\ T\ \left(\frac{\frac{€}{MWh}}{km}\right)$

$L_{ij} = Length\ of\ connection\ between\ city\ i\ and\ city\ j\ for\ i, j$
$x = indicator\ if\ there\ is\ a\ connection\ between\ i\ and\ j$
$for\ x\ \in \begin{cases} 0\ if\ i\ is\ not\ connected\ to\ j \\ 1\ if\ i\ is\ connected\ to\ j \end{cases}$

4.1.4 Hydrogen storage

Storage is implemented in the MIGHS model by adding two nodes per storage area. For example, the hydrogen storage in the Elche area will be modelled by creating an Elche_out and Elche_in. Elche_out gets a negative demand as big as the desired storage and Elche_in gets a demand as big as the desired storage. There will be no edge between those two nodes, so that the hydrogen will need to be transported to the nearest node, before it can get back into the storage. This way the flow of hydrogen in and out of the storage is modeled.

Table 17 hydrogen storage costs

Underground salt caverns	Value	Unit
Lifetime	50	years
CAPEX (Duigou et al., 2017)	3	bln€/TWh
OPEX (Duigou et al., 2017)	2	%CAPEX/year

The storage capacity will be varied in the different system designs. For pipeline transport the storage capacity will be calculated for no measures to support energy security, for a 10% hydrogen import dependency and for a 0% hydrogen import dependency (LoS1, LoS2 and LoS3 respectively). For the shipping scenario no storage will be implemented since the energy dependence is already secured by being open to other suppliers.

Table 18 hydrogen import dependency and corresponding storage capacities

Storage capacity	D1		D2	
Level of energy security	HID (%)	Storage (TWh)	HID (%)	Storage (TWh)
LoS1	14	0	35	0
LoS2	10	12	10	72
LoS3*	0	40	0	100

4.1.5 Hydrogen demand

The MIGHS will be modeled for two scenarios in hydrogen demand: 80 TWh/year and 200 TWh/year. In the first scenario, the 80 TWh/year will be divided over the cities in which the the industry of each country is located. The Portuguese industry is basically divided over two regions which use roughly the same amount of energy: Lisbon-Setúbal and Porto-Aveiro-Braga (*Portugal - Industrial Regions*, n.d.). In Spain, the large industry is divided over five regions: Catalunya (around Barcelona), Madrid, Asturias (around Oviedo), the Basque country (around Bilbao) and Andalusia (around Seville) (*Spain - INDUSTRY - Regional Concentration*, n.d.). For Spain their industrial hydrogen demand will also be equally divided over the industrial regions.

For the second scenario, the industrial cities will keep their demand from the first scenario. The rest of the 200 TWh/year will be divided evenly all Iberian cities that are included in the model. The demands for each city in both scenarios can be found in Appendix B.

4.2 conceptual model

Figure X shows how the conceptual model relates to the current natural gas transport network. The model consists of nodes that reflect hydrogen production, hydrogen storage and hydrogen demand. The edges in the conceptual model reflect the pipeline or shipping used for hydrogen transport. Table 19 gives an overview of the values that reflect the contribution to the SLCOH per step in the hydrogen supply chain. In §4.2.1 is clarified how the conceptual model calculates the system levelized cost of hydrogen and the hydrogen import dependency using the XLRM framework. The values used to calculate the SLCOH can be found in Table 19.

Table 19 values used to calculate the SLCOH

Contribution to SLCOH		CAPEX		Lifetime	OPEX
		value	unit	years	%CAPEX/year
Production	Solar	0,64	bln€/GW	30	1,3
	Wind	1,33	bln€/GW	20	1,1
Electrolysis	Alkaline	1,0	bln€/GW	7	3
Storage	Underground cavern	3,0	bln€/TWh	50	2
Transport	T1 - Retrofit	22	€/GWh/km	40	5
	T2 - Low-cost new	40	€/GWh/km	40	5
	T3 - High-cost new	107	€/GWh/km	40	5
	T4, T5 - Shipping	1,35	mln€/GWh	30	4

4.2.1 The XLRM framework applied to the MIGHS model

In this research the two relevant external factors are technological readiness and energy prices. Handling the uncertainty in which technologies are ready by 2030 and what their characteristics will be in that time is done by selecting the technology that is already ready to use and taking the characteristics from those technologies. The limitation of this assumption is that it does not include technological improvements that can occur in the years until 2030. A part of the uncertainty in development is covered by selecting two different cost scenarios for the hydrogen pipelines (high-cost and low-cost). The energy prices of alternative energy sources affect the performance metrics, which will become clear when the performance metrics are introduced.

The policy levers will be the system size (TWh/year), the level of energy security (HID %) and the means of hydrogen transport (type of pipeline or shipping). The levels of those policy levers are described in §3.2.

The relations in the model are the calculations of the capital expenditure of each step in the hydrogen supply chain. The capital expenditure can then later be calculated into the system levelized cost of hydrogen according to the formula in §2.3.

The metrics are energy security and system levelized cost of hydrogen. Choices that are made regarding the policy levers will influence the values of the SLCOH and energy security. Paragraph §3.1.7.3 explains which metrics are used to put the model outcomes in perspective. To value the SLCOH it is compared to energy price of alternative energy sources. Therefore, the external factor of energy price influences the performance metric.

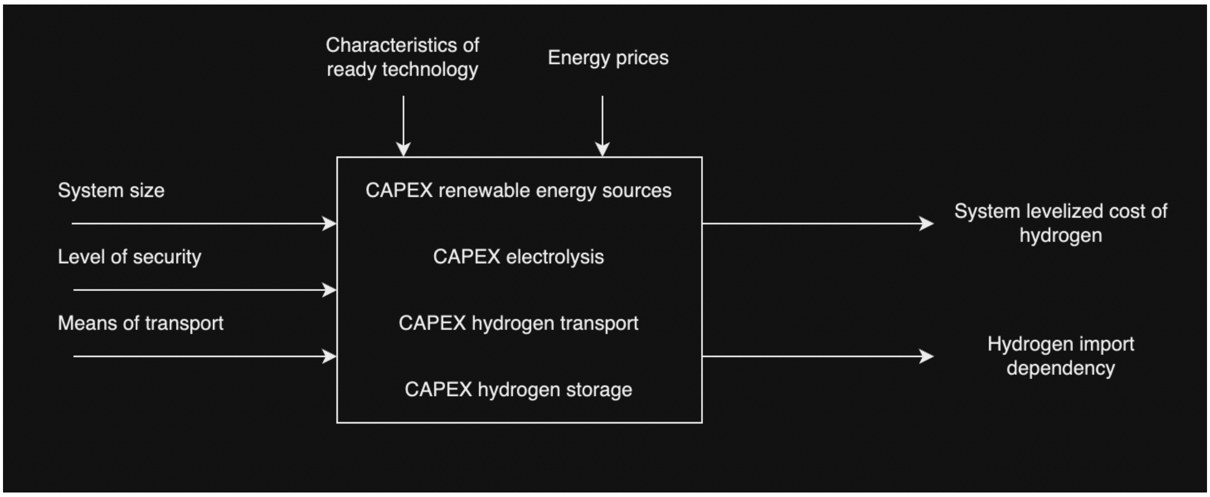

Figure 19 XLRM framework applied to the proposed model

4.3 Experiment setup

The model will be used for two experiments to answer the main research question. The first experiment should point out which production area is economically most viable to be used. In this experiment the costs of the production plants and transport to the system will be tested. The outcome of this first experiment will be input for the second experiment. The second experiment takes the whole system and calculates the system levelized costs under different design options (Figure 20).

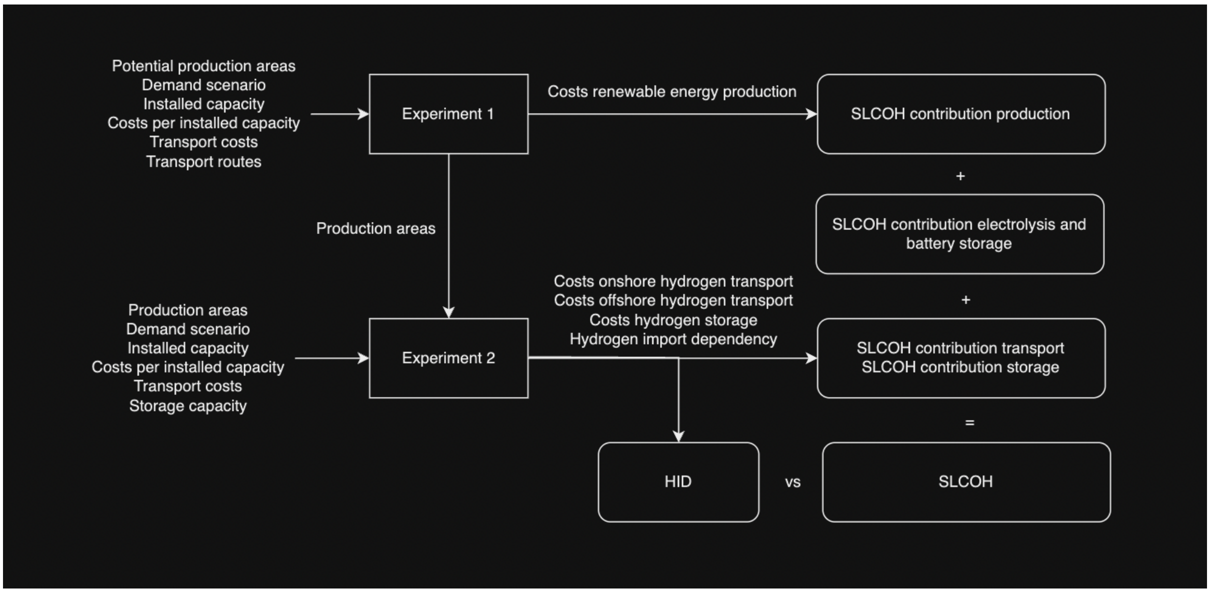

Figure 20 experiment setup

4.3.1 Production areas

Both hydrogen producing countries have two areas that are suitable for renewable energy production. The more Southern locations of both countries have lower investment and operating costs (§3.3.1). However, this does not take into account the transport costs, which will be higher because of their further position from the connection points to Europe. This first experiment calculates the costs of transporting the hydrogen from production location to connection point for two different pipeline transport options: low-cost new pipelines (T2) and high-cost new pipelines (T3). There are no pipelines yet, so retrofit pipelines are not an option and hydrogen shipping is only considered for overseas transport. The experiment input can be seen in Table 20.

Table 20 production location experiment input

Country	D	Connection	Demand	Production area	Supply
		City	GWh/year	City	GWh/year
Morocco	D1	Tangier	40.000	Bouarfa	40.000
		Tangier	40.000	Zag	40.000
	D2	Tangier	100.000	Bouarfa	100.000
		Tangier	100.000	Zag	100.000
Algeria	D1	Hassi R'Mel	40.000	El Menia	40.000
		Hassi R'Mel	40.000	Djanet	40.000
	D2	Hassi R'Mel	100.000	El Menia	100.000
		Hassi R'Mel	100.000	Djanet	100.000

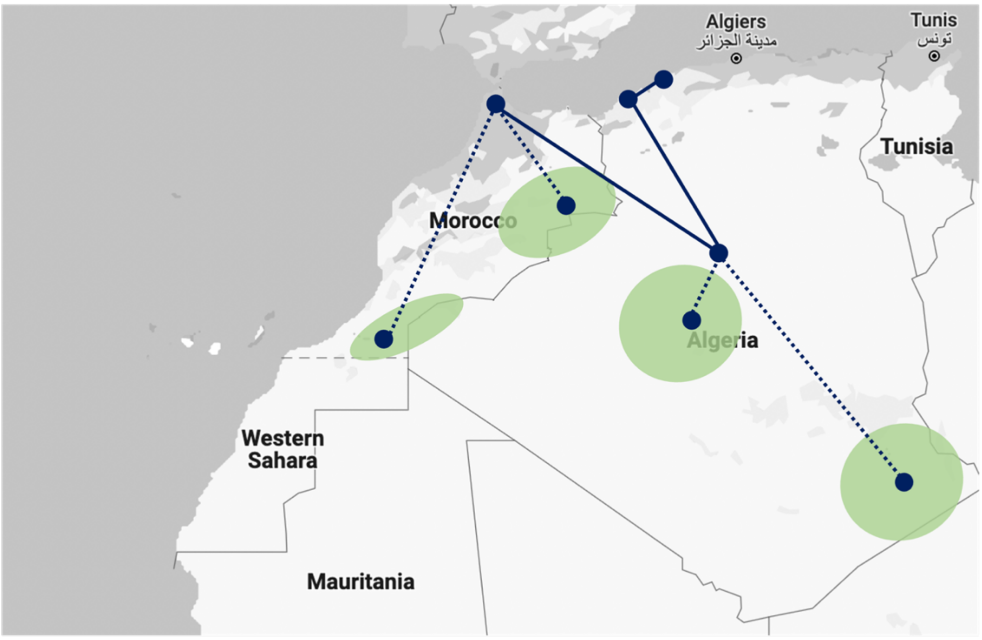

Figure 21 production areas

4.3.2 System levelized cost of hydrogen

The outcome of the first experiment determines which production area will be used in which scenario. This experiment calculates the SLCOH for the scenarios in Table 21 in the network as shown in Figure 22.

Table 21 scenarios for experiment 2

System capacity	D1: 80 TWh			D2: 200 TWh		
Level of security	LoS1	LoS2	LoS3	LoS1	LoS2	LoS3
T1: Existing pipelines	S1	S2	S3	S11	S12	S13
T2: New low-cost pipelines	S4	S5	S6	S14	S15	S16
T3: New high-cost pipelines	S7	S8	S9	S17	S18	S19
T4: Shipping (low-cost)	-	-	S10	-	-	S20
T5: Shipping (high-cost)	-	-	S21	-	-	S22

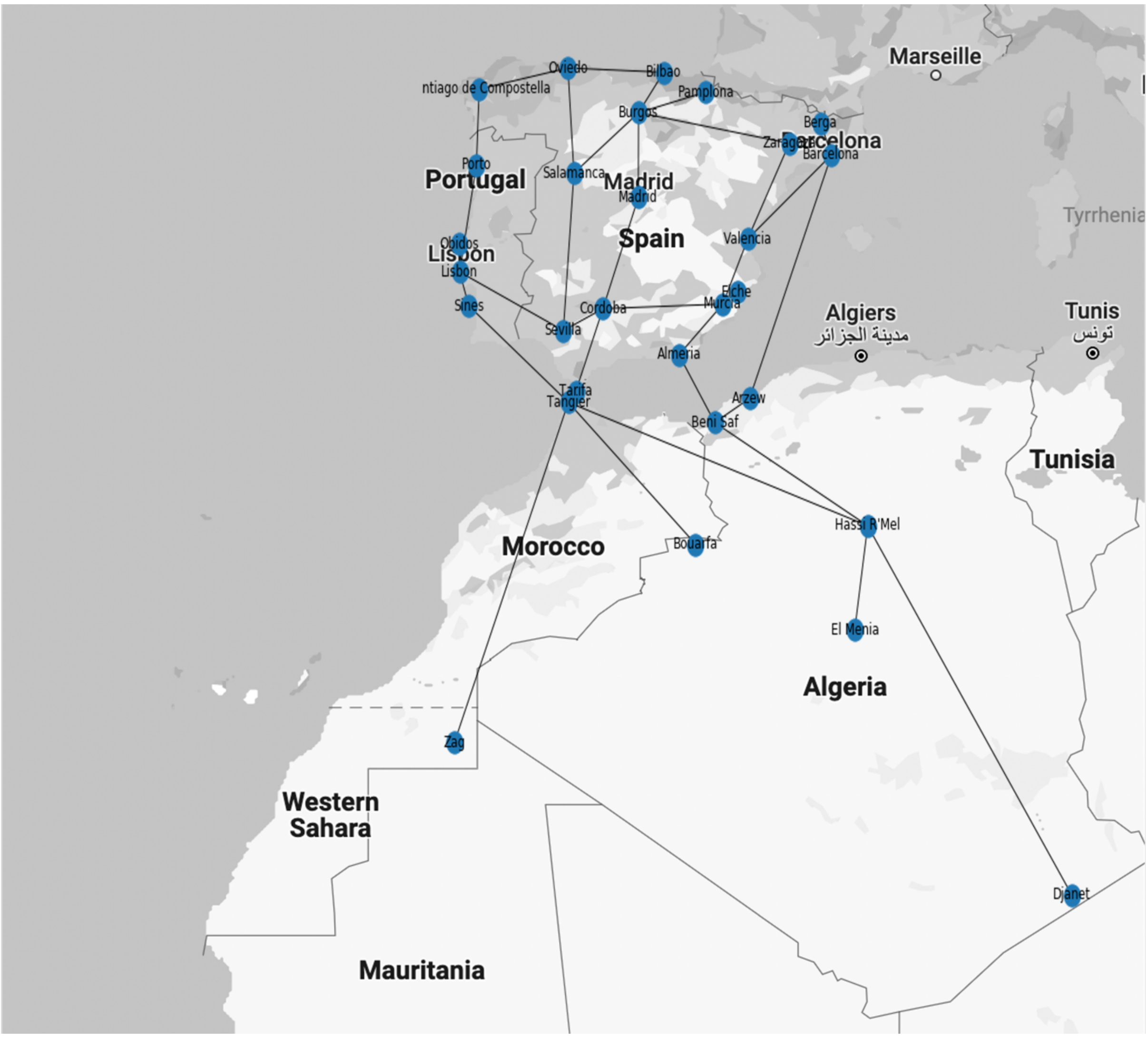

Figure 22 Model layout (NOTE: Zag is projected in Western Sahara, but it is actually in Morocco. Because of the way maps are projecting a sphere on a 2 dimensional map, the locations of the African cities are shown slightly more southern than they are in reality).

4.4 Model verification and validation

The verification and validation process plays a crucial role in any modeling research, as it ensures the reliability, accuracy, and credibility of the developed models (Nikolic et al., 2019). This chapter is dedicated to describing the comprehensive procedures employed to assess the models' correctness, consistency, and suitability in representing real-world phenomena. Through verification, which involves confirming the correctness of the implementation, and validation, which assesses the model's ability to replicate real-world behavior, this paragraph aims to establish the trustworthiness and robustness of the models, thereby enhancing the overall quality and credibility of the research outcomes.

4.4.1 Model verification

The model verification confirms whether the model does what it is supposed to do. An important way to verify a model that is very relevant to this study is unit testing. Unit testing is a software testing method that involves evaluating individual components - or units - of a program to ensure their correctness and functionality in isolation (Daka & Fraser, 2014). For the unit testing of this model, the different steps of creating a pipeline connection between Lisbon and Porto is analysed.

4.4.1.1 Pipeline length and cost

A pipeline connection is supposed to have the length in kilometres. In the model, the calculation of the length of the pipeline is based on the latitude and longitude coordinates of the cities on both ends. The model uses the Euclidean function to calculate the distance and then converts it to meters by multiplying it with a conversion factor that converts the distance that is calculated by degrees into a distance in kilometres. Steps 1-5 of appendix A show that the distance is calculated in the correct manner. The full Python script of the model can be found in appendix D.

4.4.1.2 Pipeline flow

To calculate the capacity that is needed to match supply and demand, a test case is created where the demand in Porto is 10 MWh and Lisbon supplies 10 MWh. The flow between Lisbon and Porto should be equal to 10 MWh/year in that case. Step 6 in appendix A shows this is what the model calculates.

4.4.1.3 Pipeline cost flow

Finally, the minimum cost flow is calculated by the network simplex algorithm. The outcome should equal the flow (capacity) multiplied by the costs. Step 7 in appendix A shows that this is the case, implying that the model calculates the minimum flow cost correctly.

4.4.2 Model validation

Validation is the process in which a model or system is assessed to ensure that it faithfully represents real-world behaviours and meets the intended requirements and expectations. To validate the model, the same steps of creating the pipeline connection between Lisbon and Porto is analysed.

Firstly, the distance between Lisbon and Porto is 276 kilometres according to the model (Figure 23). Figure Y shows that google maps indicates the distance between Lisbon and Porto to be 278 kilometres, proving that the distance in the model is calculated correctly. The small difference is negligible and can be explained by a slight difference in setpoints between de used dataset and Google Maps. Secondly, the costs for the pipeline are €608 per megawatt hour per year. Per kg hydrogen that is 0,66 €/1000km/kg/year, being almost equal to the 0,64 €/1000km/kg/year found in §3.1.4.1. Therefore, can be concluded that the distances calculated by the model are corresponding to reality and the costs that the model calculate are conform literature findings. The model is fit for purpose.

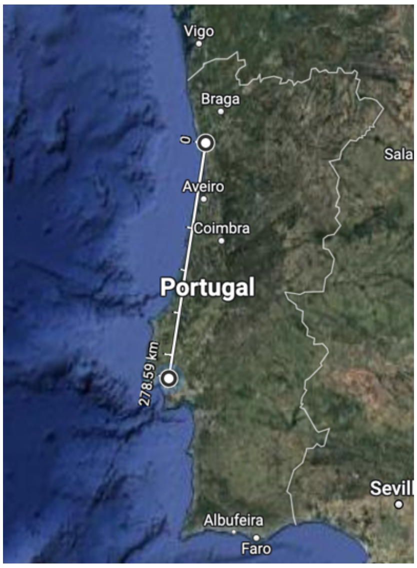

Figure 23 the distance between Lisbon and Porto

5 Results

The model is used to conduct two experiments. The first experiment determines the best production areas. The preferred areas are then used in the second experiment to calculate the overall cost of hydrogen transport and storage.

5.1 Experiment 1: production area

The results of the first experiment can be found in Table 22. The model calculated for each demand scenario what the contribution to the SLCOH (in million euros per year) would be from the hydrogen production and connection to the network for each potential production area.

Table 22 results experiment 1

Country	D	Production		T2	T3	REP	REP + T3
		City	TWh/year	mln€/year	mln€/year	bln€/year	bln€/year
Morocco	D1	Bouarfa	40	23	60	1,2	1,3
		Zag	40	38	100	1,0	1,1
	D2	Bouarfa	100	58	150	3,0	3,2
		Zag	100	95	256	2,4	2,6
Algeria	D1	El Menia	40	10	30	1,3	1,4
		Djanet	40	48	125	1,1	1,2
	D2	El Menia	100	28	73	3,1	3,2
		Djanet	100	118	313	2,6	2,9

The outcomes of the model show that the production areas in the South in both Morocco and Algeria have a lower contribution to the SLCOH than the more Northern areas. Even in the scenario where the more expensive pipelines are used (T3).

Table 23 shows the two competing production areas with the smallest difference in SLCOH contribution. To assess the robustness of the model, the difference in production costs and transport costs are analyzed. The difference in production costs is 180 million euros per year. That means that the outcome of the model changes when the input data for the production costs in El Menia decrease by 180 million euros per year (16 percent decrease), or when the same costs in Djanet would rise with 180 million euros per year (17 percent increase). For transport it means that the current difference of 40 million euros per year could rise to 220 million euros per year (550 percent increase). These margins are significant and the outcomes of the model regarding the most economical production area are considered robust.

Table 23 robustness experiment 1

Robustness (D1 – Algeria)	El Menia	Djanet	Difference
Renewable energy production (bln€/year)	1,3	1,1	0,2
Connection to the network (mln€/year)	60	100	40

Therefore, in the second experiment Zag and Djanet will be considered as the production areas. The contribution to the SLCOH of renewable energy production will be two billion euros per year (in scenario D1) and 5 billion euros per year (in scenario D2).

5.2 Experiment 2: transport and storage

The second experiment takes production areas Zag and Djanet and calculates the resulting onshore transport, offshore transport and storage capacities. The different aspects in the hydrogen supply chain are first discussed separately from each other and then put together to show the total contribution to the SLCOH of the hydrogen transport and storage.

5.2.1 Onshore hydrogen transport

Onshore there are two ways of transport: retrofit pipelines or new pipelines (low-cost or high-cost). As can be seen in Table 24, the costs of the transport network increase with the level of security. This difference can be explained by the necessary pipeline connections from and towards the storage areas in those scenarios. The shipping options (T4 and T5) correspond to the costs of T2-LoS1 and T3-LoS2 respectively, because in the scenarios with shipping as the offshore transport method, no storage is considered (§4.1.4).

Table 24 SLCOH contribution onshore hydrogen transport

SLCOH contribution (€bln/year)	D1: 80 TWh/year			D2: 200 TWh/year		
Level of security	LoS1	LoS2	LoS3	LoS1	LoS2	LoS3
HID (%)	14	10	0	35	10	0
T1: Existing pipelines	0,31	0,31	0,32	0,75	0,77	0,79
T2: New low-cost pipelines	0,56	0,57	0,59	1,36	1,40	1,43
T3: New high-cost pipelines	1,50	1,52	1,58	3,63	3,76	3,81
T4: Shipping (low-cost)	-	-	0,56	-	-	1,36
T5: Shipping (high-cost)	-	-	1,50	-	-	3,63

The validity of these outcomes is affirmed when compared to the research by Van Wijk & Wouters (2021). Their study to using the existing pipelines results in transport costs of €0,005/kWh while this study results in transport costs in the same order of €0,004/kWh in scenario T1.

5.2.2 Offshore hydrogen transport

For offshore hydrogen the extra costs are calculated in Table 25 according to the factors explained in §2.1.3. As expected, the costs for hydrogen shipping are far more expensive than the costs for offshore pipelines. However, since shipping opens the possibility to switch hydrogen suppliers in order to support energy security, no storage is needed in those scenarios. The cheaper pipeline options will need storage capacity in order to reach the same level of hydrogen import dependency.

Table 25 SLCOH contribution offshore hydrogen transport

SLCOH contribution (bln/year)	D1: 80 TWh/year	D2: 200 TWh/year
	mln€/year	mln€/year
T1: Existing pipelines	4	10
T2: New low-cost pipelines	8	11
T3: New high-cost pipelines	20	501
T4: Shipping (low-cost)	7 920	19 800
T5: Shipping (high-cost)	7 920	19 800

5.2.3 Hydrogen storage
The hydrogen storage capacity corresponding to the different levels of energy security can be found in Table 26. The investment costs to reach a 0% hydrogen import dependency in the scenario where 200 terawatt hours are imported yearly are 300 billion euros. However, due to the 50 years lifetime and 2 percent operating expenses of hydrogen storage in underground salt caverns, the SLCOH contribution is 6 billion euros yearly.

Table 26 SLCOH contribution hydrogen storage

Hydrogen storage	D1: 80 TWh/year			D2: 200 TWh/year		
Level of security	LoS1	LoS2	LoS3	LoS1	LoS2	LoS3
HID (%)	14	10	0	35	10	0
Storage capacity (TWh)	0	12	40	0	72	100
Storage investment costs (bln€)	0	35	120	0	215	300
SLCOH contribution (bln€/year)	0	0,7	2,4	0,0	4,3	6,0

5.2.4 Total transport and storage costs
Adding the storage costs to scenario T1-T3 and the shipping costs to scenario T4-T5 gives the total transport and storage costs. Table 27 shows that the differences between shipping and pipelines reduce significantly when storage capacity increases to achieve a lower level of hydrogen import dependency. However, even in the highest level of energy security pipeline transport is cheaper than shipping transport. Comparing the low-cost scenarios T2 and T4 and the high-cost scenarios T3 and T5 shows that the shipping options are approximately 3 billion (D1) and 7 billion (D2) euros more expensive per year.

This also implies that the outcome of the model regarding cost-preference for pipelines over shipping is robust in terms of sensitivity to input data. Offshore shipping transport will still be less economically attractive when the costs are decreased by 38 percent or when the storage costs increase by 225 percent.

Table 27 SLCOH contribution hydrogen transport and transport combined

Transport and storage (bln€/year)	D1: 80 TWh/year			D2: 200 TWh/year		
Level of security	LoS1	LoS2	LoS3	LoS1	LoS2	LoS3
HID (%)	14	10	0	35	10	0
T1: Existing pipelines	0,3	1,7	5,1	0,8	9,4	12,8
T2: New low-cost pipelines	0,6	2,0	5,4	1,4	10,0	13,4
T3: New high-cost pipelines	1,5	2,9	6,4	4,1	12,9	16,3
T4: Shipping (low-cost)	-	-	8,5	-	-	21,1
T5: Shipping (high-cost)	-	-	9,4	-	-	23,3

5.3 Electrolysis
For the installed renewable energy capacities at Zag and Djanet found in experiment one, the necessary electrolysis capacity is calculated (Table 28). The battery pack capacity is a third of the electrolysis capacity (§2.1.1.3). Together electrolysis and the corresponding battery pack attribute 12,3 billion euros per year (D1) and 30,8 billion euros per year (D2) to the system levelized cost of hydrogen.

Table 28 SLCOH contribution electrolysis

SLCOH contribution (bln€/year)	D1	D2
Alkaline	8,2	20,5
Battery pack	4,1	10,3
Total	12,3	30,8

5.4 System levelized costs of hydrogen

The system levelized cost of hydrogen has now been calculated for each step in the hydrogen supply chain. The costs that are not depending on transport mode or level of security can be found in Table 29.

Table 29 SLCOH contribution renewable energy production and electrolysis

SLCOH contribution (bln€/year)	D1	D2
Renewable energy production	2,0	5,0
Electrolysis	12,3	30,8
Total	14,3	35,8

These values are added to the values of transport and storage to get the system levelized cost contribution of each scenario. The costs are then divided by the output of the system (80 TWh/year and 200 TWh/year to get the system levelized cost of hydrogen (Figure 24).

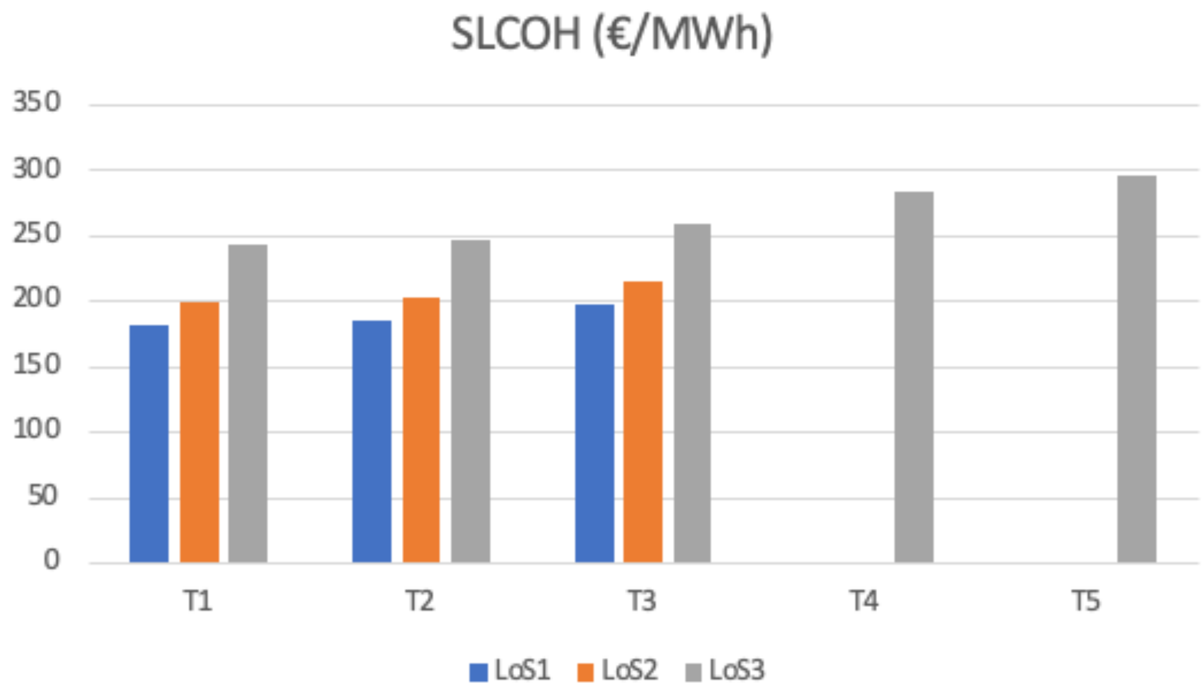

Figure 24 SLCOH per transport mode and level of security

5.5 Performance metrics

To see how these results relate to alternative energy prices, they are compared using the performance metrics from §2.1.7.3 that are also shown in Table 30.

Table 30 performance metrics

Performance metric	Valuation	Benchmark	Unit
SID	Desired HID	0 - 10	%
	Acceptable HID	10 -20	%
	Undesired HID	20 - 30	%
sLCOH	Market value competitive sLCOH	110	€/MWh
	Subsidised wind competitive sLCOH	160	€/MWh
	Subsidised solar competitive sLCOH	380	€/MWh

Table 31 shows how the system performs under the different scenarios. Without taking measures for energy security the costs range between €180 and €200 per megawatt hour, which is a little more expensive than the current costs of subsidized wind power. When measures are taken to realize a hydrogen import dependency of 10 percent, costs rise to a range of €200 and €240 per megawatt hour. When the system is designed to maintain full energy supply for a year – even when one of the suppliers decides to stop the hydrogen supply – the costs go further up to between €243 and €296 per megawatt hour. The SLCOH in scenario D2 under LoS2 are higher because it takes a relatively higher investment to get from the 35% HID to 10% HID than it does to get from 14% to 10% in D1. Remarkable is that even in that scenario the hydrogen system outperforms local subsidized solar power.

Table 31 SLCOH

SLCOH (€/MWh)	D1: 80 TWh			D2: 200 TWh		
Level of security	LoS1	LoS2	LoS3	LoS1	LoS2	LoS3
HID	14	10	0	35	10	0
T1	183	200	243	183	226	243
T2	186	203	246	186	229	246
T3	198	215	259	200	243	261
T4			285			285
T5			296			296

Figure 25 shows the system levelized cost of hydrogen for each level of security and transport scenario. The reference values for energy market value, subsidized wind power and subsidized solar power from Figure X are included for comparison.

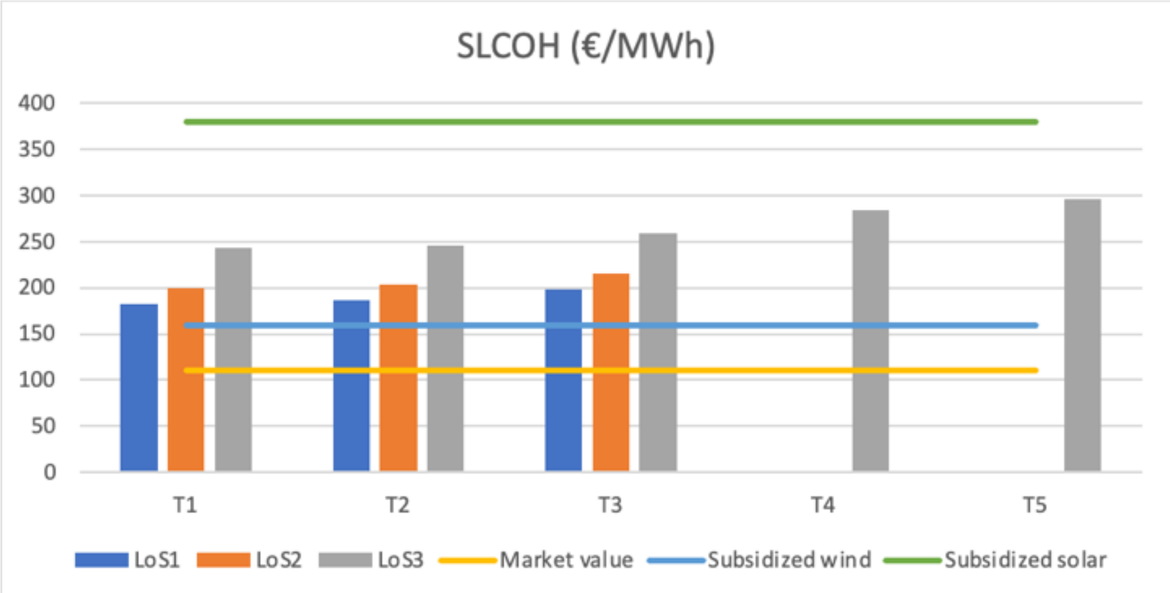

Figure 25 model output compared to performance metrics

5.6 The investment costs compared to literature

The cost range of €180 to €300 per megawatt hour corresponds to an investment range of 15 to 24 billion euros (for 80 TWh/year) or 37 to 59 billion euros (for 200 TWh/year). The period for which the investments are made are set at 30 years, in line with the most common lifetime of applied technologies and literature. The subsidies are calculated as the difference between electricity price (€110/MWh, §5.5) and the SLCOH of the system. For the cheapest scenario this implies a subsidy of €73 per megawatt hour and for the most expensive scenario it translates to €186 per megawatt hour.

Table 32 Performance in comparison to other models: MARGE (Williges et al., 2010) Dii (Dii GmbH, 2009), UW (Ummel & Wheeler, 2008), DLR (German Aerospace Center 2006) and the MIGHS model from this thesis.

Model	Size	Investment	Lifetime	Subsidy	Period	Investment	Subsidy
	GW	bln€	years	bln€	years	mln€/GW/year	mln€/GW/year
DLR	100	395	30	-	-	132	-
MARGE	157	111	21	43	21	34	13
Dii	340	4500	30	200	30	441	20
UW	20	-	-	20	10	-	100
MIGHS (low)	23	37	30	15	30	53	21
MIGHS (high)	23	59	30	37	30	86	54

In Table 32, the results demonstrate a strong alignment between the outputs of the MIGHS model and those presented in existing literature. The close correspondence between the MIGHS model outputs and established models further validates the robustness and reliability of the proposed framework.

Where literature investment costs (converted to billion euros per gigawatt divided by the lifetime) ranges from 34 to 441 million euros per GW per year, the same values for the MIGHS model range from 53 to 86. Moreover, when looking at the subsidies the model output is conform literature values that range from 13 to 100 million euros per gigawatt per year, whereas that range for the MIGHS model is from 21 to 54 million euros per gigawatt per year.

6 Model limitations and discussion

"All models are wrong, but some are useful" is a commonly cited quote by George Box (1976). Likewise, this model does not claim to be completely right. Assumptions have been made in order to be able to represent the complex reality. The most important numerical assumptions and how they influence the outcomes of this model are discussed in §6.1. The non-numerical assumptions are explained in §6.2. The way uncertainties are handled can be found in §6.3.

6.1 Numerical assumptions

One of the most important assumptions that have been made is that the routes from the current natural gas pipelines are technically and politically feasible. This assumption is based on the fact that it is not a very big step from a reality that has already been technically and politically realized. However, situations change and politics are hard to predict. For example, marine ecology has become a more prominent issue than 30 years ago when the gas pipelines were commissioned.

Another important assumption is that Morocco and Algeria do not work together and both cut off energy supply at the same time. In that case the hydrogen import dependency would increase largely. Even in the third level of energy security the HID would be 14 percent in the first scenario and 35 percent in the second scenario. In the first level of security the HID would even be 28 percent (D1) and 70 percent (D2). Yet, the countries would miss income, and – especially when the other country cuts down supply – prices and potential profit would likely increase. Besides, Morocco and Algeria find themselves on opposite sides of what is described as the "Maghreb Cold War" (Lefèvre, 2016), making a cooperation between them even less likely.

An important technical assumption is that there are no transport and storage losses incorporated in the model. Even though those losses are small, future research should include them for the model to be representing reality better. Besides, the load factor of pipelines has not been implemented in the model. To extend this research even further, a load factor of 75 percent should be included in the model (Brändle et al., 2021).

In addition to the aforementioned assumptions, it is crucial to recognize that every assumption incorporated into the modeling framework exerts its influence on the resultant outcomes. A comprehensive list of the assumptions made in this study can be found in Appendix E, where their implications and potential impact on the model results are detailed for thorough examination. It is essential to acknowledge and scrutinize these assumptions to ensure a comprehensive understanding of the model's outcomes and the robustness of the conclusions drawn from this research.

6.2 Other assumptions

An important simplification in this model is that all connections between nodes in the system are straight connections. In reality it will not be possible to have a straight pipeline between every city because of environmental aspects like mountains or existing infrastructure. However, on such a big scale and in the timeframe in which this research has been carried out, the choice of this simplification has been made.

Another limitation of this model is the lack of economies of scale. The economy of scale is a common economic principle that processes become cheaper when they are carried out in a larger scale (Stigler, 1958). Nonetheless, this assumption can be justified by the large scale in which this theoretical research takes place. Hydrogen as an energy carrier is a relatively new technology and it has not been carried out on such a scale. Besides, because of the enormous scale of this project, the argument could be made that at a certain point there are no further economies of scale.

Thirdly, the way the hydrogen demand is divided over the Iberian Peninsula is not based on actual energy consumption. Because of the scale of this research the assumption has been made that the demand is divided evenly over the industrial areas and urban areas that are connected to the system. An improvement to this model would be to include the current energy demand per area. The input data for the model can easily be modified.

6.3 Uncertainty handling

Data inherently carries uncertainty arising from various sources such as measurement errors, selection of measurement tools, and the decision of what to measure, among other factors. Therefore, in the context of modeling, it becomes imperative to explicitly address and account for uncertainty in both the input data and the model structure itself. To ensure accurate handling of input data uncertainty, a margin of error and expected developments should be discussed (Nikolic et al., 2019).

The margin of error has already shortly been addressed during the experiments. In the first experiment the choice for production location is discussed. The deciding factors in the preferable outcome are the transport cost and the production cost. The production costs are not impacting the outcome of the experiment for an increase in production costs of 17 percent of the cheaper option or a decrease of 17 percent for the more expensive option. The difference in transport costs could even increase by 550 percent before it changes the outcome of the experiment.

In the second experiment the economical advantage of pipeline transport as opposed to hydrogen shipping is determined. This result only changes when the costs of shipping decrease by 38 percent or when storage costs increase by 225 percent.

However, there is also the uncertainty of future technological developments. Partly this thesis deals with those uncertainties by choosing 2030 as the timeline. The technology should be ready by then and technological developments will only impact this research if they happen in the next seven years. Assumptions on future developments in renewable energy production have been taken from literature and can be seen as relatively stable, since the technology is already far in development (Abdelli et al., 2022; Trieb, 2021).

In electrolysis on the other hand, a lot of progress is possible in for example PEM (Chi & Yu, 2018; IREA, 2020; Kuckshinrichs et al., 2017). Also the efficiency of Alkaline electrolysis could increase.

Transport and storage technology is not expected to develop a lot in the next years, for the same reason as renewable energy production (Reddi et al., 2016; Melaina et al., 2013; Brändle et al., 2021). However, following Brändle et al. (2021) two cost scenarios for pipeline transport are implemented in the model.

The final important factor of which development is uncertain is the hydrogen consumption. The possibility conversion to hydrogen for industry is generally accepted but remains uncertain. Other sectors are even more uncertain (Acar & Dincer, 2020; Andrews & Shabani, 2012; Guillén-Gosálbez et al., 2009). The model handles this by implementing two scenarios: one in which only industry is supplied and one that relies on the possibility of nearly all processes to be possible with hydrogen.

7 Conclusions and recommendations

The outcomes of this thesis hold significant implications from both a societal and academic perspective. In section §7.1, the societal implications of the results are thoroughly examined, shedding light on how the findings can contribute to sustainable energy policies, resource management, and socio-economic development. Subsequently, section §7.2 reflects on how the research questions are addressed within this thesis, providing a comprehensive evaluation of the achieved objectives and their alignment with the original research aims.

Furthermore, section §7.3 delves into the academic relevance and implications of this study. It highlights the novel contributions to the existing body of knowledge, identifies research gaps that have been addressed, and paves the way for future investigations in the field of green hydrogen systems in the Maghreb-Iberian region.

Ultimately, this thesis concludes with valuable recommendations in section §7.4, offering insights on how the research outcomes can be harnessed to propel further research endeavors. The guidance provided encourages researchers to explore promising avenues, refine modeling techniques, and consider socio-political factors, thereby enriching the understanding of sustainable energy systems and their application on a global scale.

7.1 Societal implications and reflections

The outcomes of the model give interesting insight to the governments of the Iberian Peninsula. It shows the outcomes of different options the government can choose to design the system. The three policy levers each have their own impact on energy security and system levelized cost of hydrogen.

The model provides the governments assistance in making those decisions, by showing the effects on SLCOH and the HID. However, it remains important to emphasize that the model is a representation of reality with its limitations. Keeping in mind the limitations mentioned in chapter six it is important to use this as a guideline and not to take the costs that the model produces without considering those limitations.

7.1.1 System size

The first choice that the government needs to make is whether to invest in a system that could provide hydrogen for only the industry sector, or in a system that can provide for the full energy imports. This decides how big the investments are and has direct implications in energy security when no investments are made in means to support energy security. The investment costs to supply the industry sector with green hydrogen range from 15 to 24 billion euros. The investment costs to replace all imports with green hydrogen from the MIGHS range from 37 to 59 billion euros.

7.1.2 Means of transport

The second significant decision revolves around determining the most suitable means of transport for the green hydrogen system. Crucial considerations must be made concerning the potential trade-offs between maintaining the possibility of natural gas transport and embracing the exclusivity of hydrogen transportation. Additionally, governments must weigh the merits of establishing committed pipelines to Morocco and Algeria versus opting for hydrogen terminals that provide access to multiple suppliers. The chosen mode of transport significantly impacts both the SLCOH and the HID.

When assessing the cost implications, it shows that building entirely new pipelines is estimated to be 2 to 5 times more expensive than converting existing pipelines for hydrogen transport. Alternatively, opting for hydrogen shipping comes at a cost 15 percent higher than that of constructing new pipelines.

7.1.3 Energy security

The third critical decision revolves around determining the desired level of energy security that each country aspires to attain. This choice involves evaluating whether the countries opt for complete energy independence and invest in hydrogen terminals or storage facilities, or if they are willing to accept a reduced level of energy security, resulting in a lower System Levelized Cost of Hydrogen (SLCOH).

In the context of the first system size scenario, transitioning from a hydrogen import dependency (HID) of 14 percent to 10 percent incurs an additional cost of approximately 10 percent. Conversely, eliminating the HID entirely, i.e., moving from 14 percent to 0 percent, leads to a substantial SLCOH increase ranging from 30 to 50 percent.

Similarly, in the second scenario, reducing the HID from 35 percent to 10 percent results in a significant 24 percent increase in SLCOH.

These findings underscore the crucial trade-offs involved in deciding the level of energy security and its corresponding impact on the cost-effectiveness of the green hydrogen system. Policy and decision-makers must carefully weigh the economic considerations against the strategic implications of energy independence when determining the most optimal HID for the Maghreb-Iberian Green Hydrogen System.

7.2 Research questions

This research aimed to answer the question: *How does a technologically feasible Maghreb-Iberian green hydrogen system impact the Iberian energy cost and energy security?* To accomplish this overarching goal, the study delves into four sub-questions, each comprehensively explored in the subsequent paragraphs.

7.2.1 First subquestion

To answer the main research question first the sub-question Which technologically feasible options are there for a Maghreb-Iberian green hydrogen system by 2030? should be answered.

Literature study in chapter 2 taught that wind and solar energy are the most feasible options to produce hydrogen in Northern Africa. The electricity delivered by those sources is then best used to produce hydrogen using Alkaline electrolysis in combination with a battery pack to balance out the intermittency of the renewable energy sources. However, PEM electrolysis is promising and its developments should be monitored closely.

For hydrogen transport there are three relevant options: using the pipelines that are already there, placing new pipelines and using hydrogen vessels. For new pipelines two scenarios are implemented reflecting high and low costs. Using the current pipelines is the most economically attractive option but has as a result that natural gas can no longer be transported through those pipelines. Some see natural gas as a useful bridge fuel to help keep the energy prices low during the energy transition, making this option possibly less attractive for governments. The new pipelines are the second most affordable option. The downside of this is that the investment cost is a very strong commitment to the producing countries. The other way around, it is also a very strong commitment from the producing countries to the consuming countries. However, even with enough storage capacity to not be impacted by a year-long stop in hydrogen supply from one of the suppliers, it economically outperforms the hydrogen vessels. For hydrogen storage in Portugal and Spain there is one option that outperforms the rest, which is underground hydrogen storage in salt caverns.

7.2.2 Second subquestion
This already touches upon the second sub-question: *Which measures can be taken to support energy security?* The two relevant means to support energy security in this paper are to increase storage capacity or to be open to other suppliers. To assess a country's energy security impacted by hydrogen import this thesis introduced the hydrogen import dependency framework – derived from literature and tailored to this research. The hydrogen import dependency is the way to measure the effect of the measures to support energy security.

7.2.3 Third subquestion
Both the technologically feasible options and the measures to support energy security were input to answer the third sub-question: *Which factors influence the system levelized cost of hydrogen?* The different technological options affect the system levelized costs of hydrogen in their own way and values from literature were used to create the linear economic cost model.

7.2.3 Fourth subquestion
This thesis uses two different performance metrics to assess the performance of the proposed MIGHS. The economic performance is tested as the system levelized cost of hydrogen compared to alternative energy sources. The reference categories used are the current electricity cost and the costs of subsidized wind and solar energy. The political performance of the MIGHS is measured in the hydrogen import dependence. As a reference, the net import dependency of Germany on Russian gas has been taken as an undesired situation. A hydrogen import dependency of zero is seen as ideal since no single country has the power to use a threat of reduced hydrogen supply as a leverage. This way also an answer is provided to the fourth sub-question: *What are the appropriate performance metrics for the hydrogen system design?*

Together those sub-questions form a substantiation to reflect on the impact of the MIGHS on the system levelized cost of hydrogen and import dependence. The outcomes from the economic model resulted in a range from €180 per megawatt hour up to €296 per megawatt hour, depending on the choices that are made regarding the discussed policy levers.

7.3 Academic relevance
This master thesis contributes significantly to the existing literature by addressing several knowledge gaps. Through the utilization of a set of frameworks, the thesis presents a novel model that evaluates various design options for a Maghreb-Iberian Green Hydrogen System. What sets this study apart is its focus on a hydrogen system in this specific geographical area, which had not been thoroughly researched previously. This careful selection of the area allows for the consideration of complex political implications arising in the context of a multinational energy system.

Furthermore, the chosen geographical area already boasts an integrated energy market and utilizes existing energy transport routes, avoiding the inclusion of territories from countries not involved in the energy system. This deliberate demarcation successfully overcomes significant barriers previously identified in other research.

Additionally, this thesis enhances earlier model studies on the Desertec principle by incorporating the critical factor of energy security. In light of the Russian-Ukraine war, the focus has shifted from pure sustainability to encompassing energy security concerns. The proposed approach of hydrogen import dependency introduces a vital political dimension, effectively on the verge of technology and sociology.

As this master thesis expands the scope of existing literature and offers fresh perspectives, it also paves the way for future research endeavors. In light of the findings and insights derived from this study, several fruitful areas for further exploration emerge. Future research could delve deeper into refining the model to address potential limitations and uncertainties. Additionally, investigating the implications of this model on energy security policies in multinational regions and its potential for broader application in different geographical contexts would be valuable extensions to this work. Ultimately, this thesis lays the groundwork for advancing our understanding of sustainable energy systems in the Maghreb-Iberian area and stimulating further research in the field of green hydrogen and energy security.

7.4 Recommendations for future research

In academic research, there are often constraints that limit the scope of a study, forcing the exclusion of certain aspects of interest. In this master thesis, specific research questions were deliberately omitted due to time constraints and workload limitations.

One regrettable omission is the exploration of financing options for the project, which could serve as a valuable follow-up investigation. As the project involves a multinational cooperation spanning multiple countries, understanding the complexities of financing and ensuring a fair distribution of costs and benefits becomes a compelling area of research. Of particular concern is the risk of private investors capturing financial gains that should ideally benefit the African countries, which may lack the financial resources for significant investments.

Additionally, there is potential for expanding the model and frameworks employed in this thesis. Addressing the absence of an integrated energy grid in other regions, which is a key barrier to implementing the Desertec principle, would be a compelling avenue of research. Such an integration could extend the model's applicability to different geographical areas. Furthermore, applying this model to regions where hydrogen-consuming countries already possess integrated energy grids would be an intriguing exploration.

Moreover, refining the model to overcome limitations arising from assumptions and simplifications is a vital challenge. For instance, devising improved methods to estimate the division of expected hydrogen demand across different areas in the Iberian Peninsula would yield more robust and valid results.

Despite these limitations, this master thesis lays the foundation for future research endeavors, presenting potential directions to deepen understanding and advance the field of sustainable energy systems in the Maghreb-Iberian area. The exploration of unexplored research questions and the refinement of existing models hold promise for fostering a greener and more interconnected energy landscape.

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Appendix A: model verification and validation

```
###VERIFICATION by UNIT TESTING###
#Step 1 show the coordinates of Lisbon and Porto
print('the coordinates of Lisbon and Porto are: ',coorddict['Lisbon'], coorddict['Porto'])
#Step 2 show the Euclidean distance based on the coordinates
print('the Euclidean distance based on coordinates is:',sp.euclidean(coorddict['Lisbon'],coorddict['Porto']))
#Step 3 show the conversion from the distance based on coordinates to kilometers
print('this distance converted to kilometers is:',sp.euclidean(coorddict['Lisbon'],coorddict['Porto'])*longlat_to_km, '
#Step 4 show that the costs are calculated by multiplying the costs per km per MWh
print('the pipeline costs are:',int(pipeline_cost1*sp.euclidean(coorddict['Lisbon'],coorddict['Porto'])*longlat_to_km),
#Step 5 show that this is the same as the value attributed to the edge Lisbon-Porto where T1 is the transport 1 scenari
print(G['Lisbon']['Porto']['T1'])

#Step 6 show that the flow through pipeline Lisbon-Porto is 10 MWh
flowCostUT, flowDictUT = nx.network_simplex(G,  demand='D1', weight='T1', capacity='capacity')
print('the flow through Lisbon-Porto is:',flowDictUT['Lisbon']['Porto'], 'MWh')
#Step 7 show that the flowcost are the same as the pipeline costs multiplied by the flow
print('the minimum flow cost in the test case is equal to', flowCostUT, '€')
```

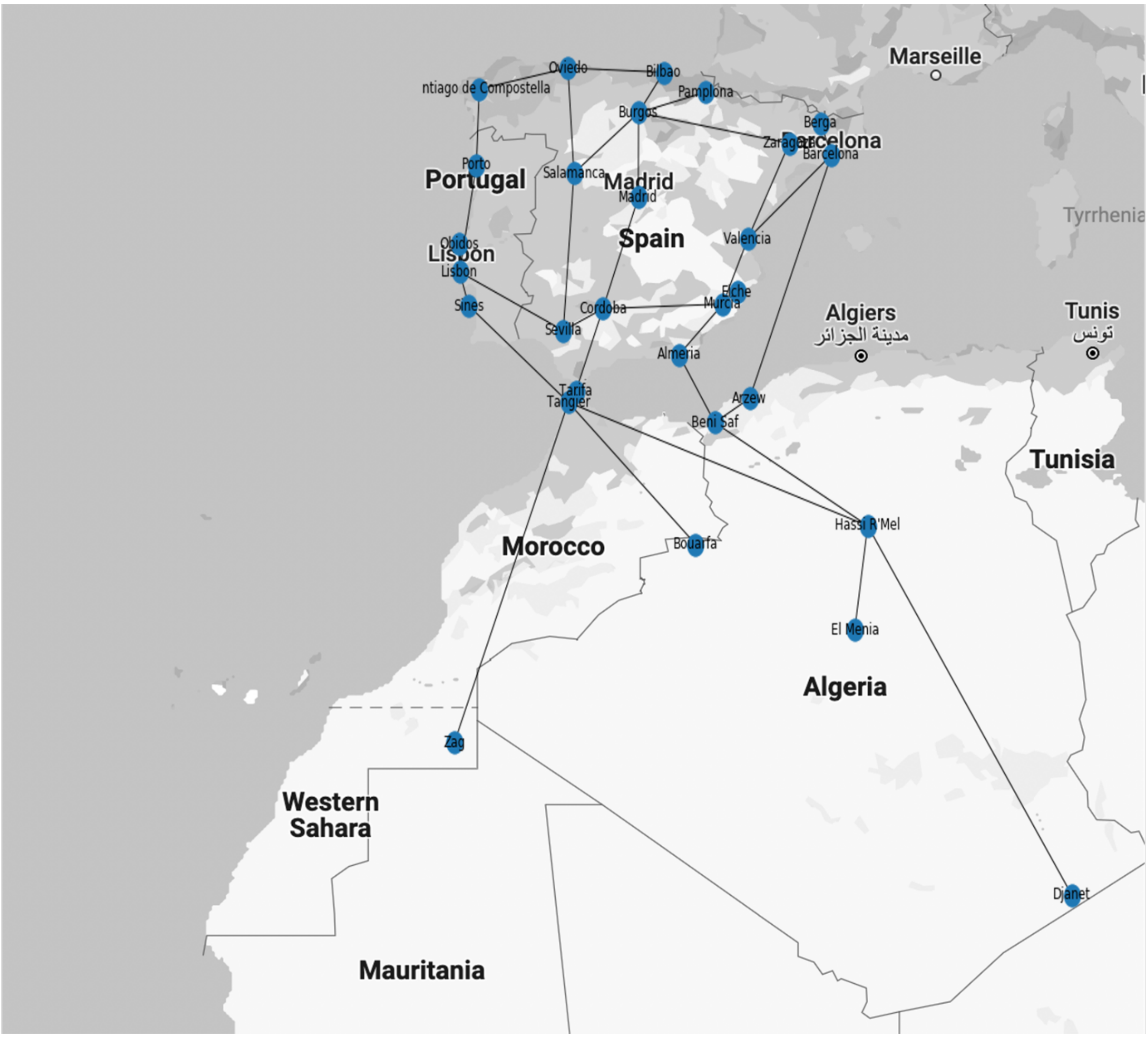
```
the coordinates of Lisbon and Porto are:  (-9.139337, 38.722252000000005) (-8.629105000000001, 41.157944)
the Euclidean distance based on coordinates is: 2.4885602690487487
this distance converted to kilometers is: 276.5760997418089 km
the pipeline costs are: 608 €/MWh
608
the flow through Lisbon-Porto is: 10 MWh
the minimum flow cost in the test case is equal to 6080 €
```

Appendix B: model input

Table X shows a list of the model inputs for the nodes representing the cities implemented in the network. Per city is identified what type of node it represents and what the latitudinal and longitudinal coordinates are. Also it shows the demand under scenario D1, the extra demand that is added per node for the second scenario, and scenario D2 which is the sum of D1 and the extra demand.

City	Type	Latitude	Longitude	D1	Extra	D2
Tarifa	Connector	36.012711	-5.602950	0	0	0
Sevilla	Industry	37.389091	-5.984459	12800	8500	21300
Cordoba	City	37.888176	-4.779383	0	8500	8500
Sines	Connector	37.954670	-8.864520	0	0	0
Lisbon	Industry	38.722252	-9.139337	8000	8500	16500
Obidos_out	Storage	39.360420	-9.158201	0	0	0
Obidos_in	Storage	39.360420	-9.158201	0	0	0
Porto	Industry	41.157944	-8.629105	8000	8500	16500
Santiago de Compostella	City	42.880619	-8.546610	0	8500	8500
Oviedo	Industry	43.360279	-5.844790	12800	8500	21300
Salamanca	City	40.970104	-5.663540	0	8500	8500
Bilbao	Industry	43.263012	-2.934985	12800	8500	21300
Burgos	City	42.343990	-3.696906	0	8500	8500
Pamplona_out	Storage	42.812527	-1.645774	0		0
Pamplona_in	Storage	42.812527	-1.645774	0		0
Madrid	Industry	40.416775	-3.703790	12800	8500	21300
Almeria	Connector	36.840092	-2.467900	0		0
Murcia	City	37.992241	-1.130654	0	8500	8500
Elche_out	Storage	38.267208	-0.695220	0		0
Elche_in	Storage	38.267208	-0.695220	0		0
Valencia	City	39.470242	-0.376800	0	8500	8500
Barcelona	Industry	41.385063	2.173404	12800	8500	21300
Zaragoza	City	41.648823	0.889085	0	8500	8500
Berga_out	Storage	42.101540	1.843810	0		0
Berga_in	Storage	42.101540	1.843810	0		0
Tangier	Connector	35.759464	-5.833954	0		0
Arzew	Connector	35.848780	-0.317360	0		0
Beni Saf	Connector	35.298080	-1.378710	0		0
Hassi R'Mel	Connector	32.951900	3.273700	0		0
Bouarfa	Producer	32.531490	-1.960500	-40000		-99500
Zag	Producer	28.029030	-9.295580	0		0
El Menia	Producer	30.579920	2.880410	-40000		-99500
Djanet	Producer	24.553921	9.485070	0		0

Appendix C: Model layout



Appendix D: model code

In [67]:

```
# Import Libraries
%matplotlib inline
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import networkx as nx
import scipy.spatial.distance as sp
```

In [68]:

```
# Read in the excel file 'nodes.xlsx' as a dataframe
city_properties = pd.read_excel(r'/Users/tijmensteensma/Documents/TM/Exp2.xlsx')
# Show contents of the dataframe
#city_properties
# Read in the excel file 'edges.xlsx' as a dataframe
pipe_properties = pd.read_excel(r'/Users/tijmensteensma/Documents/TM/edgesExp2.xlsx
')
# Show contents of the dataframe
#pipe_properties
```

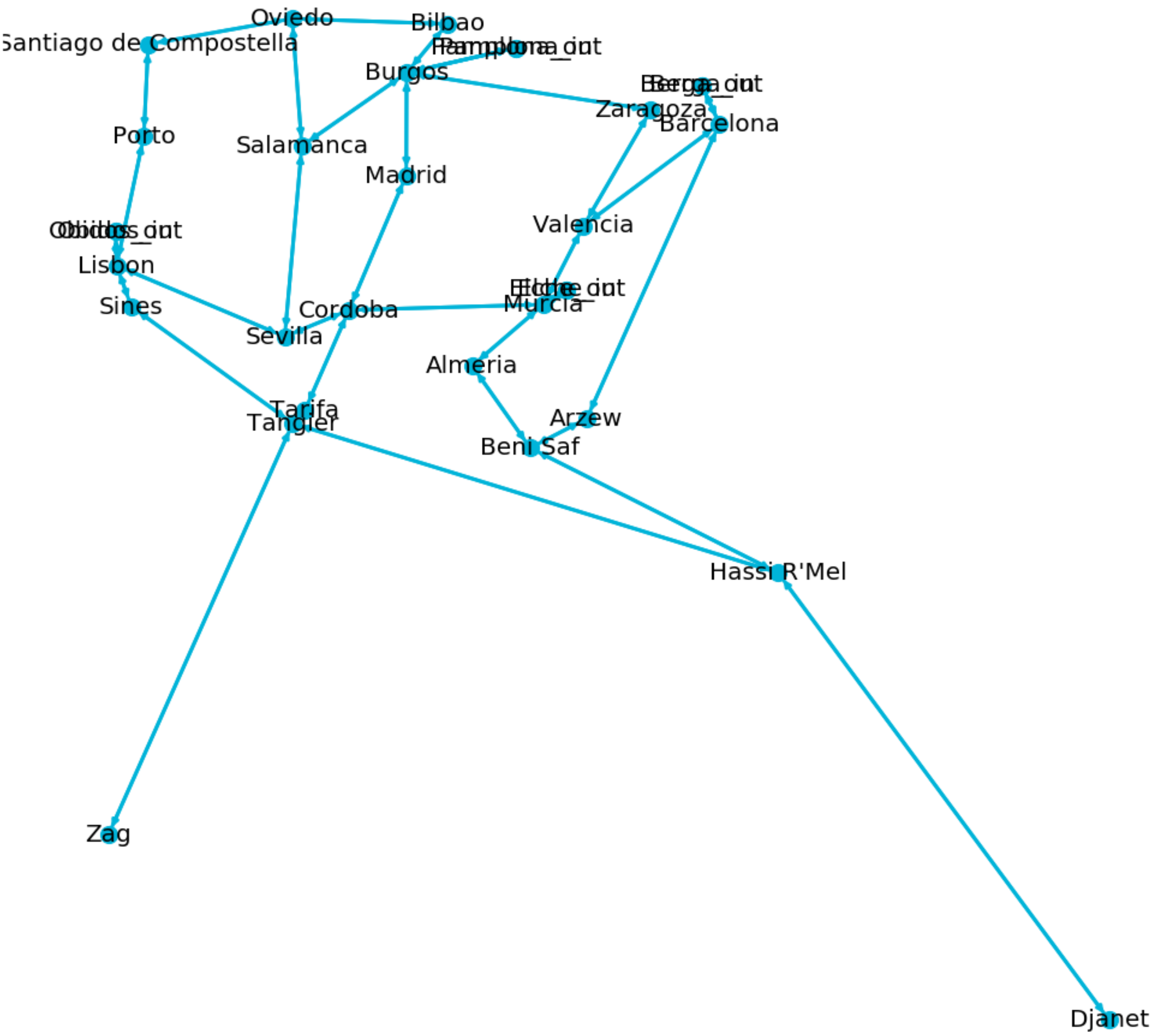
In [69]:

```
#Make graph just to have a list for the edges
MIGHS_Graph=nx.from_pandas_edgelist(pipe_properties, 'From', 'To', create_using=nx.
Graph)
```

In [70]:

```
#make a list of the cities
cities = []
for c in city_properties['City']:
    cities.append(c)


#make a list for latitude and longitude


latitude = []
for lat in city_properties['Latitude']:
    latitude.append(lat)
#print(latitude)


longitude = []
for lon in city_properties['Longitude']:
    longitude.append(lon)
```

```
#print(longitude)

#make a list for the demand for each scenario
demand1 = []
for d in city_properties['D1']:
    demand1.append(d)

demand2 = []
for d in city_properties['D2']:
    demand2.append(d)

#create a dictionary for the coordinates
coorddict = {}
for i in range(len(cities)):
    coorddict[cities[i]] = longitude[i], latitude[i]

#make a new graph G with coordinates
G = nx.DiGraph()

# create new graph with pos as coordinates and D1 as demand1
n=0
for i in coorddict:
    G.add_node(i, pos=(coorddict[i]), D1 = demand1[n], D2 = demand2[n])
    n = n + 1

#set the edges in both ways because it is a directional graph. Capacity needed for N
SM.
for i, j in MIGHS_Graph.edges:
    G.add_edge(i,j, capacity=400000000)
    G.add_edge(j,i, capacity=400000000)

#Plot the figure a bit bigger than normal and with a transparent background
plt.figure(figsize=(14,14))
nx.draw(G, nx.get_node_attributes(G, 'pos'), with_labels=True , node_size=200, node
_color='#00b4d9', width=3, edge_color='#00b4d9', font_size=20)
#plt.savefig('15July1518.png', transparent=True)
```



In [71]:

```
#define cost parameters
pipeline_cost1 = 22.21 # €/GWh/year/km
pipeline_cost2 = 40.30
pipeline_cost3 = 107.88
longlat_to_km = 111.139 #how to convert coordinates to kilometers

#costs are pipeline_costs €/km/kg * km -> capacity will be calculated

#Make variable that reflects system size#
```

```
System_size1 = 80 #D1 80 TWh/year
System_size2 = 200 #D2 200 TWh/year

#Define Level of Security for D1 and D2
LoS1_D1 = 0.7*System_size1/2
LoS2_D1 = 0.8*System_size1/2
LoS3_D1 = 0.9*System_size1/2

LoS1_D2 = 0.7*System_size2/2
LoS2_D2 = 0.8*System_size2/2
LoS3_D2 = 0.9*System_size2/2

#add costs to edges, define 3 cost scenarios
for i, j in G.edges:
    G[i][j]['T1'] = int(pipeline_cost1*sp.euclidean(coorddict[i],coorddict[j])*long
lat_to_km)
    G[i][j]['T2'] = int(pipeline_cost2*sp.euclidean(coorddict[i],coorddict[j])*long
lat_to_km)
    G[i][j]['T3'] = int(pipeline_cost3*sp.euclidean(coorddict[i],coorddict[j])*long
lat_to_km)




#showcase the costs of transporting 1 MWh hydrogen from Lisbon to Porto
#print(G['Lisbon']['Porto']['T1'], '€ / MWh')



###VERIFICATION by UNIT TESTING###
#Step 1 show the coordinates of Lisbon and Porto
print('the coordinates of Lisbon and Porto are: ',coorddict['Lisbon'], coorddict['P
orto'])
#Step 2 show the Euclidean distance based on the coordinates
print('the Euclidean distance based on coordinates is:',sp.euclidean(coorddict['Lis
bon'],coorddict['Porto']))
#Step 3 show the conversion from the distance based on coordinates to kilometers
print('this distance converted to kilometers is:',sp.euclidean(coorddict['Lisbon'],
coorddict['Porto'])*longlat_to_km, 'km')
#Step 4 show that the costs are calculated by multiplying the costs per km per MWh
print('the pipeline costs are:',int(pipeline_cost1*sp.euclidean(coorddict['Lisbon']
,coorddict['Porto'])*longlat_to_km), '€/MWh')
#Step 5 show that this is the same as the value attributed to the edge Lisbon-Porto
where T1 is the transport 1 scenario
print(G['Lisbon']['Porto']['T1'])
```

```
#Step 6 show that the flow through pipeline Lisbon-Porto is 10 MWh

flowCostUT, flowDictUT = nx.network_simplex(G,  demand='D1', weight='T1', capacity=
'capacity')

print('the flow through Lisbon-Porto is:',flowDictUT['Lisbon']['Porto'], 'MWh')

#Step 7 show that the flowcost are the same as the pipeline costs multiplied by the
flow

print('the minimum flow cost in the test case is equal to', flowCostUT, '€')
```

the coordinates of Lisbon and Porto are: (-9.139337, 38.722252000000005) (-8.629105000000001, 41.157944)
the Euclidean distance based on coordinates is: 2.4885602690487487
this distance converted to kilometers is: 276.5760997418089 km
the pipeline costs are: 6142 €/MWh
6142
the flow through Lisbon-Porto is: 8000 MWh
the minimum flow cost in the test case is equal to 3976904000 €
In [72]:

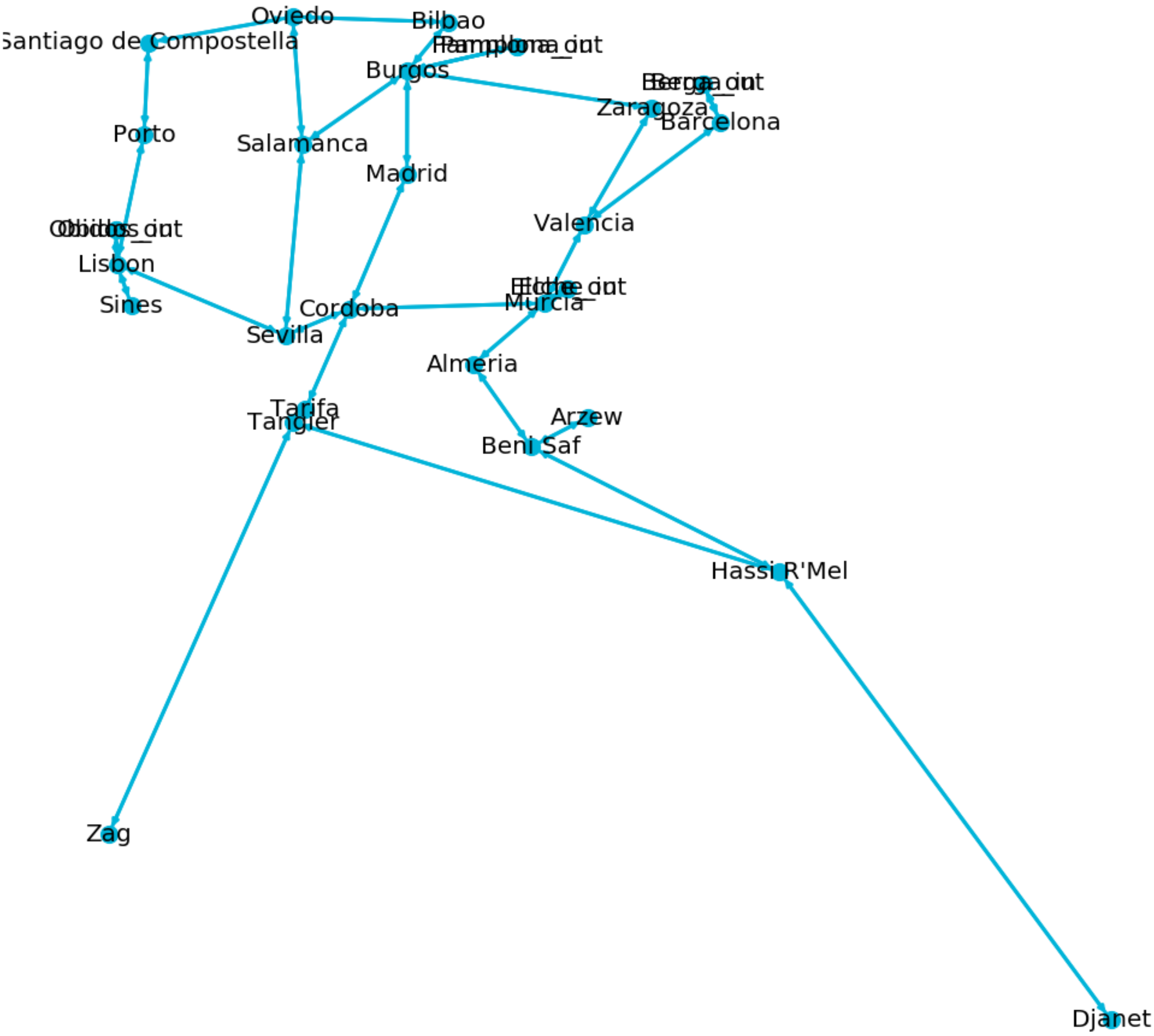
```
#Calculate the minimum flow cost using the Network Simplex Method


#flowCost, flowDict = nx.network_simplex(G,  demand='D1', weight='T1', capacity='ca
pacity')

#print(flowCost)
```

3976904000
In [73]:

```
### PIPELINE TRANSPORT OPTIONS 1,2,3 #### SHIPPING ROUTES REMOVED


G1 = G.copy()

#remove shipping routes for T1, T2 and T3

shipping_routes = [('Tangier', 'Sines'), ('Arzew', 'Barcelona'), ('Sines','Tangier'
), ('Barcelona','Arzew')]

G1.remove_edges_from(shipping_routes)


#D1 and T1

flowCost1, flowDict1 = nx.network_simplex(G1,  demand='D1', weight='T1', capacity='
capacity')

print('the CAPEX for transport under D1 and T1 are: €',flowCost1)

#D1 and T2

flowCost2, flowDict2 = nx.network_simplex(G1,  demand='D1', weight='T2', capacity='
capacity')

print('the CAPEX for transport under D1 and T2 are: €',flowCost2)

#D1 and T3

flowCost3, flowDict3 = nx.network_simplex(G1,  demand='D1', weight='T3', capacity='
capacity')

print('the CAPEX for transport under D1 and T3 are: €',flowCost3)

#D2 and T1
```

```
flowCost4, flowDict4 = nx.network_simplex(G1,  demand='D2', weight='T1', capacity='capacity')

print('the CAPEX for transport under D2 and T1 are: €',flowCost4)

#D2 and T2

flowCost5, flowDict5 = nx.network_simplex(G1,  demand='D2', weight='T2', capacity='capacity')

print('the CAPEX for transport under D2 and T2 are: €',flowCost5)

#D2 and T3

flowCost6, flowDict6 = nx.network_simplex(G1,  demand='D2', weight='T3', capacity='capacity')

print('the CAPEX for transport under D2 and T3 are: €',flowCost6)


plt.figure(figsize=(14,14))

nx.draw(G1, nx.get_node_attributes(G1, 'pos'), with_labels=True , node_size=200, node_color='#00b4d9', width=3, edge_color='#00b4d9', font_size=20)
```

the CAPEX for transport under D1 and T1 are: € 4117137600
the CAPEX for transport under D1 and T2 are: € 7470662400
the CAPEX for transport under D1 and T3 are: € 19998638400
the CAPEX for transport under D2 and T1 are: € 9965129100
the CAPEX for transport under D2 and T2 are: € 18081977400
the CAPEX for transport under D2 and T3 are: € 48404686400



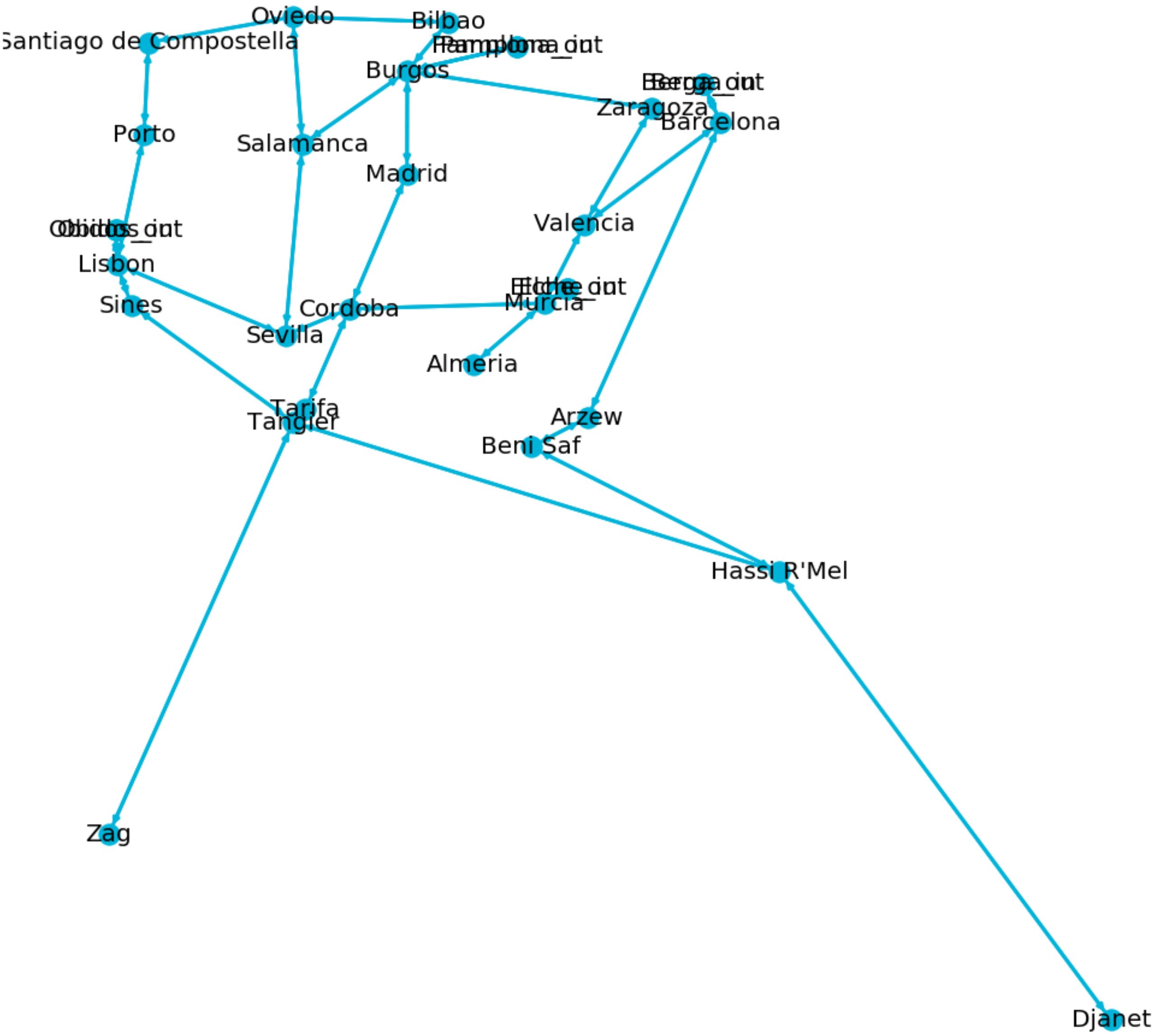
In [66]:

```
### SHIPPING ROUTE OPTION ####

G2 = G.copy()

#remove shipping routes for T1, T2 and T3

overseas_pipelines = [('Tangier', 'Tarifa'), ('Beni Saf', 'Almeria'), ('Tarifa','Ta
ngier'), ('Almeria','Beni Saf')]

G2.remove_edges_from(overseas_pipelines)



### Overseas overcost
```

```
CAPEX_T1_Sea = 0.25*int(pipeline_cost1*sp.euclidean(coorddict['Tangier'],coorddict['Tarifa'])*longlat_to_km)*40000+0.25*int(pipeline_cost1*sp.euclidean(coorddict['Beni Saf'],coorddict['Almeria'])*longlat_to_km)*40000

CAPEX_T2_Sea = 0.25*int(pipeline_cost2*sp.euclidean(coorddict['Tangier'],coorddict['Tarifa'])*longlat_to_km)*40000+0.25*int(pipeline_cost2*sp.euclidean(coorddict['Beni Saf'],coorddict['Almeria'])*longlat_to_km)*40000

CAPEX_T3_Sea = 0.25*int(pipeline_cost3*sp.euclidean(coorddict['Tangier'],coorddict['Tarifa'])*longlat_to_km)*40000+0.25*int(pipeline_cost3*sp.euclidean(coorddict['Beni Saf'],coorddict['Almeria'])*longlat_to_km)*40000


print(CAPEX_T1_Sea, CAPEX_T2_Sea, CAPEX_T3_Sea)


CAPEX_T4_D1 = int(1350000*80000)

CAPEX_T4_D2 = int(1350000*200000)




### ONLY FOR T2 ###

#D1 and T4

#flowCost7, flowDict7 = nx.network_simplex(G2,  demand='D1', weight='T2', capacity='capacity')

#print(flowCost7+CAPEX_T4_D1)

#D1 and T5

#flowCost7, flowDict7 = nx.network_simplex(G2,  demand='D1', weight='T3', capacity='capacity')

#print(flowCost7+CAPEX_T4_D1)


#D2 and T4

#flowCost8, flowDict8 = nx.network_simplex(G2,  demand='D2', weight='T2', capacity='capacity')

#print(flowCost8+CAPEX_T4_D2)


#D2 and T5

#flowCost8, flowDict8 = nx.network_simplex(G2,  demand='D2', weight='T3', capacity='capacity')

#print(flowCost8+CAPEX_T4_D2)


#plt.figure(figsize=(14,14))

#nx.draw(G2, nx.get_node_attributes(G2, 'pos'), with_labels=True , node_color='#00b4d9', width=3, edge_color='#00b4d9', font_size=20)


print(CAPEX_T4_D1,'D1')

print(CAPEX_T4_D2,'D2')

#SHIPPING COSTS
```

55060000.0 99900000.0 267440000.0
108000000000 D1

270000000000 D2



In [49]:

```
###VERIFICATION by UNIT TESTING###

#Step 1 show the coordinates of Lisbon and Porto

print('the coordinates of Lisbon and Porto are: ',coorddict['Lisbon'], coorddict['P
orto'])

#Step 2 show the Euclidean distance based on the coordinates

print('the Euclidean distance based on coordinates is:',sp.euclidean(coorddict['Lis
bon'],coorddict['Porto']))

#Step 3 show the conversion from the distance based on coordinates to kilometers

print('this distance converted to kilometers is:',sp.euclidean(coorddict['Lisbon'],
coorddict['Porto'])*longlat_to_km, 'km')
```

```
#Step 4 show that the costs are calculated by multiplying the costs per km per MWh

print('the pipeline costs are:',int(pipeline_cost1*sp.euclidean(coorddict['Lisbon']
,coorddict['Porto'])*longlat_to_km), '€/MWh')

#Step 5 show that this is the same as the value attributed to the edge Lisbon-Porto
where T1 is the transport 1 scenario

print(G['Lisbon']['Porto']['T1'])



#Step 6 show that the flow through pipeline Lisbon-Porto is 10 MWh

flowCostUT, flowDictUT = nx.network_simplex(G,  demand='D1', weight='T1', capacity=
'capacity')

print('the flow through Lisbon-Porto is:',flowDictUT['Lisbon']['Porto'], 'MWh')

#Step 7 show that the flowcost are the same as the pipeline costs multiplied by the
flow

print('the minimum flow cost in the test case is equal to', flowCostUT, '€')
```

the coordinates of Lisbon and Porto are: (-9.139337, 38.722252000000005) (-8.629105000000001, 41.157944)
the Euclidean distance based on coordinates is: 2.4885602690487487
this distance converted to kilometers is: 276.5760997418089 km
the pipeline costs are: 6142 €/MWh
6142
the flow through Lisbon-Porto is: 8000 MWh
the minimum flow cost in the test case is equal to 4176604000 €
In [50]:

```
#Printing results directly

#D1 and T1

flowCost1, flowDict1 = nx.network_simplex(G1,  demand='D1', weight='T1', capacity='
capacity')

#D1 and T2

flowCost2, flowDict2 = nx.network_simplex(G1,  demand='D1', weight='T2', capacity='
capacity')

#D1 and T3

flowCost3, flowDict3 = nx.network_simplex(G1,  demand='D1', weight='T3', capacity='
capacity')

#D2 and T1

flowCost4, flowDict4 = nx.network_simplex(G1,  demand='D2', weight='T1', capacity='
capacity')

#D2 and T2

flowCost5, flowDict5 = nx.network_simplex(G1,  demand='D2', weight='T2', capacity='
capacity')

#D2 and T3

flowCost6, flowDict6 = nx.network_simplex(G1,  demand='D2', weight='T3', capacity='
capacity')



#print(flowCost1, flowCost2, flowCost3, flowCost4, flowCost5, flowCost6, flowCost7,
flowCost8)
```

Appendix E: Assumptions

	category	assumption		Source
	Wind / solar mix	55 / 45	%	(Heide et al., 2010)
	Battery / electrolysis	20 / 60	MW	(Runzhao et al., 2023)
Alkaline electrolysis	CAPEX	1000	€/kW	(Chi & Yu, 2018)
	Lifetime	7	years	(Chi & Yu, 2018)
	Efficiency	60	%	(IREA, 2020)
Portugal	Energy consumption	49	TWh/year	enerdata.net
	Industry energy use	16	TWh/year	
	Domestic energy production	15	TWh/year	
	Energy import	34	TWh/year	
Spain	Energy consumption	235	TWh/year	
	Industry energy use	63	TWh/year	
	Domestic energy production	71	TWh/year	
	Energy import	164	TWh/year	
Alkaline electrolysis	CAPEX	1	bln€/GW	(Grigoriev et al., 2020).
	lifetime	7	years	
	Opex	2,5	%CAPEX/year	
	CAPEX	2,3	bln€/GW	
	lifetime	10	years	
	Opex	1	%CAPEX/year	
Solar power	Lifetime	30	Years	(Kaltschmitt et al., 2020).
	CAPEX	0,64	bln €/GW	
	OPEX	1,3	%CAPEX/year	
Wind power	Lifetime	20	Years	
	CAPEX	1,33	bln €/GW	
	OPEX	1,1	%CAPEX/year	
Portugal	Energy consumption	49	TWh/year	enerdata.net
	Industry energy use	16	TWh/year	
	Domestic energy production	15	TWh/year	

	Energy import	34	TWh/year	
Spain	Energy consumption	235	TWh/year	
	Industry energy use	63	TWh/year	
	Domestic energy production	71	TWh/year	
	Energy import	164	TWh/year	
Alkaline electrolysis	CAPEX	1	bln€/GW	(Grigoriev et al., 2020).
	lifetime	7	years	
	Opex	2,5	%CAPEX/year	
	CAPEX	2,3	bln€/GW	
	lifetime	10	years	
	Opex	1	%CAPEX/year	
Solar power	Lifetime	30	Years	(Kaltschmitt et al., 2020).
	CAPEX	0,64	bln €/GW	
	OPEX	1,3	%CAPEX/year	
Wind power	Lifetime	20	Years	
	CAPEX	1,33	bln €/GW	
	OPEX	1,1	%CAPEX/year	
Storage	Capex	€54.000.000	per GWh	(Linssen et al., 2020).
	Capacity Portugal	5000	TWh	
	Capacity spain	1000	TWh	
	Electricity costs	€0,11/kWh		