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Green hydrogen supply chain optimization: A game theory approach

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Abstract

Green hydrogen has gained significant attention as a key player in decarbonizing the energy sector. However, the availability of renewable resources varies across regions, creating an imbalance between countries with abundant green hydrogen potential and those with limited production capabilities. The international trade of green hydrogen offers a promising solution to address this disparity, fostering collaboration and optimization in the EU-North Africa context.

This thesis focuses on optimizing the green hydrogen supply chain between the European Union (EU) and North Africa, considering the unique opportunities and challenges presented by this cross-continental partnership. A game theory approach is employed to model the interactions and strategic decision-making of stakeholders involved in the green hydrogen market.

By analyzing factors such as production costs, transportation methods, and market dynamics, the thesis aims to design an efficient and economically viable green hydrogen supply chain between the EU and North Africa. The optimization model explores various scenarios, considering different supplier countries in North Africa and assessing the impact of pricing, competition, and market conditions on the overall system. Through a game theory approach and through the comparison with other modelling strategies, it provides valuable insights into market dynamics, and the opportunities for collaboration and trade between these regions.

Acknowledgement

First and foremost, I would like to extend my deepest gratitude to Davide Tonelli for his unwavering support and guidance throughout the entire duration of this thesis. I am very grateful for his constant availability and assistance, as well as his invaluable input in setting and meeting the necessary deadlines to achieve the objectives of this work.

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Contents

Abstract **1**

Acknowledgement **2**

1 Introduction **9**
1.1 Context . . . 9
1.2 Research question . . . 12
1.3 Thesis outline . . . 12

2 Methodology **13**
2.1 Use of AI . . . 13
2.2 Assumptions . . . 13
2.3 Data . . . 14
2.3.1 Land connections . . . 14
2.3.2 Sea connections . . . 15
2.3.3 Land distances . . . 17
2.3.4 Sea distances . . . 17
2.3.5 Demand . . . 18
2.3.6 Levelized Cost of Hydrogen (LCOH) . . . 19
2.3.7 Supply . . . 21
2.3.8 Technologies comparison . . . 22
2.4 Models . . . 23

3 Global optimum **25**
3.1 Model description . . . 25
3.1.1 Competitivity definition . . . 25
3.1.2 Sets . . . 26
3.1.3 Parameters . . . 26
3.1.4 Decision variables . . . 26
3.1.5 Constraints . . . 27
3.1.6 Objective function . . . 28
3.2 Results . . . 29
3.2.1 Set of countries . . . 29
3.2.2 Single objective . . . 30
3.2.3 Bi-objective . . . 32

4 Game theory model **37**
4.1 Model description . . . 38
4.1.1 Sets . . . 38
4.1.2 Parameters . . . 39
4.1.3 Decision variable . . . 39
4.1.4 Constraints . . . 39
4.1.5 Objective functions . . . 39
4.1.6 Penalties costs definition . . . 39
4.1.7 Monetization . . . 42
4.1.8 Gurobi implementation . . . 43
4.2 Results . . . 45
4.2.1 Simplified case . . . 45
4.2.2 9 countries study case . . . 46

5 Discussion **59**
5.1 Models comparison . . . 59
5.1.1 Game theory vs Global optimum . . . 59
5.1.2 Allocation comparison . . . 60
5.2 Models limitations . . . 63

6 Conclusion and perspectives **65**
6.1 Summary . . . 65
6.2 Perspectives . . . 67

A Game theory: EU27 **70**

B Game theory: World **71**

C Instabilities **73**

List of Figures

1.1 Number of policies to support hydrogen demand creation by sector, 2021-2022 from [1] . . . 10
1.2 CCUS = carbon capture, utilisation and storage. GHR 2021 = Global Hydrogen Review 2021. Source from [1] . . . 11
1.3 Hydrogen production costs from hybrid solar PV and wind systems for a minimum load of 40%, 2030. Source from [1] . . . 11
1.4 Uncertainty regarding future hydrogen demand and European targets. Source from [9] . . . 12

2.1 Worldwide map of the land connected countries. Darker blue is associated to a larger number of land connected countries . . . 14
2.2 Land connection distribution trend worldwide . . . 15
2.3 Green: a possible pipeline, red: no land connection. . . . 15
2.4 Worldwide map of the sea connected countries. Darker blue is associated to sea connected countries . . . 16
2.5 Worldwide map of the mean distances between countries . . . 17
2.6 Worldwide map of the green hydrogen national demand distribution. Data assessed from [2] and [8] . . . 18
2.7 Correlation between GDP and Hydrogen projected demand in 2050. Stronger correlation for countries with higher GDP. . . . 19
2.8 Countries have a widely distributed LCOH among the world. European mean LCOH . . . 20
2.9 LCOH distribution worldwide with mean at 59.6€/MWh . . . 20
2.10 Potential of supply worldwide (a_i). Europe has a low potential while North Africa is among the biggest potential supplier worldwide . . . 21
2.11 Projected hydrogen demand and supply comparison between continent in TWh/y in 2050 . . . 22
2.12 Analysis from the IEA 2022 report [1] showcases the varying impact of transportation technologies on Levelized Cost of Heat (LCOH), as depicted by the accompanying graph . . . 23

3.1 Distribution of availability and demand among selected countries . . . 29
3.2 Cost of production variation among selected countries . . . 29
3.3 Global cost variation with competitivity in between western Europe and North Africa . . . 30
3.4 Global cost per MWh of hydrogen produced vs competitivity for single objective Global optimum modelling . . . 31
3.5 Global cost per MWh of hydrogen transported vs competitivity for single objective Global optimum modelling . . . 31

3.6 Scenarios for single Objective global optimum model: map of the transportations flows and production regions 31
3.7 Cost per unit energy vs. competitivity for different weight values 33
3.8 Produced energy vs. competitivity for different weight values 33
3.9 Relationship between weight of unmet demand and hydrogen production and transportation. A focus is brought to the eye with the 2 plots on the right side emphasizing the steps of the production cost. 34
3.10 Hydrogen flows for different competitivity values (0.1, 1, 2, and 5) for the bi-objective function model with c=3.547 35
3.11 Hydrogen flows for different competitivity values (0.1, 1, 2, and 5) for the bi-objective function model with c=3.7 35

4.1 Visualization of a 3 players gain matrix (3 dimensional) 43
4.2 Convergence for different values of competitivity for the fully implemented game theory model. Taking a set of n=1000 strategies seems a justified choice. 44
4.3 G_{i2}, 3 countries, 3 strategies simplified case gain matrix 45
4.4 G_{i3}, 3 countries, 3 strategies simplified case gain matrix 45
4.5 G_{i2}+G_{i3}, 3 countries, 3 strategies simplified case gain matrix 46
4.6 Cost of under utilization analysis vs competitivity on the left and ressources allocation associated on the market on the right hand side graph 47
4.7 Cost of dissatisfaction analysis with competitivity increase and ressources allocation solution 47
4.8 Cost of creating restrictions on opponents analysis with competitivity increase and ressources allocation solution 48
4.9 Cost of creating conflicts on opponents analysis with competitivity increase and ressources allocation solution 49
4.10 Combination of every introduced costs. OMSI: Overall Mean Spline Interpolated 50
4.11 The mean value for LCOH and G_{ratio} was taken for a range of competitivity from 0.1 to 10 divided through 30 points. Each point corresponds at the mean for the 9 countries over this range. 52
4.12 The graphs are compiled from 20 different c_z values, ranging from 0.5 to 10 53
4.13 LCOH analysis for different values of c_z. We observe that the global trend OMSI (overall mean spline interpolation) has globally the same shape. . . 54
4.14 Per component analysis of the game theory model and the allocation associated to it for $c_z = 1$ 54
4.15 The competitivity points were distributed using a combination of logarithmic and linear spacing, totaling 170 points. This distribution was chosen to ensure a comprehensive representation of the studied dynamics. 55
4.16 The countries with zero allocation have been removed for the clarity of the graph. The rolling mean (wide line) aim to underline the two mains actors of the studied dynamics: Algeria and Belgium. 56
4.17 Market flows for low importance on the weight (c_z) for the cost compared to the competition aspect ($\sum G_i$) 57
4.18 Market flows for balanced importance on the weight (c_z) for the cost compared to the competition aspect ($\sum G_i$) 58

4.19 Market flows for high importance on the weight (c_z) for the cost compared to the competition aspect ($\sum G_i$) 58

5.1 Models comparison for wide competitivity range. The difference between GO. and GT. is well marked and leads to more realism in monetization of GT. 60
5.2 Flows comparison between single and GT model for competitivity=1. . . 62
5.3 Flows comparison between single and GT model for competitivity=5. . . 62

A.1 Map of the EU27 countries production and transportation flows for different levels of competitivity. 70

B.1 Worldwide map of the countries production and transportation flows for different levels of competitivity. 71

C.1 Instabilities in the allocation for different competitivities with the focus on Germany (in red) 73

List of Tables

3.1 Data sets used for the global optimum modelling. A set of two technologies are considered. Liquid hydrogen and NH_3 for ship transportation 26
3.2 Parameters used in the global optimum model. All units refer to values per year 26
3.3 Decision variables used in the global optimum model. All units refer to values per year 27

4.1 Table of the data sets used in the game theory model 38
4.2 Parameters used in the game theory model. All units refer to values per year 39
4.3 Allocation to countries i. This corresponds to the sum of the production plus the importations minus the exportation corresponding to the global optimum model 39

Chapter 1

Introduction

1.1 Context

Climate change has emerged as one of the most pressing concerns in contemporary society. To address this global challenge, a collaborative effort is required from individuals, businesses, and governments. Transitioning to renewable energy sources, prioritizing energy efficiency, implementing effective policies to reduce greenhouse gas emissions, conserving and restoring natural ecosystems, adopting sustainable agricultural practices, and increasing public awareness and education are some of the effective ways to mitigate the impact of climate warming. By adopting a multifaceted approach and working together, we can successfully combat climate change and limit its adverse effects on our planet and society.

Hydrogen has been identified among the solutions to achieve the net-zero target. In particular, IRENA[1] indicates that hydrogen and its derivatives will contribute to abate 3.7 Gt of CO2 emissions per year by 2050[3]. From a technical point of view, hydrogen could be used across a wide range of sectors:

- Transportation: In the context of the green hydrogen modeling competition, the transportation of hydrogen resources encompasses diverse modalities, including land-based options such as trucks and trains, as well as maritime transport via ships, and even aviation.
- Energy storage: Hydrogen can be stored for long periods, making it a viable option for storing renewable energy and balancing the electricity grid.
- Industry: Hydrogen can be used as a feedstock in various industrial processes, including steel and cement production, where it can replace fossil fuels and reduce emissions.
- Heating and cooling: Hydrogen can be used for space and water heating in buildings and to power cooling systems as it utilizes hydrogen as a coolant to dissipate heat.
- Power generation: Hydrogen can be used to generate electricity in fuel cells and gas turbines for power production, providing a clean and reliable source of energy.

The practical implementation of hydrogen goes beyond its technical possibilities and relies on evaluating its efficiency and cost-effectiveness. These factors play a crucial role

[1]The International Renewable Energy Agency

in determining the widespread adoption and utilization of hydrogen in various applications and industries.

The two main methods for hydrogen production are Steam Methan Reforming (SMR) and Electrolysis. SMR is for now the most common method of producing hydrogen, accounting for the majority of global production. It involves reacting natural gas with steam to produce hydrogen and carbon dioxide. Electrolysis, on the other side, may be considered as a way cleaner method for hydrogen production since electricity may be generated from renewable. In this case we speak of green hydrogen.

Green hydrogen is produced using renewable energy sources, typically by using electrolysis. Because it is produced without any emissions, green hydrogen has the potential to play a significant role in decarbonizing various sectors of the economy.

As green hydrogen production becomes more widespread, its uses are expected to grow and diversify. It has the potential to play a key role in reducing greenhouse gas emissions and transitioning to a cleaner, more sustainable energy system. As we can observe in figure 1.1, there is an increasing of policies involved in hydrogen regulations. This begin an important factor of how this resource takes a more important place in the huge global energy market.

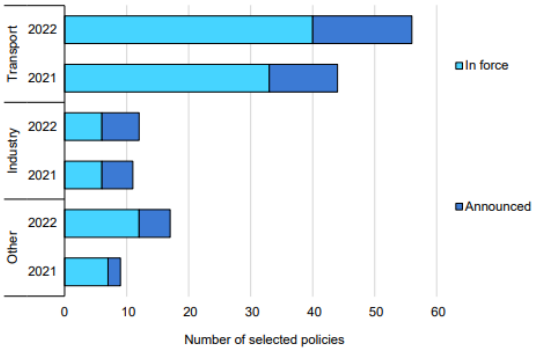


Figure 1.1: Number of policies to support hydrogen demand creation by sector, 2021-2022 from [1]

Our work here will then focus green hydrogen since this is the most effective way of production in the climate mitigation. As the demand for hydrogen grows and the world transitions to a low-carbon energy system, there is increasing interest in developing and scaling up the production of green hydrogen.

In 2021, there was a notable acceleration in the implementation of select hydrogen technologies, particularly in the area of electrolysis. The deployment of electrolysis saw a record-breaking year, with over 200 MW of additional installed capacity, marking a three-fold increase from the previous record set in 2020. This has resulted in a total operational capacity of over 500 MW as described by the International Energy Agency. [1]. The forecasts of the projected production are shown in figure 1.2.

In this context a new economy is being born. Indeed, as green hydrogen develops on the market, it is necessary to ensure that it is competitive with other production methods. According to the IEA, hydrogen production costs could fall below USD 1.5/kg H2 by 2030 in regions with exceptional renewable resources for electricity generation, provided operational requirements are met to ensure a more consistent and reliable hydrogen supply.

This new market will see different actors based on their geographical position. Indeed,

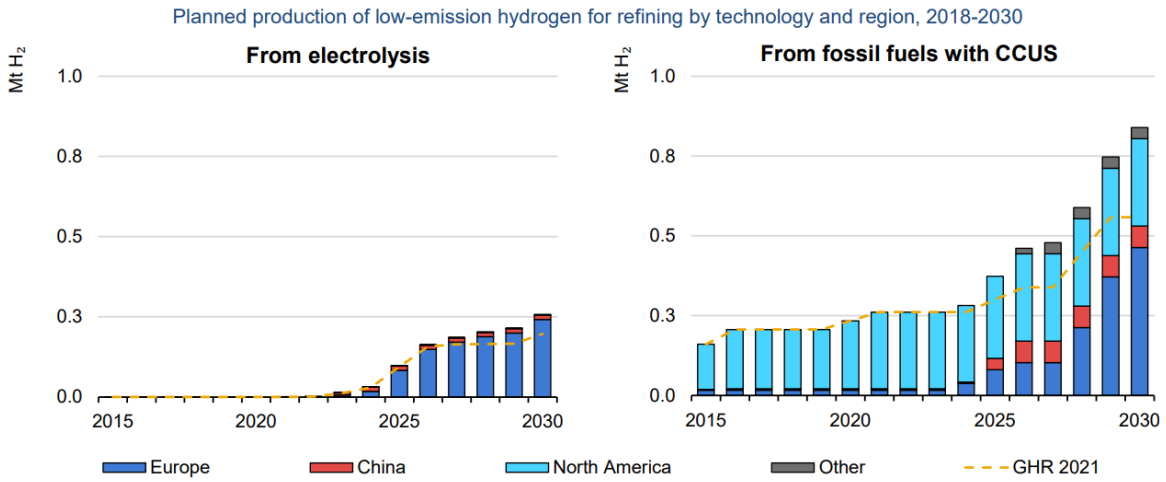


Figure 1.2: CCUS = carbon capture, utilisation and storage. GHR 2021 = Global Hydrogen Review 2021. Source from [1]

as based on renewables, the potential of green hydrogen production varies from a region to another as shown on the following map in figure 1.3

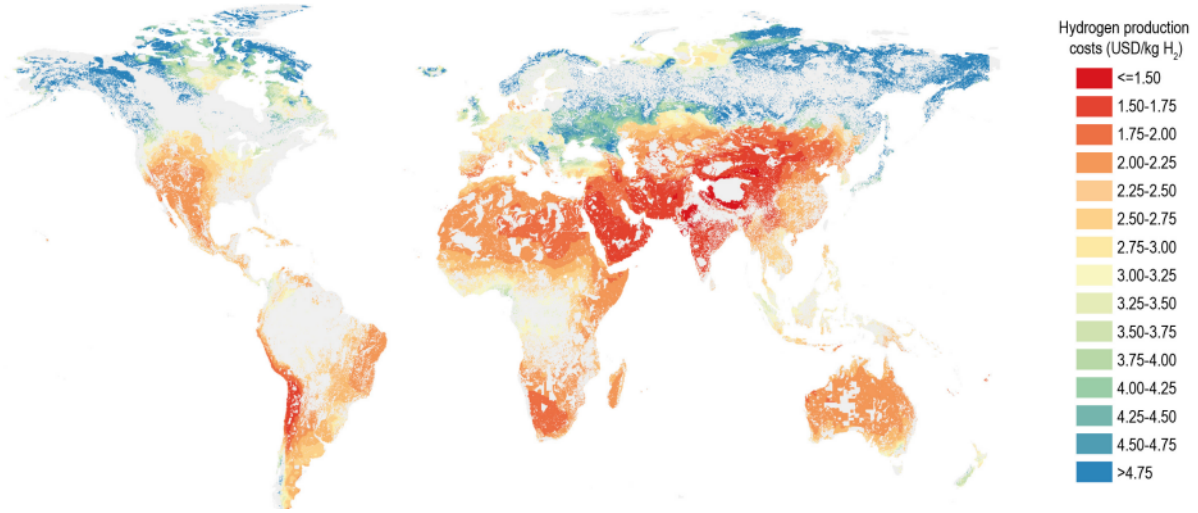


Figure 1.3: Hydrogen production costs from hybrid solar PV and wind systems for a minimum load of 40%, 2030. Source from [1]

Within the existing literature on hydrogen markets, the focus on green hydrogen has been limited despite its increasing importance in achieving the net-zero emissions target. As demand for green hydrogen is expected to surge in the coming years, traditional steam methane reforming facilities will be unable to meet this demand. Electrolysis and renewable energy infrastructure currently remain insufficient in meeting the projected demand for green hydrogen. Therefore, we propose the introduction of a competition-based approach that considers various factors, including economic viability, resource allocation, regional potential, and transportation routes, among others, to address the challenges faced by the green hydrogen market.

Figure 1.4 shows the degree of uncertainty in the future hydrogen demand and compares it with the current EU-27 targets of supply.

The REPowerEU plan set a target of 10 Mt/y of internal hydrogen production, added to 10 Mt/y of hydrogen import. In the scenario of lowest demand of hydrogen, the target of 20 Mt/y of supply would determine a surplus of hydrogen. Instead, in the scenario of highest demand of hydrogen ($>$ 20 Mt/y), there would be a deficit of supply. In this work, we consider different methodologies to study scenarios in which the supply of hydrogen is not sufficient to satisfy the hydrogen demand in 2050.

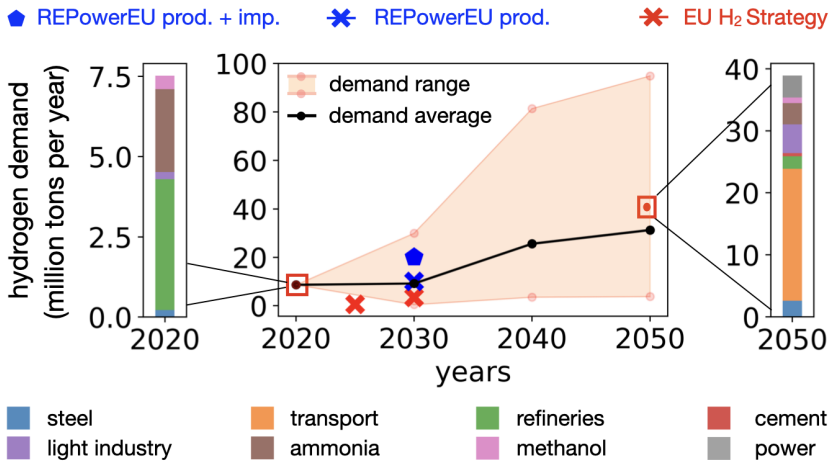


Figure 1.4: Uncertainty regarding future hydrogen demand and European targets. Source from [9]

1.2 Research question

This thesis aims at:

- Modelling the competition on the green hydrogen market by analyzing the production and transportation flows between North Africa and European countries.
- Comparing different modelling approaches in order to underline the main characteristics of the international trade of green hydrogen.

1.3 Thesis outline

The present document is organised with the following structure. Chapter 2 provides an in-depth analysis of the methodology employed in this study. It involves a comprehensive review of the data, the assumptions, and the modeling procedures. Building upon this foundation, Chapter 3 discusses the global optimum model in detail, along with an analysis of the results obtained through its application. Similarly, Chapter 4 describes and provide comments on the outcomes achieved based on a game theory model. Chapter 5 will compare the two models introduced underlying their similarities and differences. Finally, Chapter 6 evaluates different strategies and draws the main conclusions.

Chapter 2

Methodology

2.1 Use of AI

In the methodology of this master thesis, I employed ChatGPT, an artificial intelligence language model, to assist in improving the quality of the written content. The purpose of utilizing ChatGPT was to enhance the clarity and coherence of the English language, while ensuring that all the content and instructions were originated from my own knowledge and understanding of the subject matter.

Throughout the writing process, I interacted with ChatGPT by providing prompts and receiving generated responses. However, it is essential to note that I took full responsibility for the final content and the accuracy of the information presented. ChatGPT acted as a tool to provide suggestions, corrections, and help with structuring the text, but the decisions regarding the content and the overall argument were solely mine.

In accordance with the EPL guidelines, I acknowledge that the assistance of ChatGPT was used and I will duly cite its contribution in the appropriate sections of the thesis. By clearly stating the role of ChatGPT and attributing its assistance, I ensure transparency and uphold academic integrity in the writing process.

2.2 Assumptions

The formulation of the model relies on the following assumptions:

- **Yearly temporal dimension**: the model excludes daily or seasonal variations and focuses on average yearly values
- **Demand**: we aggregate the sector-specific demand of hydrogen to derive the total country-specific demand
- **Transportation**: we assume the Euclidean distance between the centroids of countries

2.3 Data

The data used in the analysis are obtained from various sources and provide essential information for modeling different aspects related to hydrogen production, demand, and transportation.

2.3.1 Land connections

We define a matrix a boolean values to represent whether transport is allowed between one country and another country via land. The values in the matrix are binary, with 1 indicating that land transport via pipeline is allowed and 0 indicating that it is not allowed. If two countries do not share any border, the value in the matrix will be 0, indicating that land transport is not possible between them. The matrix is computed using `geopandas`[1] and relies on the `shapefile` of all countries in the world to determine the border connections. The model parameter associated the possibility of connection between countries i and j via land is denoted as $b_{L,ij}$.

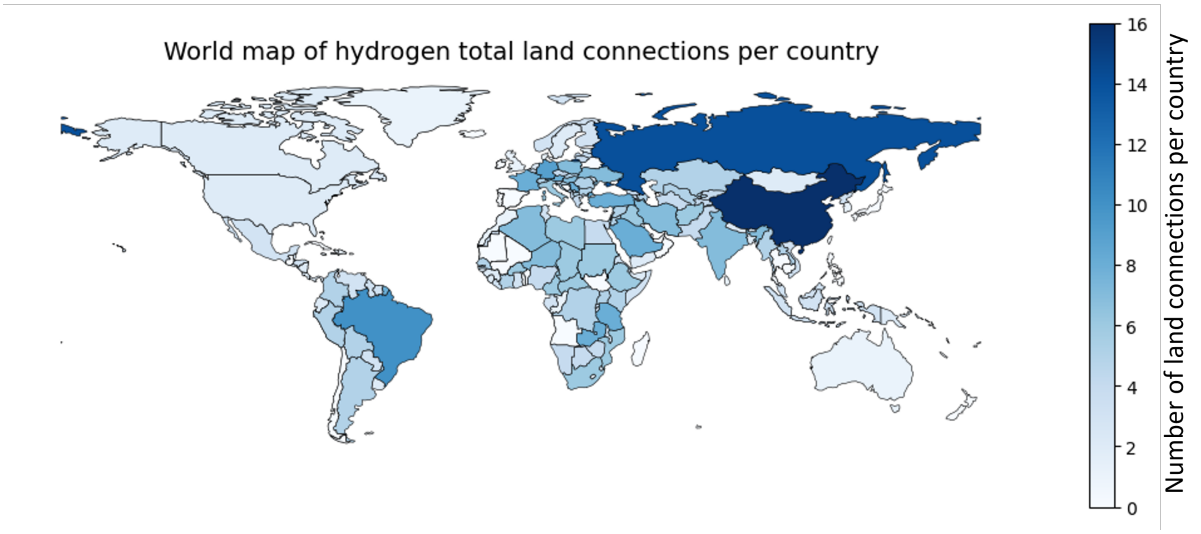


Figure 2.1: Worldwide map of the land connected countries. Darker blue is associated to a larger number of land connected countries

Figure 2.1 displays a worldwide map showcasing the countries colored according to the number of land connections they have. It is evident from the map that countries such as China, Russia, and Brazil have a higher number of land connections compared to other nations. These countries, known for their vast territories and geographical positions, enjoy the advantage of being connected to multiple neighboring countries via land. The large size of China and Russia, coupled with their extensive borders, contributes to their prominent placement on the map, indicating their numerous land connections. Similarly, Brazil, occupying a significant portion of South America, also exhibits a notable number of land connections. This visualization highlights the importance of geographical proximity and land accessibility in fostering transportation links between nations, particularly in the context of land connections.

[1] https://geopandas.org/en/v0.2.1/mapping.html

Figure 2.2 presents a histogram depicting the distribution of the number of land connections for different countries. The trend curve overlaid on the histogram reveals an interesting pattern: the majority of countries have a relatively low number of land connections, while the number of connections per country gradually decreases in a squared-like fashion as the number of connections increase. Notably, China stands out as the country with the highest number of land.

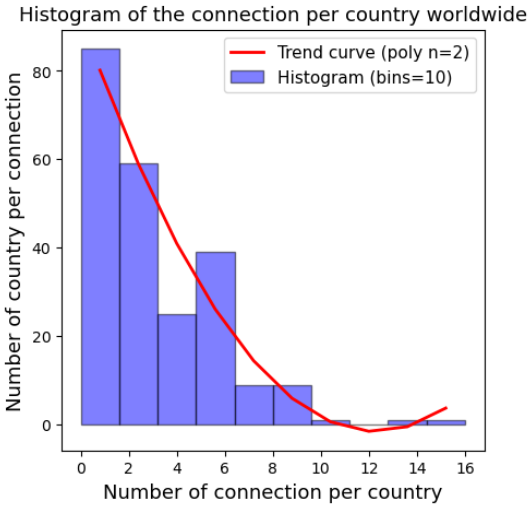


Figure 2.2: Land connection distribution trend worldwide

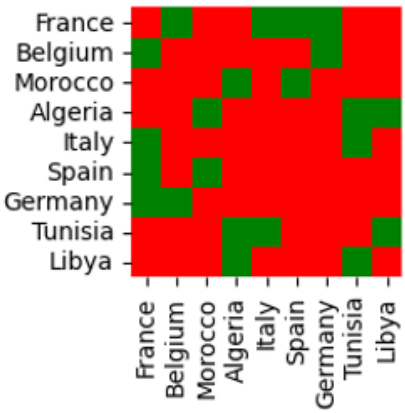


Figure 2.3: Green: a possible pipeline, red: no land connection.

The heat map reveals in Figure 2.3 limited pipeline connections between North Africa and Europe. Only France and Algeria have viable pipeline connections, while the rest of Europe lacks direct links. This constraint heavily impacts the analysis, as it necessitates a predominant focus on ship transportation for green hydrogen. Ship transportation introduces complexities and higher costs compared to pipelines. It relies on shipping routes, port capacities, and geopolitical factors. The absence of pipeline connections restricts direct and efficient hydrogen transport, emphasizing the need for careful consideration of ship transportation in the green hydrogen market analysis.

2.3.2 Sea connections

The matrix of boolean values represents whether transport is allowed between one country and another country via sea for hydrogen transportation. There are two types of technologies considered for sea transportation: NH_3 (NH_3) and LH_2 (liquid hydrogen). The values in the matrix are binary, with 1 indicating that sea transport is allowed and 0 indicating that it is not allowed. If either of the countries, A or B, is landlocked, meaning it does not have access to a sea or ocean, the value in the matrix will be 0, indicating that sea transport between these countries is not possible. The data for this matrix is computed from a database on trade connections [4]. The model parameter associated with the possibility of connection between countries i and j via transportation mode k is denoted as is denoted as $b_{S,ijk}$.

NH_3 (NH_3) and LH_2 (liquid hydrogen) are two commonly used technologies for sea transportation of hydrogen. NH_3 technology involves converting hydrogen gas into NH_3, which is a liquid at ambient conditions. NH_3 can be transported more easily and at a lower cost compared to gaseous hydrogen. LH_2 technology, on the other hand, involves cooling hydrogen gas to very low temperatures to convert it into a liquid state. Liquid hydrogen is highly energy-dense and can be transported efficiently using specialized cryogenic containers. Both NH_3 and LH_2 technologies enable the transportation of hydrogen over long distances via ships or vessels, providing a means to deliver hydrogen to regions that may not have local hydrogen production capabilities.

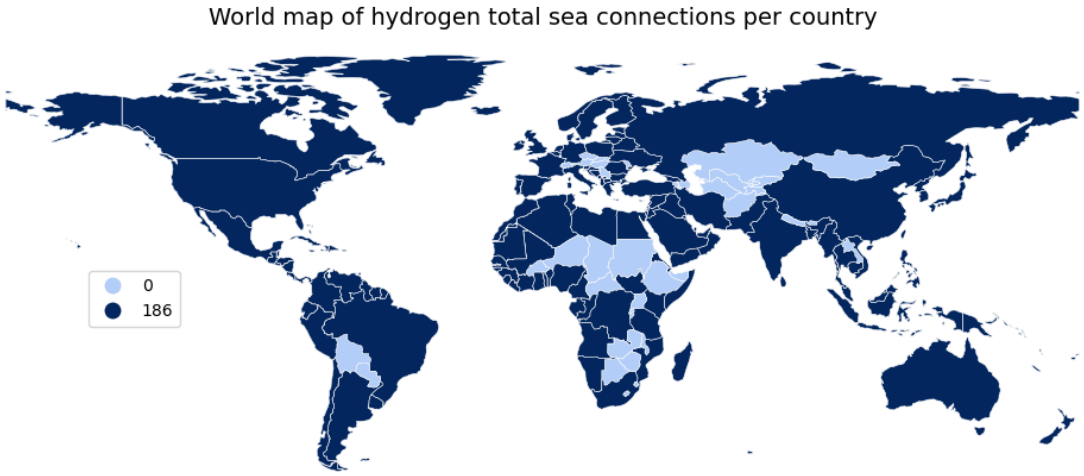


Figure 2.4: Worldwide map of the sea connected countries. Darker blue is associated to sea connected countries

Figure 2.4 presents a visual representation of landlocked and sea-connected countries. The distinct color scheme effectively distinguishes between the two categories, with landlocked nations displayed in a light blue and sea-connected countries depicted in a deep blue. The prevalence of light blue patches across certain regions, such as Central Asia and parts of Africa, underscores the challenges faced by landlocked countries in terms of accessing global markets and engaging in international maritime trade. In contrast, the dominance of dark blue in coastal areas signifies the advantageous position of sea-connected nations in terms of maritime trade routes.

Approximately 32.5% of countries worldwide are not connected to the sea. Being landlocked means that these countries lack direct access to the sea and must rely on neighboring countries for trade and transportation via land or air routes. Landlocked countries often face higher transportation costs, limited access to global markets, and a dependence on transit countries for imports and exports. Understanding the distribution and impact of landlocked countries provides valuable insights into global trade dynamics and highlights the importance of regional cooperation and infrastructure development to foster economic growth and connectivity for these nations.

2.3.3 Land distances

The distance between directly affects the cost of transport of green hydrogen. We compute the distance between country i and j as the Euclidean distance, l_{ij}, between the centroids of the countries. As transportation costs are generally proportional to the distance traveled, the distance matrix provides valuable insights into the potential expenses involved in moving green hydrogen from one country to another. Countries that are located closer to each other, characterized by shorter distances in the matrix, may benefit from relatively lower transportation costs, making the import or export of green hydrogen more economically viable.

Countries that are geographically distant from each other may face higher transportation costs, potentially affecting the market prices of green hydrogen. The distance matrix offers a quantitative tool for evaluating the feasibility and economic viability of long-distance transportation of green hydrogen, contributing to informed decision-making and strategic planning in the green hydrogen market.

2.3.4 Sea distances

The matrix representing the maritime distance between countries, considering their sea connections, is a crucial factor influencing the cost of transport of green hydrogen via sea. The distance matrix between country i and j via transportation mode k, l^S_{ijk}, is derived from a database on trade connections [4]. As with land transportation, the distance between countries plays a pivotal role in determining the expenses involved in shipping green hydrogen via sea routes. Countries that have shorter maritime distances, indicating closer proximity and better accessibility, are likely to benefit from comparatively lower transportation costs for importing or exporting green hydrogen. The map of this distribution worldwide is plotted in Figure 2.5.

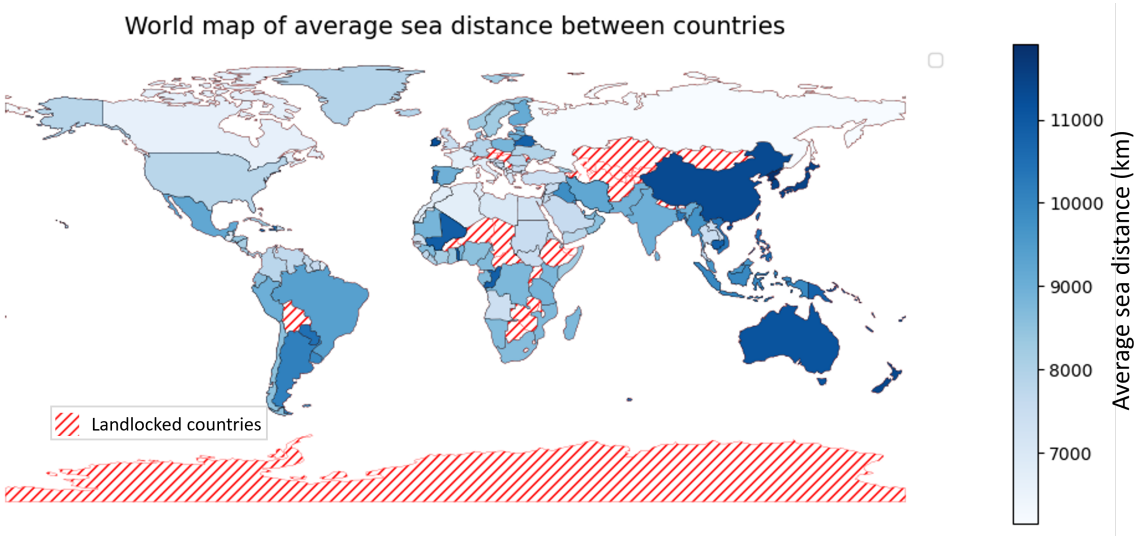


Figure 2.5: Worldwide map of the mean distances between countries

Conversely, countries that are geographically distant from each other via sea connections may face higher transportation costs, potentially affecting the market prices of green

hydrogen. The sea distance matrix provides valuable insights into the logistical challenges and economic considerations associated with maritime transportation of green hydrogen, aiding in strategic decision-making and market analysis within the green hydrogen industry.

2.3.5 Demand

We will now introduce the parameter d_i, which represents the hydrogen demand for each country i. Hydrogen demand is derived from the IEA Net-Zero scenario [2] and is split based on sectorial energy demand [8]. Looking ahead to 2050, the hydrogen demand represents the estimated amount of hydrogen required to fulfill the energy needs of different sectors in a sustainable and decarbonized manner. This demand serves as a fundamental indicator for policymakers, energy planners, and stakeholders to devise effective strategies and investments in hydrogen infrastructure and technologies. However, it's important to note that uncertainties, as we previously observe in Figure 1.4, are inherent in long-term energy.

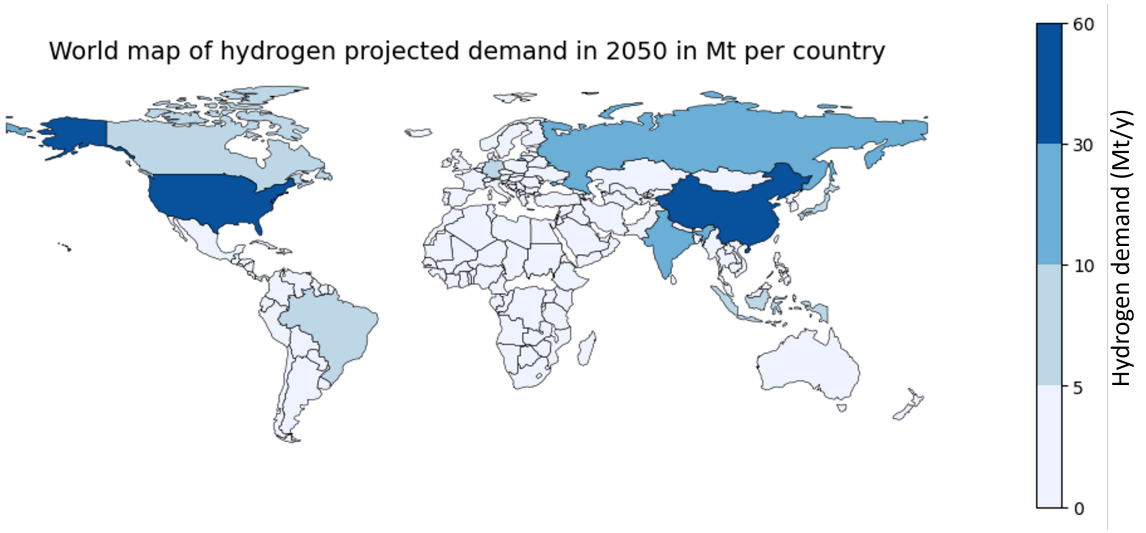


Figure 2.6: Worldwide map of the green hydrogen national demand distribution. Data assessed from [2] and [8]

The map in Figure 2.6represents the projected global hydrogen demand for the year 2050 [2]. The varying shades of blue indicate the level of demand, with darker blue representing higher demand and lighter blue indicating lower demand. Upon observation, it is evident that most countries exhibit relatively low hydrogen demand. However, notable exceptions include China and the USA, which stand out with significant demand levels. These countries, along with Russia, Brazil, and India, present a demand higher than average. In contrast, Africa and Europe exhibit relatively low demand on a per-country basis in comparison to other regions.

The figure 2.7 displays three correlation plots examining the relationship between projected hydrogen demand in 2050 (x-axis) and GDP (y-axis). Each plot represents a different range of GDP values.

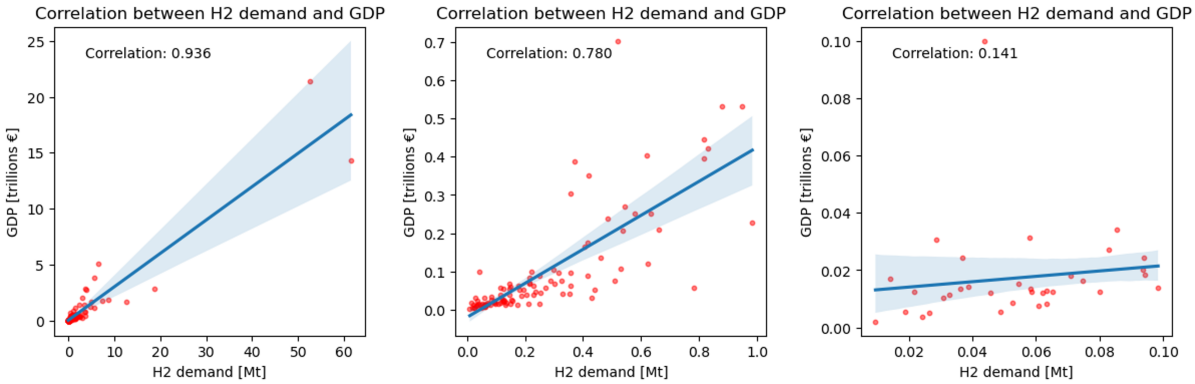


Figure 2.7: Correlation between GDP and Hydrogen projected demand in 2050. Stronger correlation for countries with higher GDP.

Starting from the left, the correlation plot shows a strong positive correlation of 0.936 between hydrogen demand and GDP for countries with high GDP values. This suggests that as GDP increases, there is a significant increase in hydrogen demand. Moving to the middle plot, which represents countries with moderate GDP levels, the correlation drops to 0.78. Although still positive, the correlation is slightly lower compared to the high GDP range. This indicates a relatively strong association between hydrogen demand and GDP, but not as pronounced as in the high GDP range. Finally, the plot on the right represents countries with low GDP levels. Here, the correlation is notably lower at 0.141, indicating a weak positive relationship between hydrogen demand and GDP for these countries.

Overall, the global trend observed in the correlation plots suggests that as GDP increases, there tends to be a corresponding increase in hydrogen demand. However, the strength of this relationship varies across different GDP ranges. Countries with higher GDP levels exhibit a stronger correlation between hydrogen demand and GDP compared to countries with moderate or low GDP levels. This highlights the potential influence of economic factors on hydrogen demand and underscores the importance of considering GDP levels when analyzing the relationship between hydrogen demand and economic indicators.

2.3.6 Levelized Cost of Hydrogen (LCOH)

Levelized Cost of Hydrogen (LCOH) is a significant metric to analyze the cost-effectiveness of hydrogen production. It takes into account various factors such as capital investment, operational expenses, and maintenance costs to calculate the average cost of hydrogen production over its entire life cycle. This data serves as a valuable resource for policymakers, industry professionals, and researchers in evaluating the cost competitivity and viability of hydrogen as an alternative energy source [8].

Figure 2.8 represents the projected Levelized Cost of Hydrogen (LCOH) values for different countries in 2050. When comparing Europe and North Africa in terms of the projected LCOH values for 2050, some interesting observations can be made. In North Africa, countries such as Morocco, Algeria, and Tunisia show lower LCOH values compared to their European counterparts. This can be attributed to the region's abundant

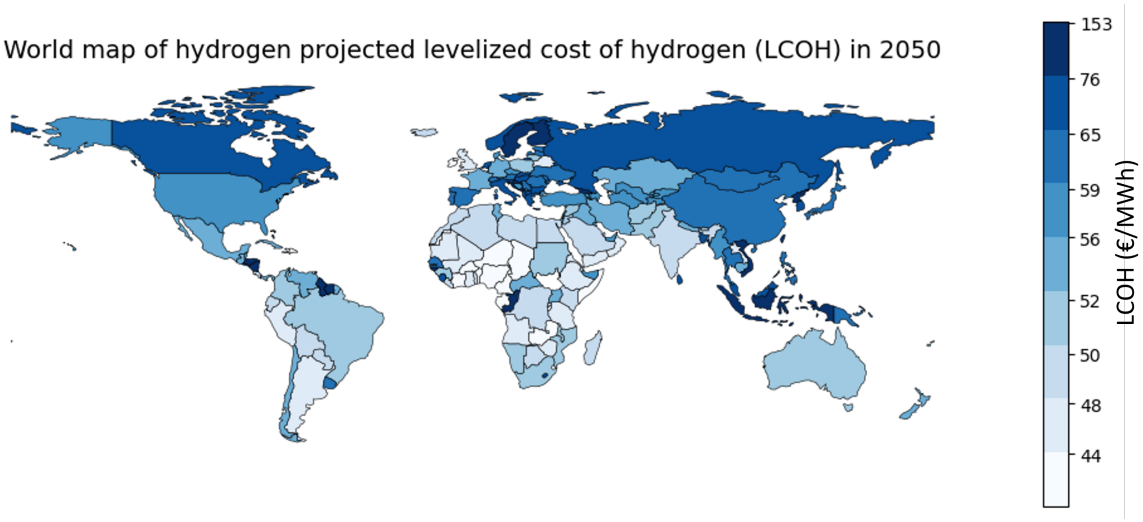


Figure 2.8: Countries have a widely distributed LCOH among the world. European mean LCOH

solar resources and vast potential for renewable energy generation. The availability of sunlight throughout the year makes North Africa an attractive location for large-scale solar-powered electrolysis, resulting in lower production costs for hydrogen.

Figure 2.9 displays the distribution of hydrogen LCOH across different countries shows variations, with Europe and North Africa being particularly notable. In North Africa, countries like Morocco and Algeria have LCOH values around 49€/MWh, indicating their potential for hydrogen production. It is worth noting that the LCOH values differ based on several factors, including renewable potential, local presence of water scarcity and variation in the cost of the technologies.

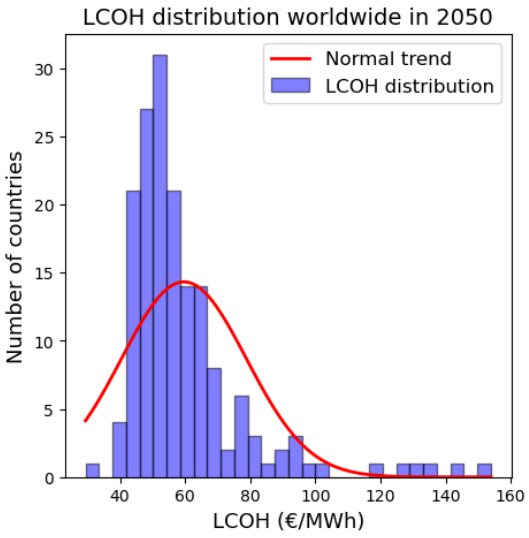


Figure 2.9: LCOH distribution worldwide with mean at 59.6€/MWh

The comparison between Europe and North Africa highlights the influence of geographical and climatic factors on the LCOH values. While Europe has made significant progress in renewable energy development, North Africa possesses a natural advantage due to its abundant solar resources. This indicates the potential for collaboration and partnerships between the two regions to leverage their respective strengths in the production and utilization of hydrogen.

Furthermore, considering the proximity of Europe and North Africa, there is potential for cross-border energy trading and sharing of resources. Europe's demand for clean energy, coupled with North Africa's renewable energy potential, presents an opportunity for a mutually beneficial relationship in hydrogen production and distribution.

Overall, the comparison between Europe and North Africa emphasizes the importance of regional dynamics and natural resources in shaping the projected LCOH values. It underscores the potential for collaboration and the need for strategic partnerships to ensure a sustainable and cost-effective transition to a hydrogen-based economy in both regions.

2.3.7 Supply

In this section, we will introduce the parameter a_i, which represents the availability of hydrogen for each country. This parameter denotes the potential amount of green hydrogen that each country is capable of producing per year. As shown in Figure 2.10, the projected hydrogen supply in 2050 shows a diverse landscape of potential markets, with Europe and North Africa standing out as key regions. Europe demonstrates promising potential due to its commitment to decarbonization and the growing emphasis on renewable energy sources. Several European countries, such as Germany and the Netherlands, have made substantial investments in hydrogen production and infrastructure, paving the way for a robust hydrogen market in the future.

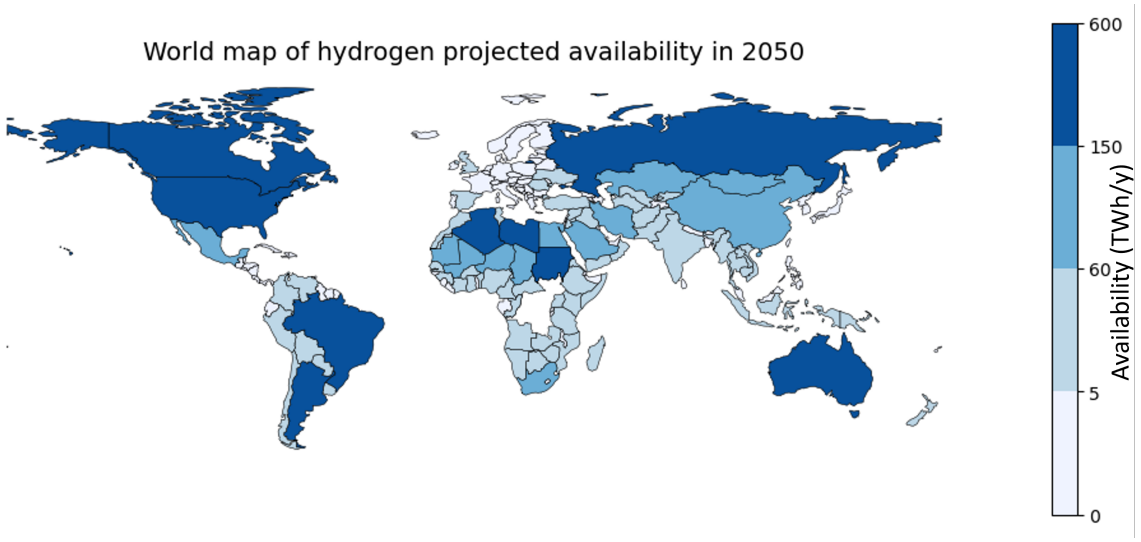


Figure 2.10: Potential of supply worldwide (a_i). Europe has a low potential while North Africa is among the biggest potential supplier worldwide

The cartographic representation of the hydrogen availability distribution vividly portrays the relatively diminished levels of availability in certain countries. These regions exhibit a discernible scarcity of hydrogen resources, as indicated by the map. This paucity of availability presents a notable challenge for the development and deployment of hydrogen-related initiatives in these areas. The limited access to hydrogen resources in these countries necessitates strategic considerations and potential collaboration to address this disparity and unlock their potential for green hydrogen utilization.

On the other hand, North Africa possesses significant potential in terms of solar-based hydrogen production. Countries like Algeria and Morocco, with ample solar resources and favorable geographical conditions, are well-positioned to become major players in

the global hydrogen market. North Africa's proximity to Europe also presents an opportunity for close collaboration and trade between the two regions.

The potential market between Europe and North Africa holds strategic importance, as Europe can leverage North Africa's solar energy potential to meet its growing hydrogen demand. Cooperation in the form of cross-border infrastructure development, such as pipelines and shipping routes, would enable the export of low-cost green hydrogen from North Africa to Europe. This collaboration would not only foster energy security and sustainability but also strengthen the economic ties between the two regions.

Overall, the projected hydrogen supply in 2050 highlights the significance of Europe and North Africa in shaping the future of the hydrogen market. The combination of Europe's strong commitment to decarbonization and North Africa's abundant solar resources positions the two regions for a mutually beneficial partnership in achieving a sustainable and efficient hydrogen economy.

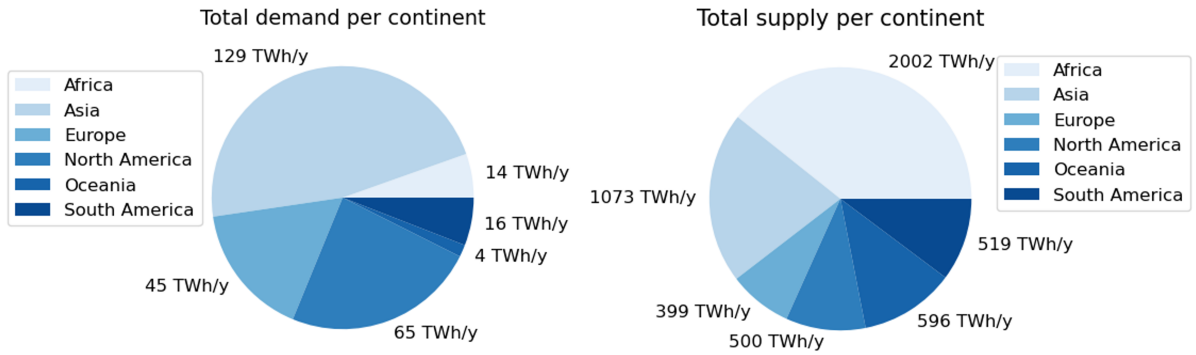


Figure 2.11: Projected hydrogen demand and supply comparison between continent in TWh/y in 2050

In Figure 2.11 we observe that Europe is projected to have a higher demand for hydrogen compared to Africa. However, Africa, specifically North Africa, possesses a significantly higher supply of hydrogen compared to Europe. Africa's hydrogen supply is approximately five times greater than Europe. This presents an opportunity for Europe to establish partnerships and collaboration with North Africa to meet its hydrogen demand. Importing hydrogen from North Africa or developing joint hydrogen production and transportation projects could help bridge the supply-demand gap. Additional considerations such as infrastructure, logistics, politics, and technology would need to be taken into account for a comprehensive analysis of the situation between Europe and North Africa in the hydrogen sector.

2.3.8 Technologies comparison

The graph in Figure 2.12 shows the cost for delivering hydrogen through different modes of transportation in 2030. The modes considered include pipeline and ship transport, utilizing carriers such as LH_2, LOHC, and NH_3, as well as electrical transmission.

One notable observation is that the cost of hydrogen delivery tends to vary significantly depending on the transportation method and distance. For shorter distances, pipeline

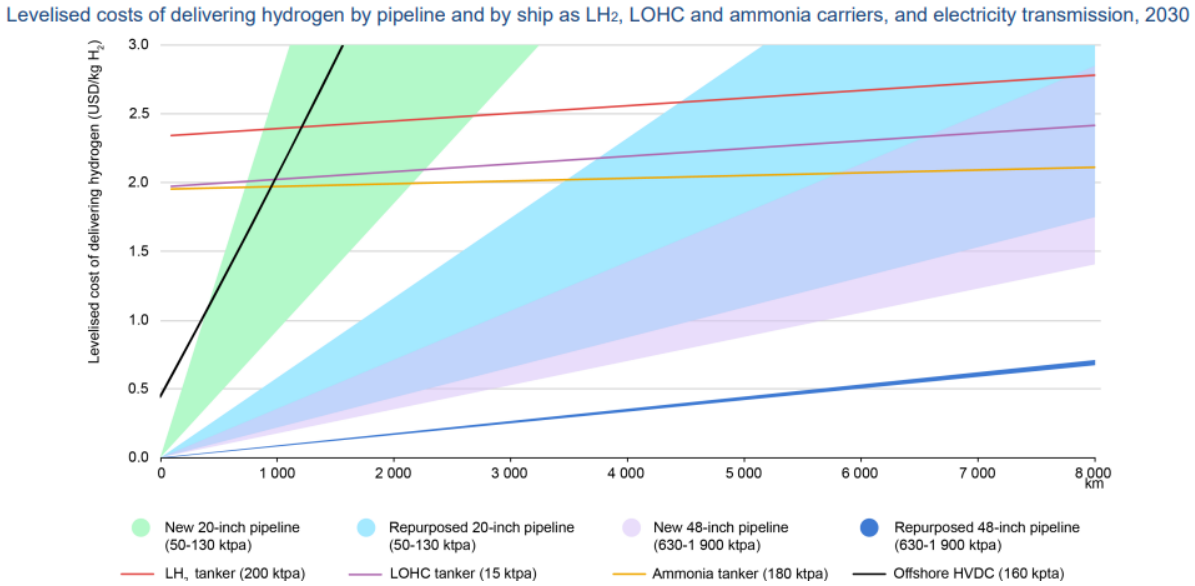


Figure 2.12: Analysis from the IEA 2022 report [1] showcases the varying impact of transportation technologies on Levelized Cost of Heat (LCOH), as depicted by the accompanying graph

transport appears to be the most cost-effective option, likely due to its efficiency and established infrastructure. On the other hand, for longer distances where pipeline networks may be impractical or uneconomical, alternative methods like shipping hydrogen as LH_2, LOHC, or NH_3 carriers come into play. These options involve additional processing steps and associated costs but provide a means to transport hydrogen over greater distances.

Ship transportation, exhibit a lower LCOH compared to 20 inch pipelines from a distance of 1000 kilometers. This finding underscores the cost advantages associated with using NH_3 carriers for long-distance hydrogen transport. The lower LCOH values for NH_3 suggest its potential to offer more economically efficient solutions compared to pipelines beyond the 1000-kilometer mark. These insights highlight the competitivity and attractiveness of NH_3 and ship transport as viable options for cost-effective hydrogen delivery over extended distances.

It is worth noting that Figure 2.11 provides a comparative analysis rather than absolute cost values. This approach allows for a clear understanding of the relative cost differences among different transportation technologies. It also emphasizes the importance of considering the specific requirements and constraints of each transport method when assessing the overall cost of hydrogen delivery.

2.4 Models

The models that will be described in the next chapters are implemented in `python` using an academic licence of `Gurobi optimization solver`. This allows us to create linear and MILP models.

MILP stands for Mixed Integer Linear Programming. It is a mathematical optimization

technique that is used to solve complex problems that involve both discrete and continuous variables. Those models involve linear functions, which means that the relationship between the variables can be represented by a linear equation or inequality. The "mixed" part refers to the fact that some of the variables can take on integer values, while others are continuous. The objective of an MILP model is to minimize or maximize a linear objective function subject to a set of linear constraints. These constraints can include bounds on the variables, equality and inequality constraints, as well as logical constraints that enforce the integer requirement on some of the variables.

This allows us to solve efficient models and to lose ourselves in over complicated non linear solving methods. The formulation of the models take into account 4 components:

1. **Data set**: The foundational element on which the model is constructed, encompassing relevant production data.
2. **Decision variables**: Primarily determining the import and export quantities for each country involved.
3. **Constraints**: Establishing the boundaries and limitations that govern the potential hydrogen flows.
4. **Objective function**: Defining the optimization goal or desired outcome we aim to achieve through the model.

These components form the essential building blocks of a comprehensive analysis, allowing for a systematic evaluation of hydrogen distribution and aiding decision-making processes in the energy sector.

Chapter 3

Global optimum

Europe and North Africa will be a focal point in the following modeling of hydrogen competition for several reasons. Firstly, these regions possess significant renewable energy potential, with favorable conditions for the production of hydrogen from renewable sources such as solar and wind power. The abundance of renewable resources allows for cost-effective and sustainable hydrogen production. Additionally, Europe has set ambitious decarbonization goals and is actively promoting the transition to a hydrogen economy. The European Union's Hydrogen Strategy aims to establish a clean and competitive hydrogen market, making it an attractive region for hydrogen investments. Moreover, North Africa's proximity to Europe offers an opportunity for exporting renewable hydrogen, leveraging its renewable energy potential to meet the growing hydrogen demand in Europe. Considering these factors, focusing on the Europe-North Africa situation in modeling hydrogen competition enables a comprehensive analysis of the potential and challenges associated with hydrogen production, distribution, and market integration in these regions.

3.1 Model description

The focus of the global optimum model is to minimize the global price for green hydrogen. This objective implies finding the most cost-effective solutions that lead to the lowest possible price of green hydrogen on a global scale. By minimizing the global price, the model aims to enhance the competitivity and affordability of green hydrogen, making it a viable and attractive option for various industries and sectors. Achieving a low global price involves optimizing production, transportation, and distribution processes, as well as leveraging economies of scale and utilizing renewable energy sources efficiently. Lowering the global price of green hydrogen not only benefits consumers by reducing energy costs but also encourages the widespread adoption of clean energy technologies, contributing to the global transition towards a more sustainable and decarbonized future.

3.1.1 Competitivity definition

In the following section, we define the competitivity as the ratio of the total demand for hydrogen (sum of d_i introduced in section 2.3.5) to the total available hydrogen (sum of a_i introduced in section 2.3.7) for a set of countries or regions. It represents the relationship between the demand for hydrogen and the available supply. It is defined as follow with c in the following equation:

$$c = \frac{\sum_i d_i}{\sum_i a_i} \quad \forall i \in \mathcal{C}$$

A higher competitivity value indicates that the total demand for hydrogen is relatively high compared to the available supply, suggesting a potentially favorable market situation for hydrogen producers and suppliers. Conversely, a lower competitivity value suggests that the available supply of hydrogen exceeds the total demand, indicating a potentially less challenging market environment as the ressources are more abundant. In the particular case where competitivity equals to one we just have the exact amount of available resources tot fulfill the overall demand of the market.

3.1.2 Sets

Sets	Index	Description
$\mathcal{C}$	i	Set of considered countries
$\mathcal{D}$	k	Set of considered sea transportation modes
$\mathcal{C}'^{\mathcal{L}}$	i, j	Set of bilateral relations in considered countries ij
$\mathcal{C}'^{\mathcal{S}}$	i, j, k	Set of bilateral relations in considered countries ij under technology k

Table 3.1: Data sets used for the global optimum modelling. A set of two technologies are considered. Liquid hydrogen and NH_3 for ship transportation

3.1.3 Parameters

Parameter	Description	Unit
p_i	Total cost of production of green H_2 in country i	€/ MWh
a_i	Green hydrogen availability in country i	MWh
d_i	Demand for importing country i	MWh
r_k^S	Sea re-conversion cost under technology k	€/MWh
l_{ij}^L	Land distance between 2 countries i, j	km
t_{ij}^L	Land transportation cost between 2 countries i, j	€/MWh/km
b_{ij}^L	Boolean for land connection (0 : no, 1 : yes)	/
l_{ijk}^S	Sea distance between i, j under technology k	km
t_{ijk}^S	Sea transportation cost between i, j under technology k	€/MWh/km
b_{ijk}^S	Boolean for land connection under technology k	/

Table 3.2: Parameters used in the global optimum model. All units refer to values per year

3.1.4 Decision variables

In this particular analysis, our emphasis lies on the examination of global trends within the hydrogen market. To facilitate this investigation, we identify two key variables:

the production of hydrogen based on its production potential (availability) and the import/export dynamics between the countries under consideration. These variables serve as crucial factors for understanding the interplay of hydrogen supply and demand, enabling us to gain insights into the evolving landscape of the global hydrogen market.

Var	Unit	Dom	Description
P_i	MWh	$\mathbb{R}+$	Green H_2 production of country i
T^L_{ij}	MWh	$\mathbb{R}+$	Land cost and between 2 countries i, j
T^S_{ijk}	MWh	$\mathbb{R}+$	Sea cost between 2 countries i, j under technology k

Table 3.3: Decision variables used in the global optimum model. All units refer to values per year

3.1.5 Constraints

No competition

In this scenario, we consider multiple constraints to ensure an optimal analysis. Firstly, we incorporate the energy balance as a fundamental constraint with c_1. This constraint ensures that the energy inputs and outputs remain in equilibrium, allowing for a comprehensive assessment of the system. Secondly, we implement c_2 which ensures that the production quantities do not exceed the available potential, thereby maintaining feasibility and practicality. Additionally, we address the essential aspect of sea and land connections by introducing c_3 and c_4

$$
\begin{aligned}
c_1: \quad & d_i + \sum_{j \in C}(T^L_{ij} + \sum_{k \in D} T^S_{ijk}) = P_i + \sum_{j \in C}(T^L_{ji} + \sum_{k \in D} T^S_{jik}) && \forall i \neq j \in \mathcal{C}, k \in \mathcal{D} \\
c_2: \quad & P_i \leq a_i && \forall i \in \mathcal{C} \\
c_3: \quad & T^L_{ij} = 0 \ \text{, if } \ b^L_{ij} < 1 && \forall i \neq j \in \mathcal{C} \\
c_4: \quad & T^S_{ijk} = 0 \ \text{, if } \ b^S_{ijk} < 1 && \forall i \neq j \in \mathcal{C}, k \in \mathcal{D}
\end{aligned}
$$

Competition

We here are in the case where the global demand is higher than the availability ($\sum_{i \in c} d_i > \sum_{i \in c} a_i$). In this specific case, the energy balance constraint is not applicable. Instead, we prioritize meeting the high demand by imposing the condition that we produce everything that is available within our production capacity. This approach acknowledges the demand surpassing our production capabilities, necessitating a focus on maximizing output to satisfy market needs. By ensuring the utilization of all available resources, we aim to address the challenge posed by limited production capacity and meet the prevailing demand in an optimal manner.

$$
\begin{aligned}
c_1 &: \quad \sum_{i \in c} a_i = \sum_{i \in c} P_i && \forall i \in \mathcal{C} \\
c_2 &: \quad P_i \leq a_i && \forall i \in \mathcal{C} \\
c_3 &: \quad T^L_{ij} = 0 \ \text{, if } \ b^L_{ij} < 1 && \forall i \neq j \in \mathcal{C} \\
c_4 &: \quad T^S_{ijk} = 0 \ \text{, if } \ b^S_{ijk} < 1 && \forall i \neq j \in \mathcal{C}, k \in \mathcal{D}
\end{aligned}
$$

3.1.6 Objective function

In our analysis, we explore two distinct approaches to optimize the system. Firstly, the single objective approach focuses on minimizing the overall cost of the system. This entails finding the most cost-efficient solution while considering various factors and constraints. On the other hand, the bi-objective approach introduces an additional element by minimizing the combined cost of the system along with the cost of unmet demand. This approach assigns weight to the cost of unproduced hydrogen necessary to maintain the energy balance. By incorporating this weighted cost, we seek to strike a balance between cost optimization and ensuring the fulfillment of the energy balance, thereby providing a more comprehensive evaluation of the system's performance.

3.1.6.1 Single objective

The analytical expression of the single objective function is as follows:

$$\min[\sum_{i \in C} P_i \cdot p_i + \sum_{i \in C} \sum_{j \in C} T^L_{ij} \cdot t^L_{ij} \cdot l^L_{ij} + \sum_{i \in C} \sum_{j \in C} \sum_{k \in D} T^S_{ijk} \cdot (t^S_{ijk} \cdot l^S_{ijk} + r^S_k)]$$

3.1.6.2 Bi-objective

The analytical expression of the bi-objective function is as follows:

$$\min[\sum_{i \in C} P_i \cdot p_i + \sum_{i \in C} \sum_{j \in C} T^L_{ij} \cdot t^L_{ij} \cdot l^L_{ij} + \sum_{i \in C} \sum_{j \in C} \sum_{k \in D} T^S_{ijk} \cdot (t^S_{ijk} \cdot l^S_{ijk} + r^S_k) + c \cdot \overline{p_i} \cdot \sum_{i \in C} (d_i - P_i)]$$

It is worth noting that in the dual objective function, there is no imposition to utilize all available hydrogen as it was the case for the single objective int the competitive case with c_1. The weight assigned to the unmet demand plays a crucial role in determining its influence on the optimization process. The average cost of production $\overline{p_i}$ serves as a suitable starting point for determining the weight of the unmet demand in my research. This value provides an approximate representation of the underlying price basis for the unproduced items on average. To tailor the weight to the specific requirements of the analysis, a coefficient denoted as c is introduced. This coefficient allows for further adjustment of the weight, accommodating the unique needs and considerations of the study.

3.2 Results

3.2.1 Set of countries

The modeling approach focuses on several countries, namely France, Belgium, Morocco, Algeria, Italy, Spain, Germany, Tunisia, and Libya. These countries are selected based on their relevance and significance in the context of the hydrogen market and their geographical distribution across Europe and North Africa. By considering multiple countries, the modeling framework can capture the interdependencies and interactions between different regional markets, allowing for a more comprehensive analysis of the hydrogen landscape. The inclusion of these specific countries enables a holistic examination of factors such as regional policies, infrastructure development, and market dynamics, which are crucial in understanding the overall competitivity and potential of the green hydrogen market in Europe and North Africa.

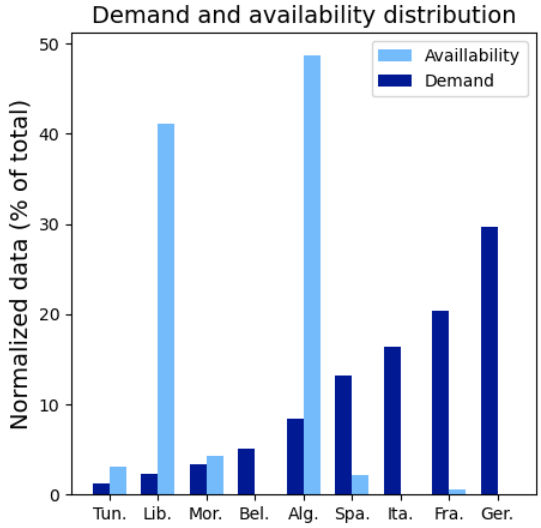


Figure 3.1: Distribution of availability and demand among selected countries

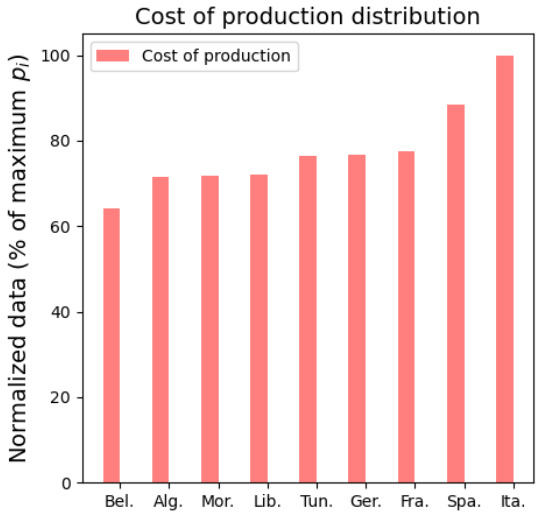


Figure 3.2: Cost of production variation among selected countries

The left graph in Figure 3.1 illustrates the distribution of availability and demand among the selected set of countries. It is evident that the demand is primarily concentrated in European countries, indicating a substantial market for hydrogen. Conversely, the availability of hydrogen resources is more prominent in North African countries, particularly in Algeria and Libya. This highlights the necessity of collaboration between these regions, as North African countries possess significant production potential along with lower production costs.

Moving to the right graph in Figure 3.2, we observe that the cost of production is generally higher for European countries, with the exception of Belgium. Consequently, it can be inferred that there may be expectations from North African countries towards European nations, as they offer a combination of higher production potential and comparatively lower production prices. This underscores the potential for mutually beneficial partnerships and collaborations in the hydrogen market between these regions.

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3.2.2 Single objective

The graph in Figure 3.3 depicts the relationship between total cost in the market and competitivity, measured as the global demand over global availability. At competitivity equals to 1, the entire demand is fulfilled. As the availability increases, the global price reduces due to enhanced possibilities for obtaining better prices. However, on the right side of the graph, where competitivity increases, there is a decrease in overall hydrogen production. It is important to note that this reduction in production does not necessarily imply a decrease in the levelized cost of hydrogen (LCOH), which will be further examined in subsequent analysis.

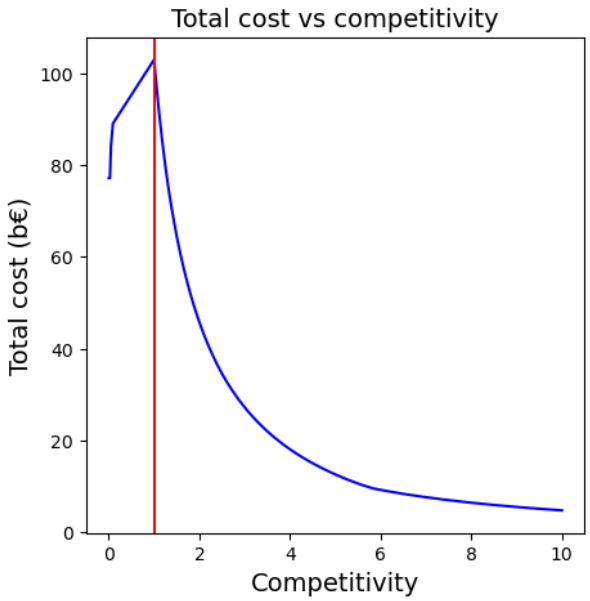


Figure 3.3: Global cost variation with competitivity in between western Europe and North Africa

In Figure3.4 we have the global cost per unit of hydrogen produced plotted against competition. We observe a maximum at a competitivity value of one. In the competitive range, where resources become scarce compared to demand, the overall global price per unit decreases as countries with lower production costs can be utilized. We also notice a decrease in the overall cost for competitivity values greater than one, indicating a shift towards more localized interactions in the market. This is evident in the right-side graph in Figure 3.5 depicting the cost per unit of hydrogen transport, where a significant increase occurs in a competitive regime. As we aim to minimize global costs, transportation costs tend to decrease significantly. The observed shift in slope around a competitivity value of 5.5 in the graph is attributed to Spain's behavior within the discrete set of countries. With an increase in competition, Spain shifts its strategy by reducing hydrogen imports from Algeria. This alteration in import patterns contributes to the change in the graph's slope.

Within the comprehensive context of the green hydrogen market, we chose four distinct competition cases that represent diverse strategic possibilities as shown inf Figure 3.6

In the first situation depicted on the left, Algeria emerges as a significant producer, satisfying a substantial portion of the hydrogen demand for both Europe and itself. This aligns with our earlier observation that Algeria boasts lower production costs, making it

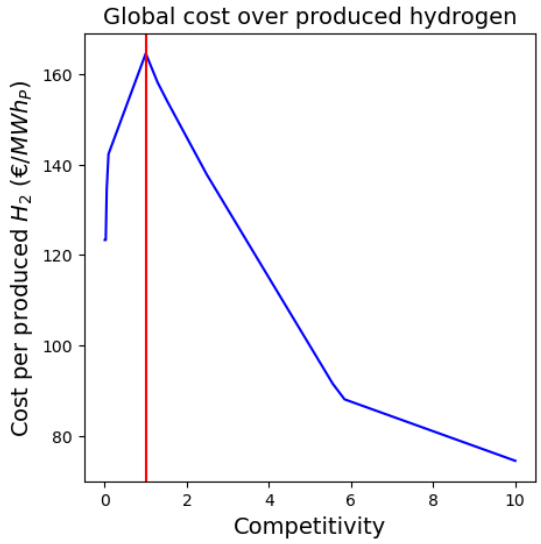


Figure 3.4: Global cost per MWh of hydrogen produced vs competitivity for single objective Global optimum modelling

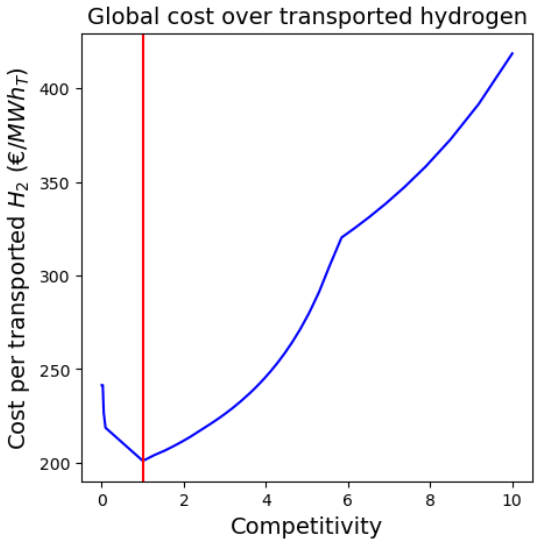


Figure 3.5: Global cost per MWh of hydrogen transported vs competitivity for single objective Global optimum modelling

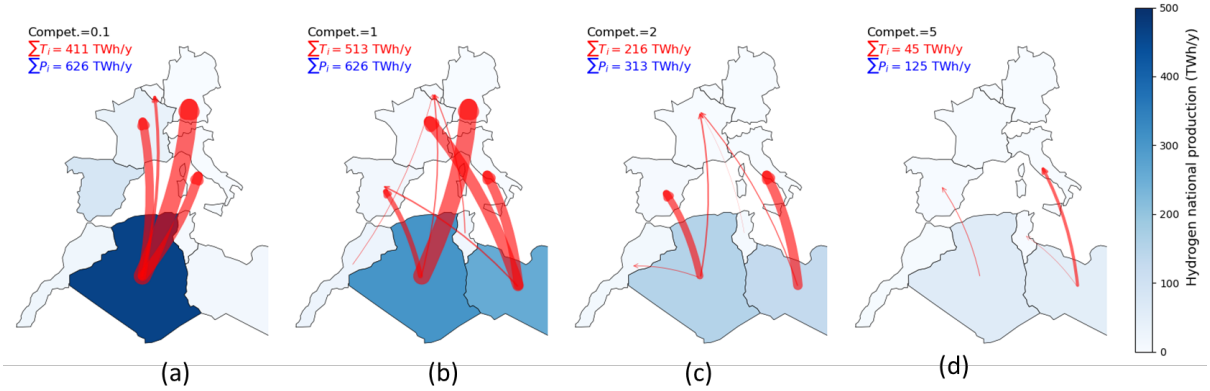


Figure 3.6: Scenarios for single Objective global optimum model: map of the transportations flows and production regions

a logical choice for fulfilling the hydrogen requirements. In the case where there is ample availability of hydrogen resources, exporting to Europe remains more cost-effective compared to producing for domestic consumption. As a result, approximately 65% of the hydrogen production is allocated for export purposes. This map provides a visual representation of the intricate dynamics between availability, production costs, and trade patterns within the hydrogen market.

In the scenario where the exact amount of hydrogen available matches the demand, we observe that the transportation flows are quite similar to the first case. However, there are slight differences in terms of imports, with slightly higher importations from Morocco and Libya. This can be attributed to factors such as better connectivity and trade relations between Libya and Spain, as well as Italy. Additionally, Algeria already utilizes its full production potential in this scenario, further influencing the trade dynamics. Overall, the transportation flows reflect the equilibrium between supply and demand,

with each country strategically engaging in imports and exports based on their respective capabilities and connectivity.

The analysis of the last two maps reveals a significant shift in connections, particularly with Germany and France, and positions Libya as the primary exporting country in situations where resources are highly limited compared to demand. This shift can be attributed to the cost associated with transporting hydrogen over longer distances to Germany and France. This is further exemplified by the fact that, at a competitivity value of 5, the ratio of transported hydrogen to produced hydrogen drops to 36%. Notably, in the case of competitivity 5, Algeria exports exclusively to Tunisia, a neighboring country that is much closer in proximity. These observations underscore the impact of distance on trade dynamics within the hydrogen market, and emphasize the strategic role of neighboring countries as primary trading partners when resources are constrained.

The analysis of the maps for different competitivity cases reveals key insights into production and transportation flows. When resources are abundant, a balanced distribution of production and imports is observed, with European countries importing from neighboring countries with lower production costs. In scenarios with limited resources, Libya becomes a prominent exporter due to its lower costs and closer proximity to certain European countries. As competitivity increases, there is a shift towards more localized interactions, resulting in a decrease in the ratio of transported hydrogen to produced hydrogen. These findings highlight the influence of resource availability, demand, and competitivity on strategic decision-making in the global hydrogen market.

3.2.3 Bi-objective

The bi-objective function in this context considers both cost minimization and the maximization of energy balance fulfillment. The goal is to minimize the total cost while also addressing the unmet demand. Unmet demand is defined as the difference between the country's total demand and the sum of the produced units on the market. By incorporating both cost optimization and energy balance fulfillment, the bi-objective function aims to find an optimal solution that balances economic efficiency and meeting the energy needs of the country.

3.2.3.1 Weight definition

In the context of determining the weight for the unmet demand, it is defined as a factor c multiplied by the average price of production worldwide, denoted as $\overline{p}$. This weight is calculated as $c \cdot \overline{p}$ as described in 3.1.6.2. This approach allows for a flexible weighting mechanism that takes into consideration the average price of production in determining the weight assigned to the unmet demand. By incorporating this weight in the analysis, it provides a quantitative measure of the significance and impact of the unmet demand on the overall optimization process.

3.2.3.2 Weight of unmet demand analysis

An analysis will be conducted to assess the weight of the unmet demand in order to determine the various possibilities and scenarios for hydrogen production and transportation. The selected data points enable us to examine the diverse distribution of production and

transportation in these different cases. By studying these scenarios, we can gain insights into the potential outcomes and explore the varying dynamics of hydrogen supply and demand.

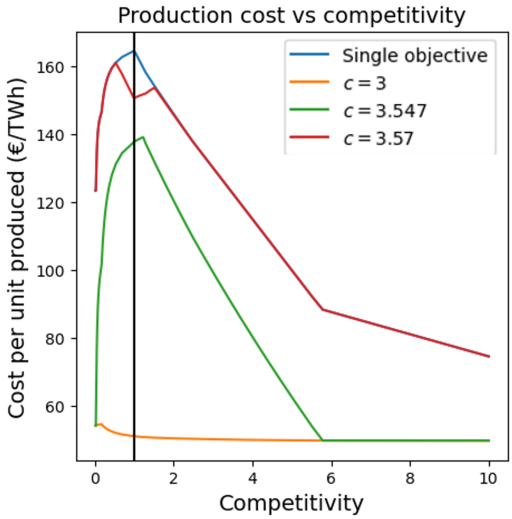


Figure 3.7: Cost per unit energy vs. competitivity for different weight values

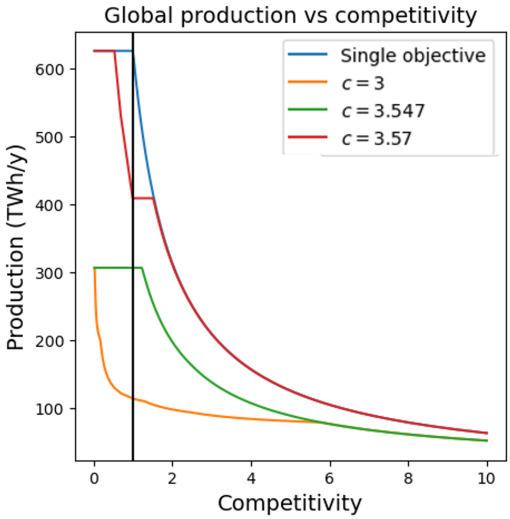


Figure 3.8: Produced energy vs. competitivity for different weight values

In Figure 3.7, we observe four different scenarios. The first scenario represents the objective function maximized at a competitivity value of one, where we impose the constraint of utilizing all available hydrogen. As we move towards decreasing competitivity values, we also observe a decrease in the cost per unit of production. This can be attributed to the increased emphasis on fulfilling the energy balance, where more hydrogen is produced to minimize costs. It becomes costlier to fulfill the energy balance, and thus, it is valuable to study the different cases in which we balance meeting demand and minimizing expenses.

It is worth noting that in the case where the weight is 3.57, a local minimum occurs for competitivity equal to one. This phenomenon arises due to a halt in global production around competitivity value one, as the weight is not sufficiently large to align with the single objective for values close to one. The cost of producing the entire available hydrogen at competitivity equal to one becomes excessively high. However, as availability increases while maintaining the same production level as shown in Figure 3.8, the same quantity of hydrogen is produced but at a more favorable price. Consequently, this leads to a decreasing price per unit of production and the the observed local minimum.

The Figure 3.9 consists of three graphs. The left graph illustrates the variation of the cost per unit of hydrogen production as a function of the weight of the unmet demand. We observe distinct step-like patterns. The two graphs on the right provide a closer look at these steps. The first step, represented by the top graph, occurs for weights close to one. Despite a minimal increase in production cost, the fulfilled demand increases by nearly 20%. This indicates a situation where no hydrogen is produced initially, as the emphasis is on minimizing the cost and the absence of a market. As we gradually increase the weight, there is a growing importance placed on satisfying the demand of each country. This first step corresponds to an increase in production without any import or export, resulting in zero transportation. It is during the second step, with a weight above

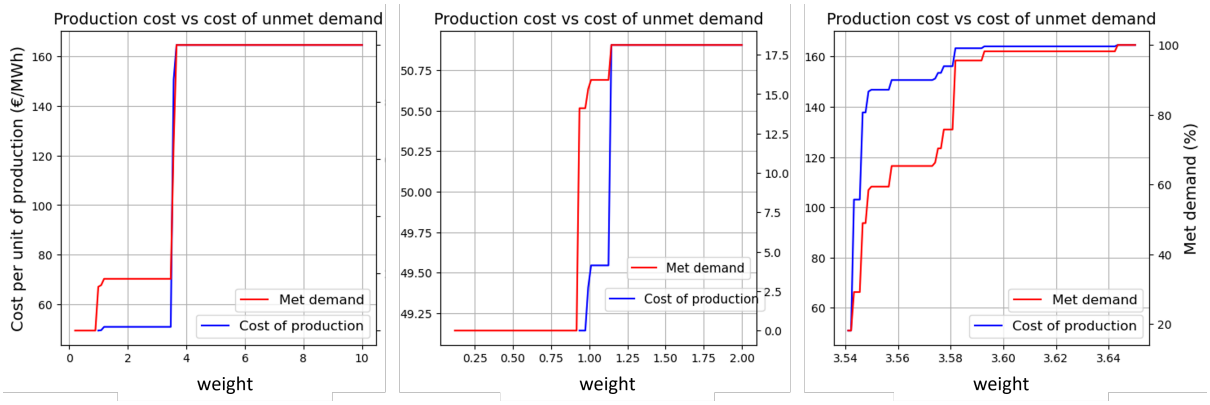


Figure 3.9: Relationship between weight of unmet demand and hydrogen production and transportation. A focus is brought to the eye with the 2 plots on the right side emphasizing the steps of the production cost.

3.54, that hydrogen starts to be exported to other countries, fulfilling the demand up to 100%. This confirms the phenomenon observed in the single-objective model but with an emphasis on achieving energy balance satisfaction.

In conclusion, the more importance we give to satisfying the hydrogen demand compared to the price we pay, the higher the impact on increasing both the unit production cost and the overall cost of transportation. This can be observed in two distinct steps. Firstly, there is an increase in local hydrogen production to meet the demand without any import or export. Secondly, as the emphasis on demand fulfillment intensifies, the market opens up for transportation, resulting in a sudden surge in transportation and production for each country involved.

3.2.3.3 Global market trends

Studying the case with a low weight value is unnecessary as the focus is primarily on price minimization. With such emphasis on cost reduction, there are no exportations observed. Furthermore, for weight values below one, there is no production as there is no imposition to satisfy the demand, which differs from the approach taken in the single objective analysis.

That being said there are four transportation flow maps in the Figure 3.10. The leftmost map represents the case where the competitivity is 0.1 and the weight is 3.5. It can be observed that only 29.7 percent of the produced hydrogen is being transported. Several countries choose not to fulfill their hydrogen demand. Algeria stands out as the country with the highest production, and due to favorable relations between Algeria and France, France is the only European country benefiting from hydrogen exportation by Algeria.

In the second map from the left map, the competitivity is now set to one, and the ratio of transported hydrogen to produced hydrogen is 63%. Compared to the previous situation, it can be observed that when resources are constrained, Algeria, with its significant production potential and low production cost, tends to centralize hydrogen production. Moreover, as more resources become available, the global price tends to be minimized, encouraging further exportation. A relatively low weight to fulfill the energy balance

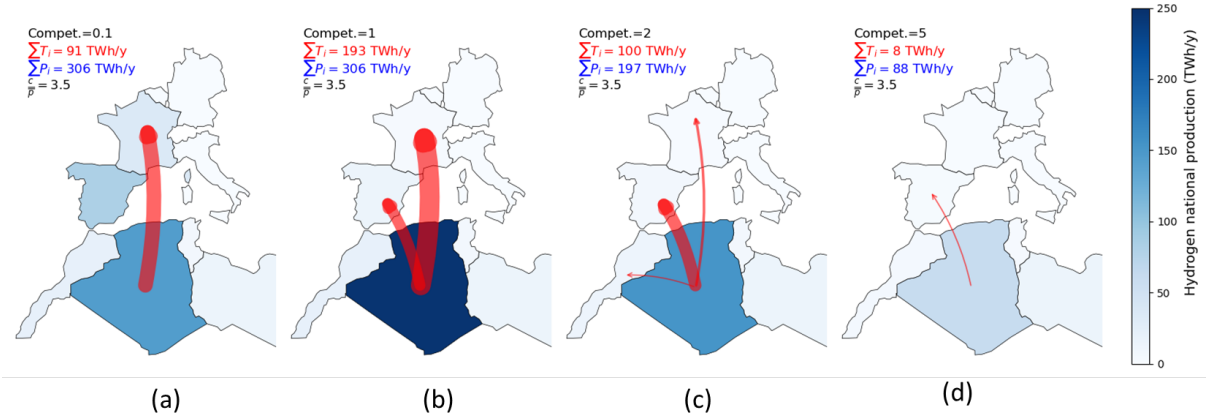


Figure 3.10: Hydrogen flows for different competitivity values (0.1, 1, 2, and 5) for the bi-objective function model with c=3.547

leads to fewer countries satisfying their demand by centralizing hydrogen production, with Algeria being a prominent player due to its low production cost.

In the third map from the left, we observe the case of competitivity equal to two, where there are only half the available resources compared to the demand. The same trend of centralization by Algeria in production and exportation of resources is observed. In this scenario, Algeria tends to export to geographically closer countries, such as Morocco, Spain, and France, in order to minimize costs relative to the energy balance.

Finally, on the rightmost figure, we can see that Algeria is the last country to satisfy its demand and export hydrogen. It chooses to export to Spain, which has the lowest export cost for Algeria.

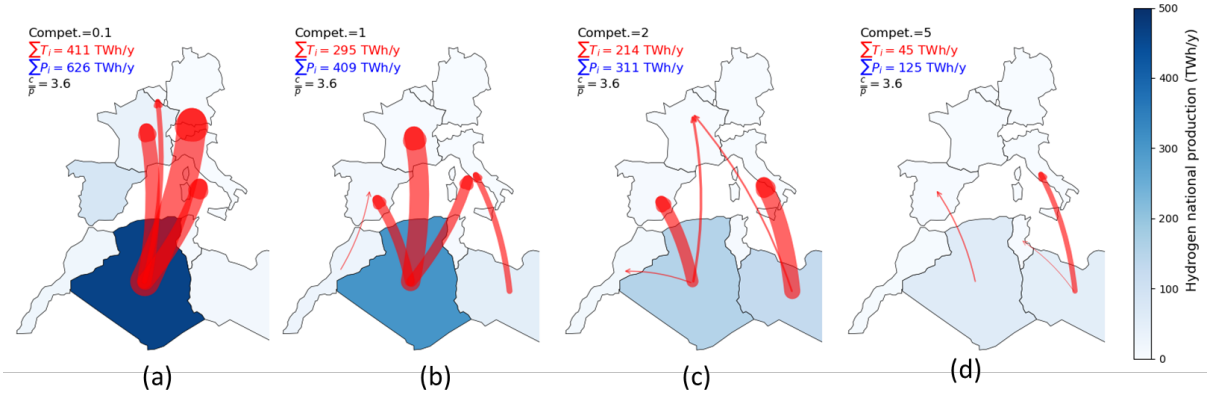


Figure 3.11: Hydrogen flows for different competitivity values (0.1, 1, 2, and 5) for the bi-objective function model with c=3.7

Now let's compare it briefly with Figure 3.11. It consists of four maps arranged from left to right, representing increasing competitivity values. In this case, we consider a competitivity value of c=3.7, which is very close to the single objective case we previously examined in Figure3.6, particularly for high competitivity values. This is because in the single objective definition, there is a greater emphasis on fulfilling the energy balance, and

therefore, we are closer to that objective with a competitivity value of c=3.7 compared to c=3.547.

The most significant differences are observed when competitivity equals 1. In this scenario, we observe that Algeria exports more to Germany and less to France. These differences highlight that in markets where fulfilling the demand is of utmost importance, variations in competitive scenarios with global availability close to the demand can result in different commercial flows as shown also in 3.7. In more extreme situations of competitivity, the subtle differences between countries become more pronounced as the competition intensifies, leading to clearer trends and some countries taking the lead.

Finally, we can summarize as follow:

1. Low competitivity leads to limited hydrogen transportation and countries choosing not to satisfy their demand.

2. Increasing competitivity results in a higher ratio of transported hydrogen to produced hydrogen, with Algeria centralizing production and export.

3. Limited resources lead to a continued trend of centralization by Algeria in production and export, with a focus on geographically closer countries.

4. In scenarios where availability is close to the demand (competitivity close to one), we observe a greater diversity of strategies. The sensitivity to competition is higher, resulting in more pronounced differences between countries. On the other hand, for more extreme competitivity values, countries tend to adopt clearer positions, leading to more distinct and evident trends.

Chapter 4

Game theory model

A Nash equilibrium is a concept in game theory that represents a stable state in a game where each player's strategy is the best response to the strategies chosen by the other players. In a Nash equilibrium, no player has an incentive to unilaterally change their strategy because doing so would not improve their own payoff. It is a self-enforcing state where all players are satisfied with their choices given the choices of others. Nash equilibria can exist in both cooperative and non-cooperative games and provide a framework for predicting and analyzing strategic interactions among multiple players.

In our case, using Nash equilibrium to model competition on the green hydrogen market is justified by its realistic assumptions and applicability to complex strategic interactions. Here are some reasons why it is suitable:

1. **Decentralized decision-making:** Nash equilibrium assumes that each market participant acts independently and makes decisions based on their self-interest. In the green hydrogen market, multiple players, such as producers, suppliers, and consumers, operate autonomously, striving to maximize their own benefits. Nash equilibrium captures this decentralized decision-making process.

2. **Strategic interactions:** Competition in the green hydrogen market involves strategic interactions among players who anticipate and react to each other's choices. Nash equilibrium provides a framework to analyze and understand how players' strategies interact and influence market outcomes. It helps capture the dynamics of competition and the interplay between supply and demand.

3. **No unilateral improvements:** Nash equilibrium implies that no player can unilaterally deviate from their chosen strategy to achieve a better outcome. This assumption aligns with the real-world dynamics of the green hydrogen market, where participants face constraints and limitations in terms of resources, infrastructure, and technology. Players must carefully consider their strategies and anticipate the actions of others to maintain a competitive position.

4. **Market stability:** Nash equilibrium represents a stable state where no player has an incentive to change their strategy, assuming rational behavior. This stability is desirable in the green hydrogen market, as it provides predictability and helps inform investment decisions and long-term planning. It allows market participants to assess the potential outcomes and risks associated with their strategies.

While Nash equilibrium has its limitations, such as assuming perfect information and rationality, it still offers valuable insights into the competitive dynamics of the green hydrogen market. By considering players' strategic decision-making and the interdependence of their choices, it provides a realistic and practical framework for modeling competition and analyzing market outcomes.

4.1 Model description

This model is first based on the implementation of the game theory model developed in [6]: «Game Theory-Based Allocation of Critical Resources during Natural Disasters ».

In our study, we have adapted an allocation model originally developed for disaster resource allocation to address the specific context of the green hydrogen market. This adaptive model incorporates four penalty costs that capture various aspects of resource allocation. We will utilize the Nash equilibrium as a benchmark for analyzing the market dynamics. Given that it is a game involving multiple players and strategies, we have tailored the model to appropriately reflect the dynamics and complexities of the green hydrogen market.

In the context of game theory with n players and n strategies, a gain matrix represents the potential outcomes or payoffs that each player can achieve based on their chosen strategies and the actions of other players. Each element in the gain matrix corresponds to the gain or utility that a player obtains when they play a particular strategy against the strategies chosen by other players. The gain matrix provides a comprehensive view of the interdependencies and interactions among players, allowing for the analysis of strategic decision-making and the identification of optimal strategies that maximize individual or collective gains.

4.1.1 Sets

In contrast to the global optimum model, our approach in modeling the green hydrogen market differs in terms of considering bilateral sets at the initial stage. Rather than focusing on specific allocations between individual countries, our allocation model takes into account the collective potential of global availability within the set of countries involved. This distinction highlights the perspective of allocating resources based on the overall capacity and competition among the participating countries, rather than prioritizing bilateral relationships. By considering the broader set and the global availability of resources, we aim to capture the dynamics and strategic decision-making within the market more comprehensively.

Sets	**Index**	**Description**
$\mathcal{C}$	i	Set of considered countries

Table 4.1: Table of the data sets used in the game theory model

4.1.2 Parameters

In our current modeling approach, the parameters involved are reduced in scope. As we do not consider bilateral relationships at this stage, the focus is primarily on two essential factors: the demand for green hydrogen and the availability of resources. By simplifying the parameters to these fundamental elements, we aim to establish a foundational understanding of the market dynamics based on the overall supply-demand balance and adapt the model described in the studied article to be sure it is correctly implemented. This approach allows us to analyze the allocation of resources within the context of the global availability and the varying levels of demand across the participating countries.

Parameter	Description	Unit
a_i	Green hydrogen availability in country i	MWh
d_i, d_j	Demand for country i and associated demand for country j	MWh

Table 4.2: Parameters used in the game theory model. All units refer to values per year

4.1.3 Decision variable

Decision variable	Description	Unit
K_i	Allocated amount of hydrogen to country i	MWh

Table 4.3: Allocation to countries i. This corresponds to the sum of the production plus the importations minus the exportation corresponding to the global optimum model

4.1.4 Constraints

$$\sum_i K_i \leq \sum_i a_i \quad \forall i \in \mathcal{C}$$
$$K_i \geq 0 \quad \forall i \in \mathcal{C}$$
$$0 \leq G_{i1}, G_{i2}, G_{i3}, G_{i4} \leq 1 \quad \forall i \in \mathcal{C}$$

4.1.5 Objective functions

The objective function is defined as:

$$\min(G_{i1} + G_{i2} + G_{i3} + G_{i4})$$

The penalty costs from this additive model are defined in the following section 4.1.6.

4.1.6 Penalties costs definition

We will describe those penalty costs here. Those were simplified in order to avoid quadratic expressions for the following reasons:

1. Computational Efficiency: Solving linear problems is generally faster than solving quadratic problems, especially for large-scale optimization models. The computational complexity of quadratic expressions can significantly increase solution time.

2. Uniqueness of Solutions: Quadratic expressions can have multiple local optima, making it challenging to determine the global optimum. Linear expressions, on the other hand, often result in unique solutions, ensuring the optimality of the obtained results.

3. Numerical Stability: Quadratic expressions can be more prone to numerical instability, such as rounding errors and ill-conditioned matrices. Linear expressions, being simpler mathematically, tend to exhibit better numerical stability and robustness.

4.1.6.1 Penalty of under utilization

$$G_{i1} = \max\{0, \sum_{i}^{n} a_i - K_i - \sum_{j \neq i}^{n} K_j\} \cdot \frac{d_i - K_i}{d_i} \quad \forall i \in \mathcal{C}$$

1. The function $\max 0, \sum_i^n a_i - K_i - \sum_{j \neq i}^n K_j$ calculates the difference between the total available resources ($\sum_i^n a_i$) and the allocated resources to country i (K_i), subtracting the allocated resources to all other countries ($\sum_{j \neq i}^n K_j$). If this difference is negative (indicating under utilization), the function returns zero, otherwise it returns the difference.

2. The term $\frac{d_i - K_i}{d_i}$ represents the fraction of the unmet demand for country i compared to its total demand. It quantifies the extent to which the demand is not fulfilled due to under utilization.

The product of these two components reflects the cost incurred due to underutilization. It assigns a higher penalty when the underutilization is more significant, indicated by a larger unmet demand fraction. This cost term is multiplied by the weight assigned to the underutilization penalty to determine its overall impact on the optimization objective.

In order to implement it, we need to normalize the coefficient in such a way that it can interact equally with the other variables. Then, we need to adjust its form so that the decision variables do not appear in a quadratic manner.

if competitivity ≥ 1 :

$$G_{i1} = \left(1 - \frac{\sum_{j \in \mathcal{C}_i} K_j}{\sum a_i}\right) \cdot \left(1 - \frac{K_i}{d_i}\right) \quad \forall i \neq j \in \mathcal{C}$$

else:

$$G_{i1} = 0 \quad \forall i \neq j \in \mathcal{C}$$

As you noticed, we made an exception for G_{i1} by keeping it as a quadratic expression for two reasons:

1. Differentiation: G_{i1} serves a distinct purpose from G_{i2}, which represents its weight. By keeping G_{i1} quadratic, we can differentiate it clearly from G_{i2}.

2. Stability and Efficiency: Despite the general recommendation to avoid quadratic expressions, we found that including G_{i1} in this form did not significantly affect stability or computational efficiency in our tests.

Considering the specific characteristics of our problem, we determined that retaining G_{i1} as a quadratic term was a reasonable choice.

4.1.6.2 Penalty of dissatisfaction

$$G_{i2} = \frac{d_i - K_i}{d_i} \quad \forall i \in \mathcal{C}$$

By dividing the difference between the demand and allocated resources by the demand itself, the penalty cost G_{i2} is computed. This ratio represents the relative dissatisfaction or inefficiency in meeting the demand. A higher value indicates a larger deviation from the demand and implies a higher cost of dissatisfaction.

In summary, the penalty cost G_{i2} captures the cost associated with the dissatisfaction arising from the shortfall between the demand and the allocated resources for country i. It provides a measure of the relative inefficiency or shortfall in meeting the demand, enabling the evaluation and optimization of resource allocation in the context of hydrogen distribution.

4.1.6.3 Penalty of creating restrictions on opponent

$$G_{i3} = \max\{0, \sum_{j}^{n} d_j - \sum_{i}^{n} a_i + K_i\} \cdot \frac{1}{\sum_{j}^{n} d_j} \quad \forall i, j \in \mathcal{C}, i \neq j$$

The penalty cost G_{i3} is determined based on the difference between the total demand of all countries and the sum of available resources, taking into account the allocation to country i. The maximum function ensures that G_{i3} is non-negative, and the weight is defined as the reciprocal of the sum of demands of all countries. This penalty captures the cost associated with creating restrictions on opponents, indicating the impact of resource scarcity on allocation decisions.

4.1.6.4 Penalty of creating conflicts

G_{i4} represents the penalty cost for creating conflicts in resource allocation among countries. It is determined by the excess allocation of resources ($K_i + \sum_j^n K_j - \sum_i^n a_i$) and the fairness factor based on the ratio of allocated resources to demand for each country ($\frac{\frac{K_i}{d_i}}{\frac{K_i}{d_i} + \sum_j^n \frac{K_j}{d_j}}$). The penalty cost is incurred only when there is a conflict (excess allocation) and is influenced by the fairness of resource distribution. It is defined as follow:

$$G_{i4} = \max\{0, K_i + \sum_{j}^{n} K_j - \sum_{i}^{n} a_i\} \cdot \frac{\frac{K_i}{d_i}}{\frac{K_i}{d_i} + \sum_j^n \frac{K_j}{d_j}} \quad \forall i, j \in \mathcal{C}, i \neq j$$

The simplified expression of G_{i4} is the following:

$$G_{i4} = \frac{\sum_{j \in \mathcal{C}_i} K_j}{A} \cdot \frac{1}{1 + \frac{d_i}{D - d_i}} \quad \forall i \in \mathcal{C}$$

The simplified expression involves constraining the sum of allocated resources to be greater than or equal to half of the minimum availability ($\text{mini} \cdot 0.5$). Then, for each country i, the value of G_{i4} is calculated using the simplified expression, ensuring that it is proportional to the allocated resources K_i and adjusted based on the availability and demand factors. If the competitivity is less than 1, G_{i4} is set to 0 for all countries.

4.1.7 Monetization

The monetization process involves converting the penalty costs and price differentials into weighted factors that can be combined and minimized to determine an optimal solution. Here are the steps involved:

1. **Compute the allocation weight based on the penalty cost:** The penalty costs, such as the ones associated with under utilization or dissatisfaction etc. are calculated for each player in the market. These costs reflect the negative consequences of not meeting demand or creating restrictions. The allocation weight is then derived from these penalty costs, representing the importance or priority given to each player's allocation in the overall optimization process.

2. **Associate a weight to the price:** The actual price of green hydrogen is compared to a reference or minimal price. The difference between the actual price and the minimal price indicates the deviation or premium associated with that particular price. A weight is assigned to the price, which captures the relative significance of the price difference in the overall optimization objective.

3. **Minimize the sum of allocation and price weight:** The optimization problem aims to find the allocation of green hydrogen resources that minimizes the overall weighted sum of the allocation and the price weight. By minimizing this combined objective, the process aims to find a solution that balances the efficient allocation of resources while considering the price differentials.

By incorporating both the allocation weight based on penalty costs and the weight associated with the price, the monetization process takes into account the trade-off between meeting demand and minimizing price differentials. It seeks an optimal solution that strikes a balance between efficient resource allocation and cost considerations in the green hydrogen market.

A bridge can be established through the constraints involving variables P_i and T_i with the coefficients K_i represented as:

$$K_i = P_i + \sum_j (T_{L_{j,i}} + \sum_k T_{S_{k_{j,i}}}) - \sum_j (T_{L_{i,j}} + \sum_k T_{S_{k_{i,j}}})$$

In this equation, K_i represents the coefficient associated with the bridge, while P_i, $T_{L_{j,i}}$, $T_{S_{k_{j,i}}}$, $T_{L_{i,j}}$, and $T_{S_{k_{i,j}}}$ are the respective variables and coefficients involved in the computation. The sums are taken over the appropriate indices, with j representing one range

of indices and k representing another range. We then introduce the following expression, which represents the objective function of our global optimum single objective model:

$$Z_i = \sum_{i \in C} P_i \cdot p_i + \sum_{i \in C} \sum_{j \in C} T_{ij}^L \cdot t_{ij}^L l_{ij}^L + \sum_{i \in C} \sum_{j \in C} \sum_{k \in D} T_{ijk}^S \cdot (t_{ijk}^S l_{ijk}^S + r_k^S)$$

In order to ensure a robust normalization with the allocation penalties G_i, we introduce the weight c_z to represent the significance of the cost component. The variable $p_{\min}$ represents the minimal price that is computed based on a given level of competitivity within the global optimum model. It reflects the minimum price at which the system can operate while still maintaining the desired level of competitivity. By considering this minimal price, we can evaluate the economic viability and feasibility of the solution, ensuring that the system remains competitive while optimizing its overall performance. We then normalize Z_i:

$$G_{iZ} = \frac{Z_i}{p_{\min}}$$

Finally, our new objective:

$$\min(G_{i1} + G_{i2} + G_{i3} + G_{i4} + G_{iZ} \cdot c_Z)$$

4.1.8 Gurobi implementation

In a game with n players and m strategies, the minimum value of the gain matrix corresponds to the Nash equilibrium. The Nash equilibrium represents a set of strategies where no player can unilaterally improve their gain by deviating from their chosen strategy, assuming all other players stay consistent.

It's important to note that the Nash equilibrium may not be unique. There can be multiple combinations of strategies where players achieve the same minimum gain. This means that there can be several Nash equilibria in a game, and the players can choose different strategies while still reaching a stable outcome. The existence of multiple Nash equilibria highlights the complexity and strategic interactions present in the game. The unique combination of strategies chosen by players can depend on various factors, such as their preferences, beliefs, and the specific rules and dynamics of the game itself.

When implementing a continuous set of variables in a game, it introduces the possibility of an infinite number of strategies. This means that the resulting game can be represented by an n by m dimensional matrix, where n is the number of players and m is the number of potential strategies.

Due to the potentially infinite number of strategies, it becomes impractical to test every possible minimum as a Nash equilibrium.

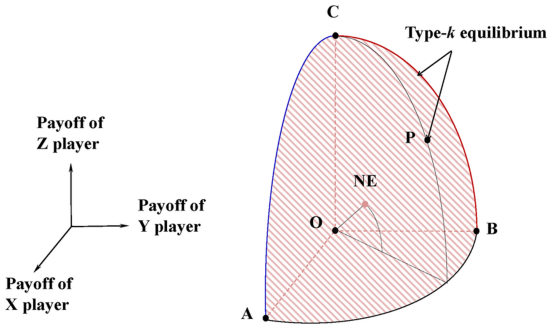


Figure 4.1: Visualization of a 3 players gain matrix (3 dimensional)

The large dimensionality of the matrix makes it challenging to ensure uniqueness and stability of the equilibrium solution.

As a result, the complexity and computational burden of considering every potential minimum can lead to instabilities in the solution as we had in the beginning C. To address this, it is common to simplify the problem by employing certain assumptions, approximations, or restrictions on the strategies and variables. This allows for more manageable and reliable analyses of the game's equilibrium.

By reducing the dimensionality and employing appropriate techniques, it becomes feasible to explore and identify meaningful Nash equilibria within the game, balancing the trade-off between accuracy and computational efficiency.

We introduced a set of binary variables, denoted as x_{ij}, to represent the selection of strategies within each player's set of available options. These variables take binary values: $x_{ij} = 1$ if strategy j is selected by player i, and $x_{ij} = 0$ otherwise. Additionally, we introduced a set of continuous variables, denoted as K_i, to represent the allocation of hydrogen for each player's strategy. These variables are bounded between 0 and the sum of the available hydrogen, denoted as A.

To ensure feasibility, we imposed constraints on the total allocation of hydrogen, which should not exceed the available amount. This can be expressed as: $\sum_{i \in \mathcal{C}} K_i \leq A$. We also added constraints to enforce non-negativity of the allocation variables: $K_i \geq 0$ for all $i \in \mathcal{C}$. Next, we ensured that each player selects exactly one strategy by imposing the constraint: $\sum_{j \in \mathcal{S}} x_{ij} = 1$ for all $i \in \mathcal{C}$, where $\mathcal{S}$ represents the set of all possible strategies.

Finally, we established the relationship between the binary selection variables (x_{ij}) and the continuous allocation variables (K_i) using the strategy matrix (strat). This relationship can be expressed as: $K_i = \sum_{j \in \mathcal{S}} \text{strat}_{ij} \cdot x_{ij}$ for all $i \in \mathcal{C}$.

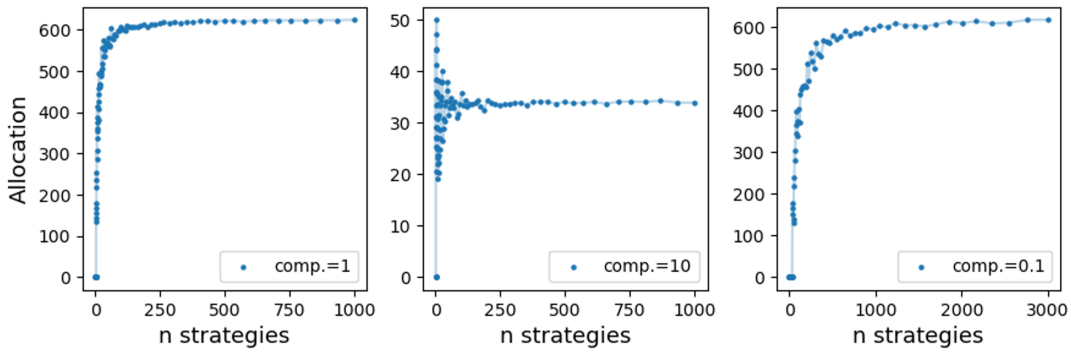


Figure 4.2: Convergence for different values of competitivity for the fully implemented game theory model. Taking a set of n=1000 strategies seems a justified choice.

The figure displayed above in 4.2 illustrates the convergence behavior of the solution as the number of strategies increases. As we can observe, the solution rapidly converges to a stable point with increasing numbers of strategies. This convergence indicates that the essential trends and optimal solutions are captured effectively even with a relatively

small number of strategies. Further increasing the number of strategies is unlikely to significantly alter the overall outcome. Therefore, this bounded set of strategies provides a sufficiently accurate representation of the problem, allowing us to focus on the larger trends and avoid excessive computational complexity.

4.2 Results

4.2.1 Simplified case

The following matrices represent a scenario involving three players (Belgium, France, and Morocco) and three strategies. Each country has a different level of demand, indicated by the values (3, 8, 1), with a total demand of 12. The players can choose from three different strategies: 0, 1, and 3. The maximum availability of resources for each country is given by (3, 3, 3), totaling 9. The competitivity factor is set to 0.75.

This plot provides a visual representation with the color scale: greener representing minimal values, more red the worst values (associated to maximum penalty). This helps us to introduce the concept of solving for gain matrices that will later be implemented in Gurobi with n dimension.

By subtracting the allocated resources from the desired demand and dividing it by the desired demand, we obtain a normalized value that represents the extent to which the player's demand is not being fully satisfied. A lower value of G_{i2} indicates a better allocation and a lower dissatisfaction cost for player i.

Therefore in Figure 4.3 we well see that G_{i2} aims to minimize the penalty or cost associated with the deviation between the allocated and desired resources for each player leading to the maximization of the allocation as we see with the minimal value achieved for (3,3,3).

Belgium: 0

France \ Morocco	0	1	3
0	3.0	2.0	0.0
1	2.9	1.9	-0.1
3	2.6	1.6	-0.4

Belgium: 1

France \ Morocco	0	1	3
0	2.7	1.7	-0.7
1	1.5	0.5	-0.8
3	1.3	0.3	-1.0

Belgium: 3

France \ Morocco	0	1	3
0	2.0	1.0	-1.0
1	1.9	0.9	-1.1
3	1.6	0.6	-1.4

Figure 4.3: G_{i2}, 3 countries, 3 strategies simplified case gain matrix

In Figure 4.4 we observe that the minimal values are attained when there is no allocation of resources for France, Morocco, and Belgium (0,0,0). This corresponds to setting the allocation values for these countries to zero. The resulting cost associated with imposing restrictions on resource allocation is found to be 1.6. This cost represents the penalty or cost incurred when resources are restricted or not allocated to certain countries.

Belgium: 0

France \ Morocco	0	1	3
0	1.6	1.7	1.9
1	1.9	2.0	2.2
3	2.4	2.5	2.7

Belgium: 1

France \ Morocco	0	1	3
0	1.8	1.8	2.0
1	2.0	2.1	2.3
3	2.5	2.6	2.8

Belgium: 3

France \ Morocco	0	1	3
0	2.0	2.1	2.2
1	2.2	2.3	2.5
3	2.7	2.8	3.0

Figure 4.4: G_{i3}, 3 countries, 3 strategies simplified case gain matrix

By combining G_{i2} and G_{i3}, we observe that the minimal cost is achieved by allocating a value of 3 to Belgium while allocating nothing to Morocco and France. Interestingly, this strategy was not present in the minimal solutions obtained from G_{i2} or G_{i3} alone as shown in Figure 4.5

Belgium: 0

France \ Morocco	0	1	3
0	4.6	3.7	1.9
1	4.8	3.9	2.0
3	5.0	4.1	2.3

Belgium: 1

France \ Morocco	0	1	3
0	4.4	3.5	1.4
1	3.5	2.6	1.5
3	3.8	2.9	1.7

Belgium: 3

France \ Morocco	0	1	3
0	4.0	3.1	1.2
1	4.1	3.2	1.4
3	4.4	3.4	1.6

Figure 4.5: G_{i2}+G_{i3}, 3 countries, 3 strategies simplified case gain matrix

This highlights the unpredictability and complexity that arises when considering the combination of multiple strategies. The interplay between different factors and objectives can lead to unexpected optimal solutions. This phenomenon mirrors the dynamics of real-life competitions, where cooperation, unexpected alliances, and strategic interactions can significantly impact outcomes.

The findings underscore the importance of considering the holistic perspective and exploring various combinations of strategies to uncover unique and potentially advantageous solutions. It highlights the need to account for the intricacies and complexities inherent in real-world competitive scenarios, where the interplay of multiple factors can yield unconventional and unforeseen outcomes.

4.2.2 9 countries study case

Utilizing the same set of countries as considered in the global optimum allows for a more streamlined and comprehensive comparison among them. By maintaining consistency in the country selection, we can effectively analyze and evaluate their respective strategies, allocations, and associated costs in a coherent manner. This approach facilitates a more focused examination of the specific dynamics and variations exhibited by each country, enabling us to draw meaningful insights and make informed decisions based on the observed outcomes.

4.2.2.1 G_{i1}: under utilization

From Figure 4.6, G_{i1} demonstrates a significant decrease in value when considered independently, as evident from the allocation of resources towards the right side of the plot. The corresponding penalty associated with this allocation is remarkably low, as depicted on the left side. It is noteworthy to mention that, based on the simplified definition, the value of G_{i1} for competitivity values less than 1 is zero.

This outcome arises due to the inherent characteristics of the max function and the scenario where available resources surpass the total demand. In such cases, discussing under utilization becomes ambiguous since the system is intrinsically constrained by its own demand. This situation gives rise to a singularity, rendering the function non-continuous specifically at competitivity equals to 1.

4.2.2.2 G_{i2}: dissatisfaction

In Figure 4.7, we have two graphs. The one on the left represents the cost of penalty, G_{i2}, which reflects dissatisfaction, as a function of competitivity. We observe a minimum at a competitivity value of one, and a maximum as competitivity approaches zero, indicating infinite resource availability. It is logical to observe an increase in the penalty cost with an increase in competitivity, as G_{i2} is inherently proportional to the unmet demand, which decreases with decreasing resources. However, we also notice an increase in this cost for

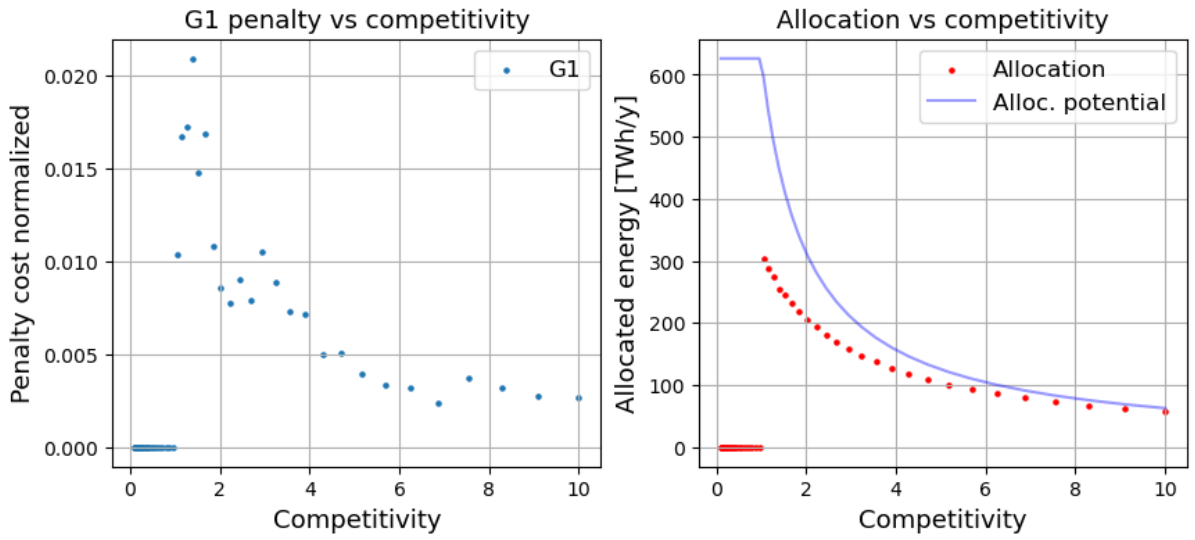


Figure 4.6: Cost of under utilization analysis vs competitivity on the left and ressources allocation associated on the market on the right hand side graph

non-competitive cases. This is because G_{i2} is also proportional to the difference between available resources and allocation, but constraints prevent allocation beyond the demand. As resource availability tends towards infinity, the cost of dissatisfaction also increases. This is reflected on the right graph, showing a decrease in allocation with an increase in penalty cost, resulting in maximum allocation at a competitivity value of one, where resources exactly match the global demand.

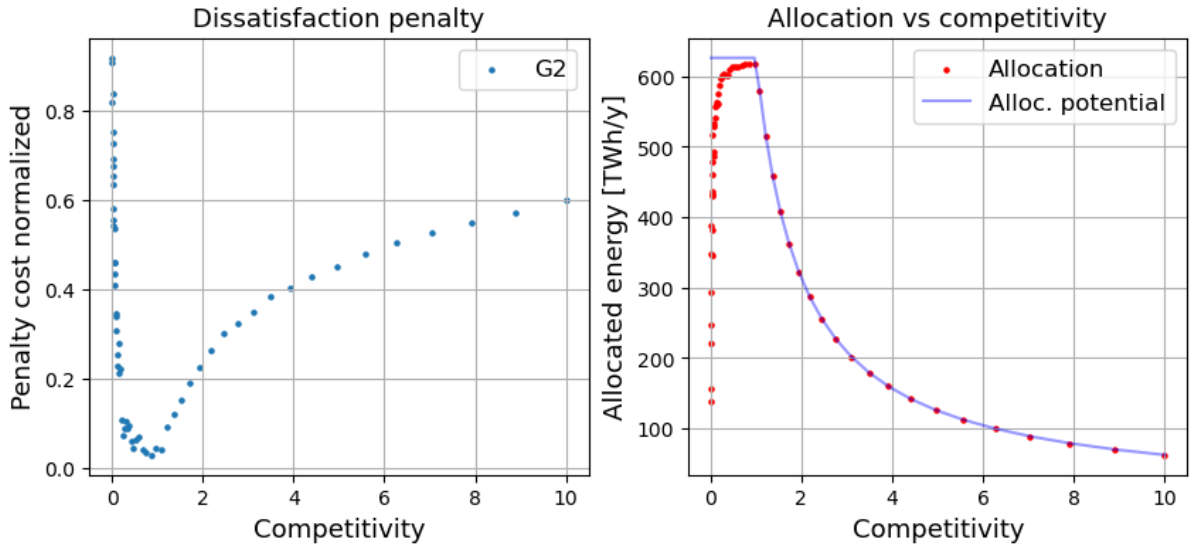


Figure 4.7: Cost of dissatisfaction analysis with competitivity increase and ressources allocation solution

4.2.2.3 G_{i3}: imposing restrictions

In the following Figure 4.8, we observe that an increase in the penalty coefficient always leads to a decrease in the allocation. However, for the case of G_{i3}, we see that for

a competitivity value lower than 0, the coefficient becomes zero. This is because, in this situation, the availability of resources exceeds the demand, and therefore, G_{i3} is zero according to its definition. As we enter a competitive system, G_{i3} increases with the restriction of resources, as the cost of restricting other competitors becomes higher. When we examine the allocation for G_{i3} alone, we find that it remains almost zero, except around a competitivity value close to 1. For values lower than 1, there is no incentive to have a non-zero allocation at the moment, as the cost of G_{i3} will remain the same.

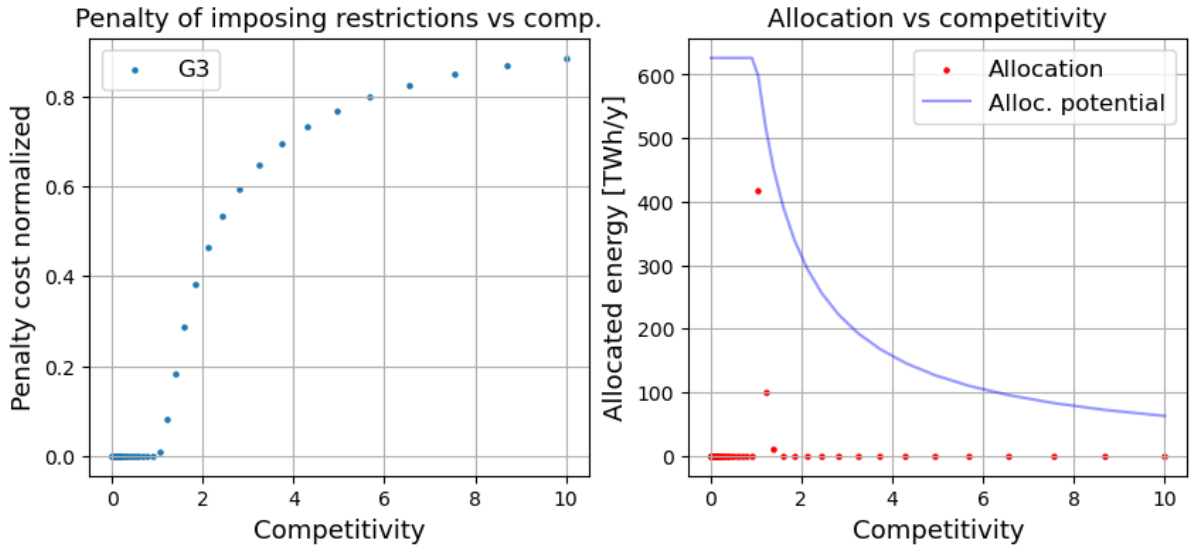


Figure 4.8: Cost of creating restrictions on opponents analysis with competitivity increase and ressources allocation solution

4.2.2.4 G_{i4}: creating conflicts

The inclusion of the constraint to use at least half of the available hydrogen ensures that there is a minimum level of resource allocation among the countries. Without this constraint, the penalty cost for creating conflicts (G_{i4}) would be zero for all countries, as the optimal strategy to minimize conflicts would be to allocate no resources at all. By requiring a minimum allocation of half the available hydrogen, the model considers a realistic scenario where some allocation is necessary for the functioning of the system and allows for the evaluation of conflicts arising from resource distribution.

In Figure 4.9we see that G_{i4} is zero in the non-competitive case. This outcome is both logical and reflects the non-discontinuity observed in the function. However, as the competitivity increases, G_{i4} becomes highly unstable. It is intuitive to expect that conflicts would introduce a certain level of instability, and this cost component behaves accordingly. Although G_{i4} is not quadratic in nature, its sensitivity to increasing values aligns with the notion that conflicts inherently bring about a sense of instability.

4.2.2.5 Overall penalty

The combination of the four coefficients, G_{i1}, G_{i2}, G_{i3}, and G_{i4}, provides valuable insights into the cost dynamics associated with different scenarios in Figure 4.10:

G_{i1}, the cost for under-utilization, exhibits moderate instability in the competitive case. It remains relatively low, hovering around 0.25. This suggests that the penalty

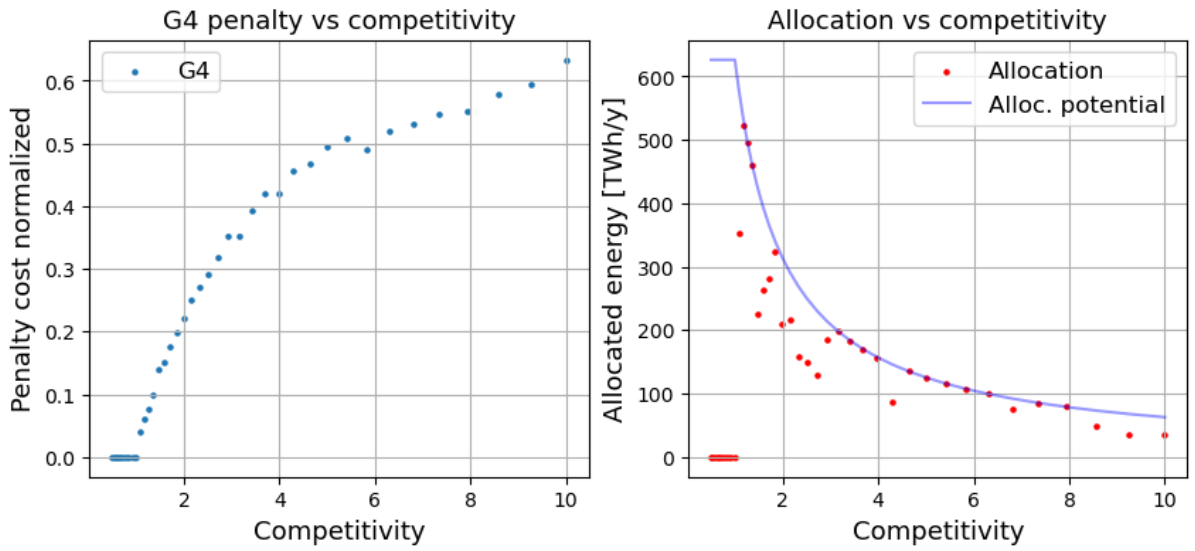


Figure 4.9: Cost of creating conflicts on opponents analysis with competitivity increase and ressources allocation solution

for not fully utilizing available resources is relatively mild but varies to some extent in competitive scenarios.

G_{i2}, the cost for dissatisfaction, is relatively high and stable. It shows a discontinuity at competitivity=1, the only coefficient that is non-zero in non-competitive cases. As competitivity increases, G_{i2} also increases, indicating a higher penalty for not meeting demand and satisfying players.

G_{i3}, the cost for imposing restrictions on opponents, demonstrates stability in its behavior. It steadily increases with competitivity, reaching its highest values from competitivity=3 to approximately 0.9 at competitivity=10. This coefficient reflects the cost associated with limiting opponents' resource allocation and highlights the increasing penalty as competitivity intensifies.

G_{i4}, the cost for creating conflicts on available resources, exhibits instability similar to G_{i1}. It follows a somewhat comparable pattern but shows a slight increase with competitivity. On average, G_{i4} hovers around 0.35, suggesting that creating conflicts among available resources incurs a moderate cost.

The spline interpolation of the mean of all the coefficients forms a shape resembling a logarithmic curve. It increases with competitivity and approaches zero for competitivity values below 1. There is a sharp slope just above 1 due to the discontinuity observed in G_{i2}. Overall, the general penalty associated with resource allocation rises with competitivity, reflecting the increased stressfulness of the market and the greater penalties imposed on allocations in situations of resource scarcity.

From the analysis of these coefficients, we can infer that as competition intensifies, players face higher penalties for under-utilization, dissatisfaction, and restrictions on opponents, while the cost of creating conflicts on available resources remains relatively

stable. This suggests that resource allocation strategies need to be carefully considered in highly competitive scenarios to minimize costs and ensure efficient utilization.

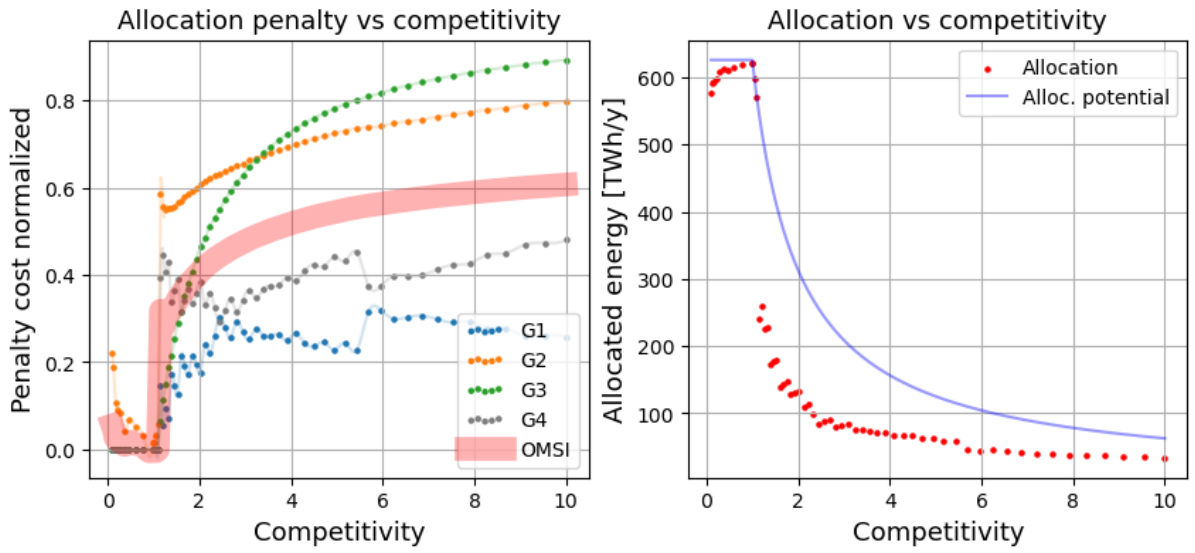


Figure 4.10: Combination of every introduced costs. OMSI: Overall Mean Spline Interpolated

As we further analyse Figure 4.10, we notice that in competitive scenarios, we observe that resource allocation remains around half of the total potential. This can be attributed to the lowest level of under utilization, indicating that participants are efficiently utilizing available resources. However, as competitivity reaches 1, which represents a balanced state of demand and supply, we see a significant increase in resource allocation, where all available potential is utilized. This shift highlights the impact of competitivity on resource allocation decisions.

The graph also reveals an interesting pattern in the global coefficient curve. As competitivity decreases from high values towards 1, there is a steep decreasing slope in the coefficients. This decrease in penalty values leads to an increase in resource allocation. Notably, the range between 1 and 1.2 exhibits significant changes, suggesting a critical threshold where market dynamics undergo substantial transformations. A similar phenomenon is observed in the bi-objective analysis of the global optimum model.

Furthermore, the graph illustrates that even a slight shortage in resources can trigger substantial changes in the market. In the range of competitivity from 1 to 1.5, where demand slightly surpasses supply, there is an increase in dissatisfaction and conflicts among participants. This reflects the market's effort to maintain equilibrium and balance in the face of resource scarcity. As competitivity continues to increase beyond this range, the magnitude of market shocks and disruptions becomes relatively smaller. Dissatisfaction levels continue to rise, but conflicts decrease in intensity. However, the cost associated with imposing restrictions on resource allocation experiences a significant increase. The phenomenon observed in situations with a high level of availability (comp«1) where dissatisfaction increases significantly can be described as the "satiation effect."[1] It reflects

[1]Economic satiation: The economic principle of satiation[1] is the effect whereby the more of a good

a psychological phenomenon where individuals become less satisfied as the quantity of resources available to them increases.

Overall, the graph provides valuable insights into the dynamics of the green hydrogen market, emphasizing the sensitivity of resource allocation to competitivity and the impact of resource shortages or surpluses on market behavior. Understanding these dynamics is crucial for effective market management, strategic decision-making, and achieving sustainable outcomes.

The key points:

- Maintaining balance: In competitive scenarios, participants strive to maintain equilibrium and fight for it.
- Dissatisfaction increases with distance from equilibrium: As the market moves further away from the balanced state, dissatisfaction among participants increases.
- Peak of conflicts: When an imbalance occurs after a period of equilibrium, it creates a shock to the market, leading to a peak in conflicts among participants.
- Scarce resources and restrictions: In situations with limited availability of resources, the cost associated with imposing restrictions on resource allocation becomes dominant compared to other costs.
- Underutilization and incentive: Underutilization of resources plays a crucial role in preventing the market from stagnating. It ensures that each country has the incentive to fulfill its own demand, promoting market activity and dynamics.
- Additive model combination: The combination of the various costs and penalties in the additive model provides a comprehensive framework for understanding the dynamics and trade-offs in resource allocation within the green hydrogen market.

4.2.2.6 Monetization

Finding the appropriate balance for the coefficient c_z can pose a challenge. To achieve a desirable equilibrium between components, we can seek the ratio closest to one by varying the c_z value. Specifically, we aim to calculate the mean of the ratios with our set of $n = 9$ countries:

$$G_{\text{ratio}} = \frac{1}{n} \sum_{i=1}^{n} \left(\frac{G_{i1} + G_{i2} + G_{i3} + G_{i4}}{G_{iZ}} \right) \forall i \in \mathcal{C}$$

where G_{i1}, G_{i2}, G_{i3}, G_{i4}, and G_{iZ} represent different components in the model, and N is the total number of instances. Likewise, we can apply a similar approach by examining the variation of the Levelized Cost of Hydrogen (LCOH) concerning the c_z coefficient. By evaluating the mean ratios resulting from different c_z values, we can determine the impact on the equilibrium between the LCOH component and other factors in the model.

one possesses, the less one is willing to give up to get more of it. This effect is caused by diminishing marginal utility, the effect whereby the consumer gains less utility per unit of a product the more units consumed.

These analyses will assist in identifying the most suitable weight for the c_z coefficient, ensuring a balanced consideration of its influence on the overall model dynamics. The results are presented in Figure 4.11 in which three graphs are presented. The left graph illustrates the relationship between the Levelized Cost of Hydrogen and c_z. As c_z increases, the LCOH value also increases, indicating a higher cost of hydrogen production.

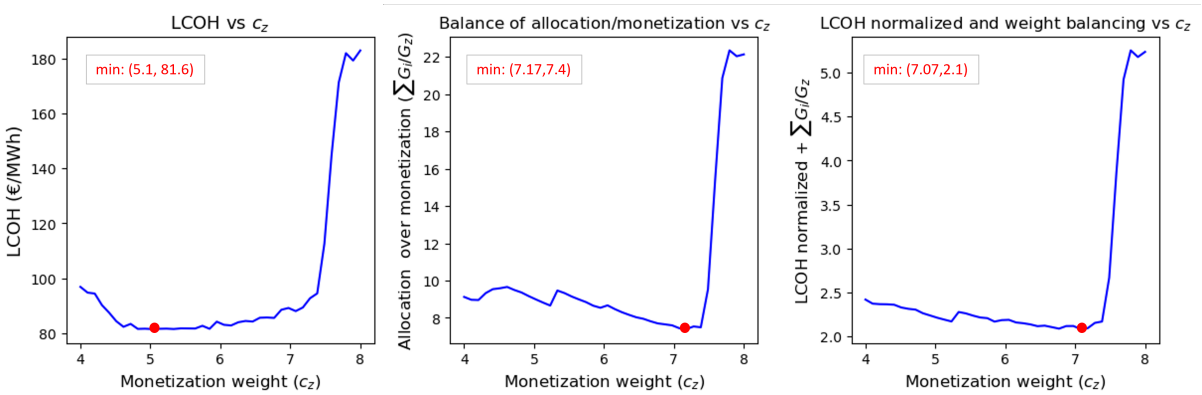


Figure 4.11: The mean value for LCOH and G_{ratio} was taken for a range of competitivity from 0.1 to 10 divided through 30 points. Each point corresponds at the mean for the 9 countries over this range.

The middle graph shows the relationship between the G_{ratio} and c_z. The G_{ratio} represents the ratio of the sum of the coefficients $G_{i1} + G_{i2} + G_{i3} + G_{i4}$ to G_{iZ}. As c_z varies, the G_{ratio} fluctuates accordingly, representing the balance of allocation based on the game theory model.

The right graph displays the sum of the LCOH and G_{ratio} plotted against c_z. The minimal value of this sum occurs at $c_z = 7.09$. However, for practicality and a rounded value, we choose $c_z = 7$ as the reference value for the model. This minimum represents the best balance between the effect of price on the market (G_{iZ}) and the effects of allocation developed through the game theory model (the sum of the coefficients $G_{i1}+G_{i2}+G_{i3}+G_{i4}$).

In practice, it has been observed that a c_z coefficient equal to 7 is not representative of the model. In reality, there are three different coefficient values that result in different scenarios: low values, medium values, and high values. In the Figure 4.12, there are two graphs illustrating different aspects of the relationship between allocated hydrogen, competitivity , and various scenarios based on the c_z coefficient.

On the left graph, we observe the allocation of hydrogen versus competitivity . The graph showcases three distinct scenarios: black representing low c_z values, red representing middle c_z values, and yellow representing high c_z values. As defined, a higher c_z value indicates a greater emphasis on minimizing the total cost (Z) compared to the allocation components (Gi). Consequently, as c_z increases, less energy is allocated, prioritizing cost reduction and favoring cheaper options.

On the right graph, we see the relationship between the LCOH and competitivity . Several interesting observations can be made:

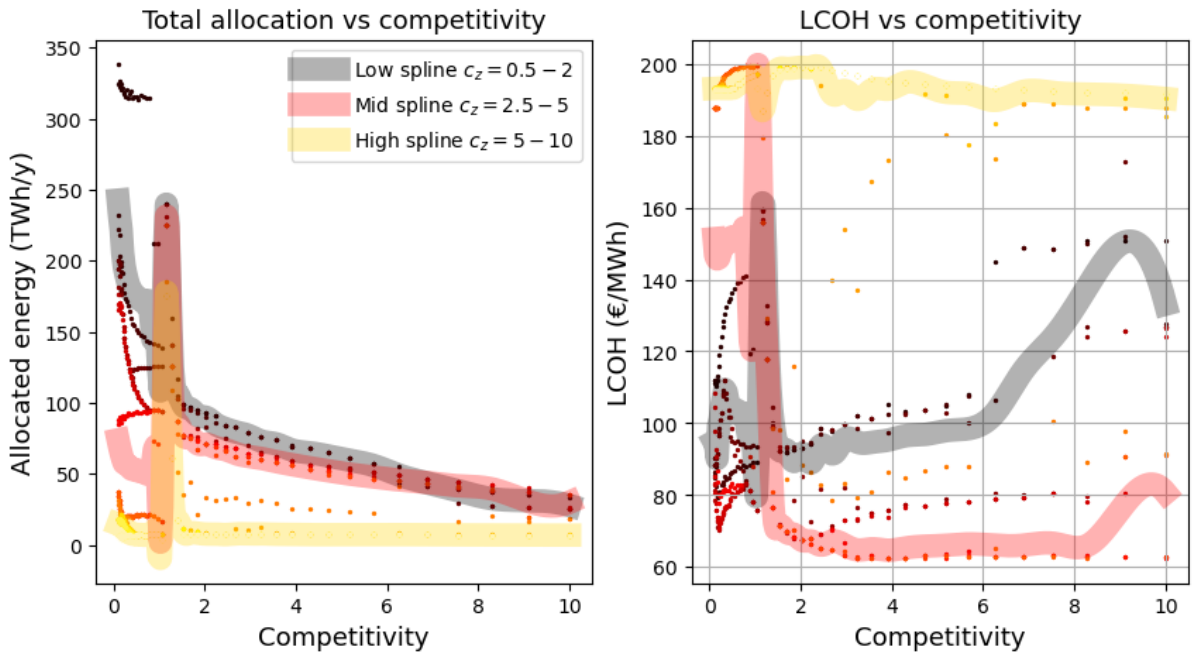


Figure 4.12: The graphs are compiled from 20 different c_z values, ranging from 0.5 to 10

- Low c_z values show a trend of increasing LCOH as competitivity rises.
- Middle c_z values exhibit the lowest LCOH overall, suggesting a more cost-effective allocation strategy.
- High c_z values maintain high LCOH for all levels of competitivity . This indicates that emphasizing cost minimization does not necessarily lead to a lower LCOH; in fact, it may result in higher costs.

In summary, the key observations from these graphs are that higher c_z coefficients prioritize minimizing the total cost over energy allocation, while middle c_z values tend to yield the lowest levelized cost of hydrogen. Additionally, increasing competitivity may lead to higher LCOH for certain c_z scenarios, suggesting the existence of limited resources and heightened competition in the market.

By analyzing the figure 4.13 it becomes evident that the shape of the graph remains consistent for both low and high values of c_z. This leads us to an important conclusion: the behaviors differ based on the degree of importance assigned to allocation competition. In reality, these behaviors are simply focused on minimizing costs for each country, rather than favoring one component over the other.

To achieve a balanced situation, we can consider the non-extreme point, which lies at the intersection of low and high c_z values. This point represents an average behavior where neither component is prioritized over the other. Therefore, the game theory model takes into account the significance of prices as well as the behavioral aspects described by G_i. This conclusion is derived from experimental simulations that involved examining extreme values and inferring information about intermediate situations.

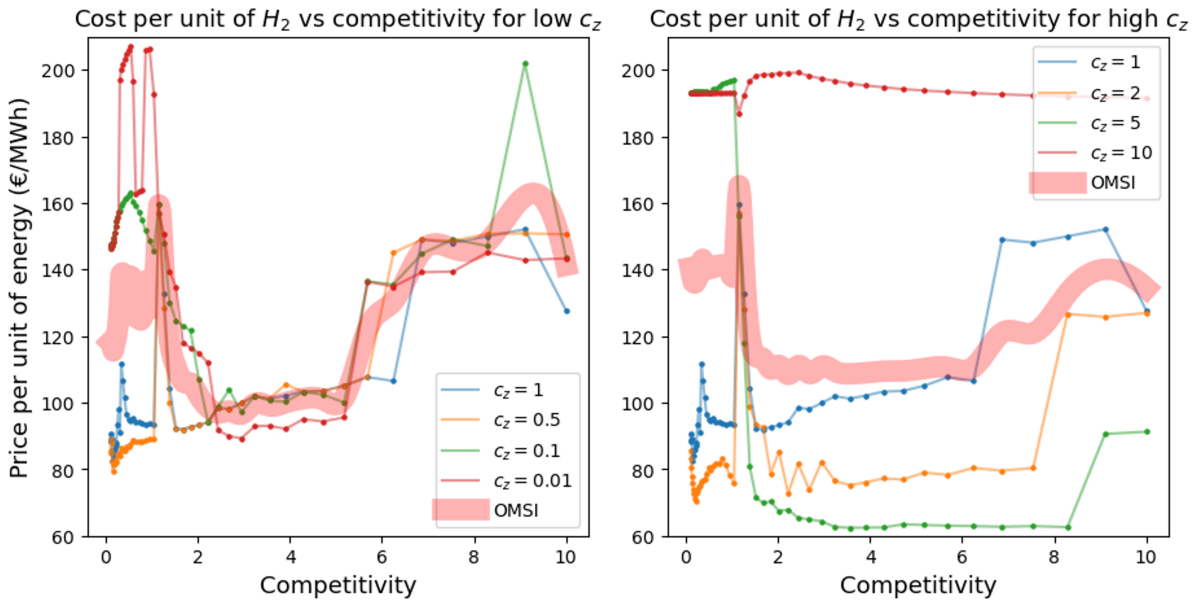


Figure 4.13: LCOH analysis for different values of c_z. We observe that the global trend OMSI (overall mean spline interpolation) has globally the same shape.

An interesting observation is that we observe converging behavior for extreme values ($c_z < 1$ and $c_z > 8$). However, for values around 5, we encounter a different scenario. In this case, we can conclude that both components of the model are taken into account. Furthermore, it is noteworthy that these intermediate values minimize the levelized cost of hydrogen (LCOH), making them particularly intriguing as we saw in Figure 4.11.

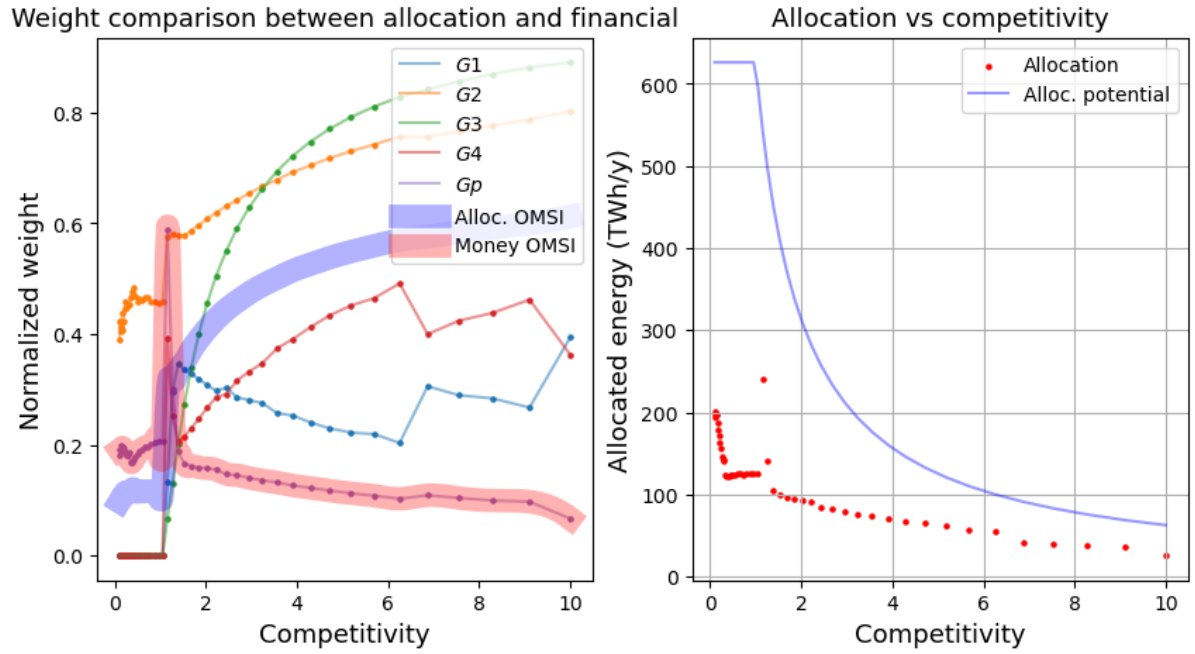


Figure 4.14: Per component analysis of the game theory model and the allocation associated to it for $c_z = 1$

The next figure in 4.14 the normalized weights for G_{ratio} and all the G_i components. On the left side of the graph, we observe that as competition increases, penalty coefficients

for G_i become higher, while they decrease for G_p. This indicates that as competition intensifies, the effects of allocation, such as conflicts and restrictions, become more significant compared to the importance of achieving a better price. This observation aligns with logic, as the cost of these behaviors in a scarce resource market becomes more pronounced. Consequently, minimizing the price of resources becomes secondary since there is no guarantee of obtaining a sufficient quantity of resources.

In conclusion, we can consider a C_z value of 1 as a well-balanced coefficient compared to $C_z = 7$. This is because the analysis shows that simply minimizing the LCOH is not a reliable indicator of an optimal solution. Instead, considering a balanced approach that takes into account both allocation competition and cost considerations can lead to more favorable outcomes.

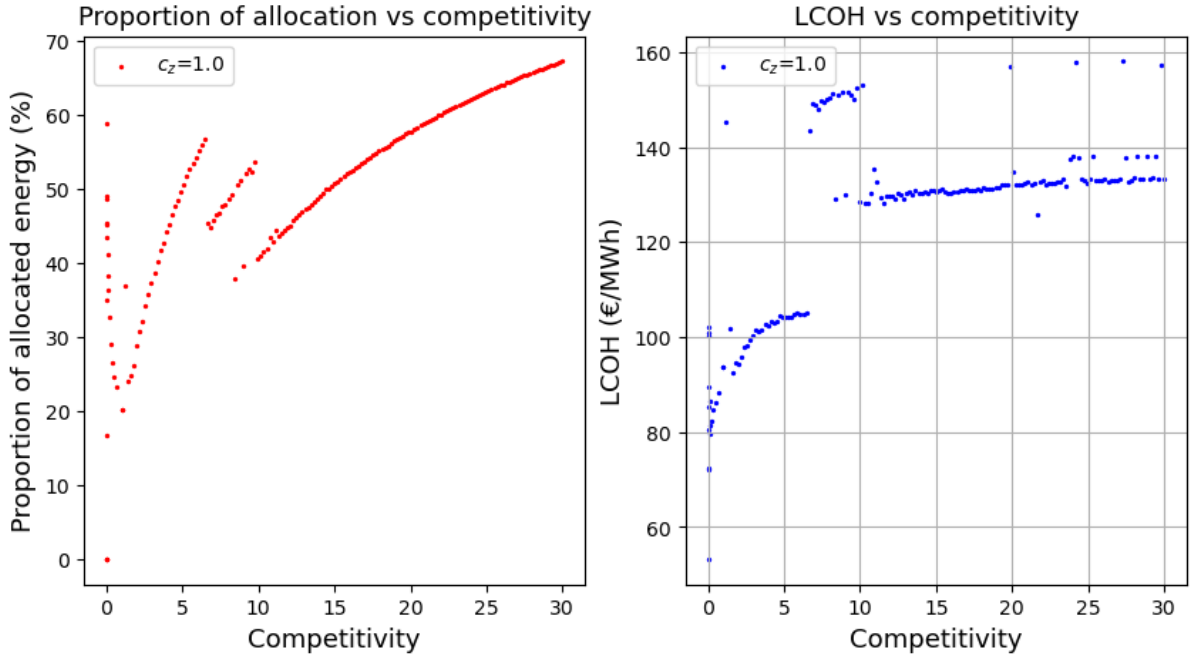


Figure 4.15: The competitivity points were distributed using a combination of logarithmic and linear spacing, totaling 170 points. This distribution was chosen to ensure a comprehensive representation of the studied dynamics.

In the Figure 4.15, we can observe the following:
On the left side, we see the percentage of potential allocation, which is calculated as the allocation divided by the maximum possible allocation. This percentage tends to increase with more scarce resources. Despite increased market competition, the total resource allocation proportionally increases. This suggests that even in a competitive environment, the overall allocation of resources tends to rise when resources become more limited.

On the right side, we have the levelized cost of hydrogen, which increases with higher competitivity . However, as resources become more available, the LCOH decreases. This decrease occurs because countries have more options and can choose suppliers offering better prices. Notably, once competitivity reaches a level of 10, the LCOH remains relatively stable. This indicates a relatively stable market where resource allocation among countries does not have strong incentives to change, as each country chooses a

strategy that minimizes their penalty cost of allocation and price.

Contrarily, we observe a different pattern between competitivity levels of 6 to 10. In this range, a different market flow strategy emerges, resulting in higher global LCOH values. This suggests that the dynamics of the market shift in this situation, leading to an overall increase in the cost of hydrogen production.

The hydrogen market defined here is inherently characterized by its variability. As we impose constraints on resources, such as increasing competitivity , the ideal production and transportation flows can undergo significant redefinition as we saw in Figure 4.15 within the 7-10 competitivity range. In reality, bilateral agreements between countries play a crucial role in mitigating these shifts and ensuring a certain level of reliability in import and export dynamics. By establishing bilateral agreements, countries create a framework of stability and cooperation, avoiding abrupt and disruptive changes in import and export patterns. These agreements foster a sense of reliability and trust among nations, allowing for smoother and more predictable trade relations in the hydrogen market.

In summary, bilateral agreements serve as a means to address the market's natural variability, ensuring a more controlled and consistent approach to production and transportation flows, and fostering reliability and stability in import and export dynamics between countries.

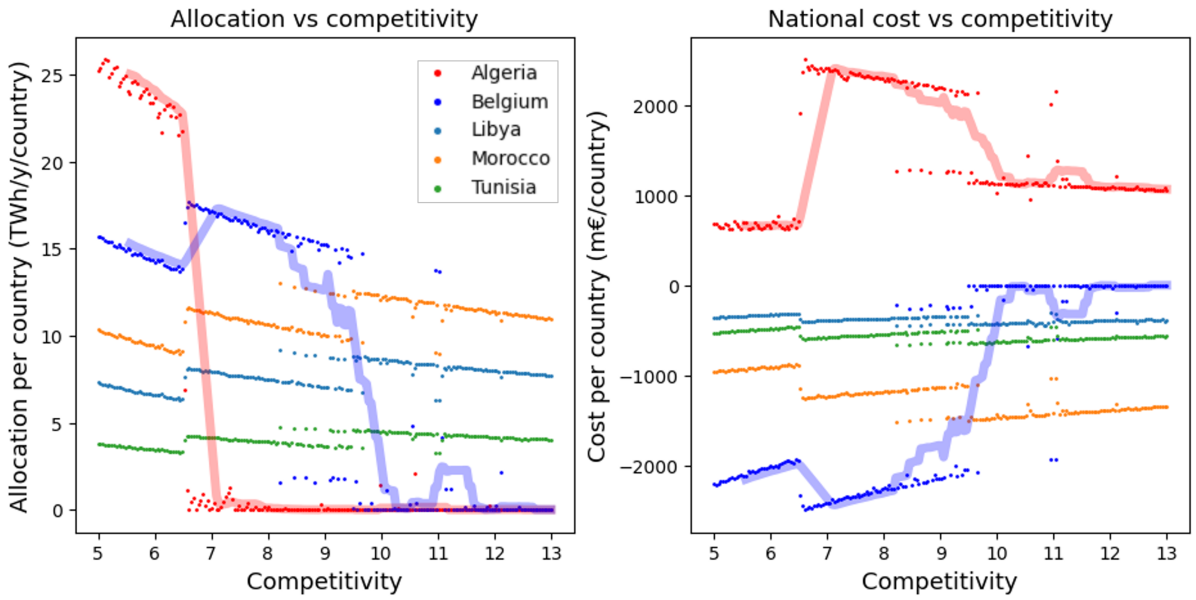


Figure 4.16: The countries with zero allocation have been removed for the clarity of the graph. The rolling mean (wide line) aim to underline the two mains actors of the studied dynamics: Algeria and Belgium.

We observe in Figure 4.16 a significant dynamic between two countries in the analysis: Belgium and Algeria. Surprisingly, as competition intensifies, there is a sharp reduction in the allocation to Algeria at a competitivity level of 7, followed by a decrease for Belgium shortly after. This underlines the fact that any country can choose to quickly change its strategy on the market, implicating quick re adaptations of the general dynamics.

Furthermore, in the graph depicting Algeria's perspective, we notice that ceasing self-allocation leads to higher revenues (indicated by positive cost being a gain and negative cost being a loss in the graph). This implies that certain countries may deliberately choose to develop their electrolysis facilities and export the produced hydrogen, rather than consuming it domestically, as the model suggests it would be more advantageous. Consequently, Belgium ceases its imports as the cost of importing becomes prohibitively high. In response, the three remaining countries slightly increase their own allocations, taking advantage of the temporary decrease in market constraints and the opportunity for a proportionally lower penalty.

As we introduced the global dynamics, it is necessary to dive into the country specific situation as we can represent it on the following maps with the production and transportation flows:

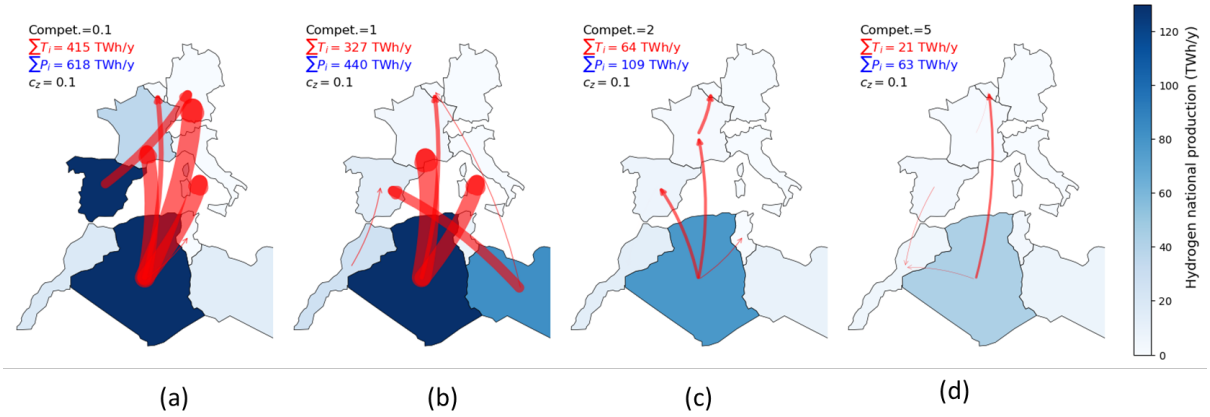


Figure 4.17: Market flows for low importance on the weight (c_z) for the cost compared to the competition aspect ($\sum G_i$)

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Figure 4.17 illustrates a scenario with low competitivity (c_z). It shows a behavior close to pure allocation, with significant exports from Algeria to the entire Europe. However, the pipeline connections are constrained to Belgium and Spain through Morocco, leading to a specific route for high competition cases.

In Figure 4.18 , with $c_z = 1$, a different pattern emerges. At low competitivity , Algeria produces for its own consumption, while France serves as the primary exporter to Europe. This focus on price optimization is due to the higher competitivity compared to Figure 1. It suggests that when Europe has ample availability of green hydrogen, it becomes more cost-effective to produce domestically rather than import from North Africa. However, in high competition scenarios, similar to Figure 1, Algeria remains the cheapest option when Europe faces insufficient production capacity.

Figure 4.19 represents the case with $c_z = 10$, where the Levelized Cost of Hydrogen (LCOH) is very high. Despite this, the global price appears to be more minimized. The low hydrogen production capacity explains this trend. Surprisingly, in low competition scenarios, it becomes cheaper to export hydrogen from Europe to North Africa due to the bilateral price differences. In high competition situations, a combination of Algerian and European sources is observed.

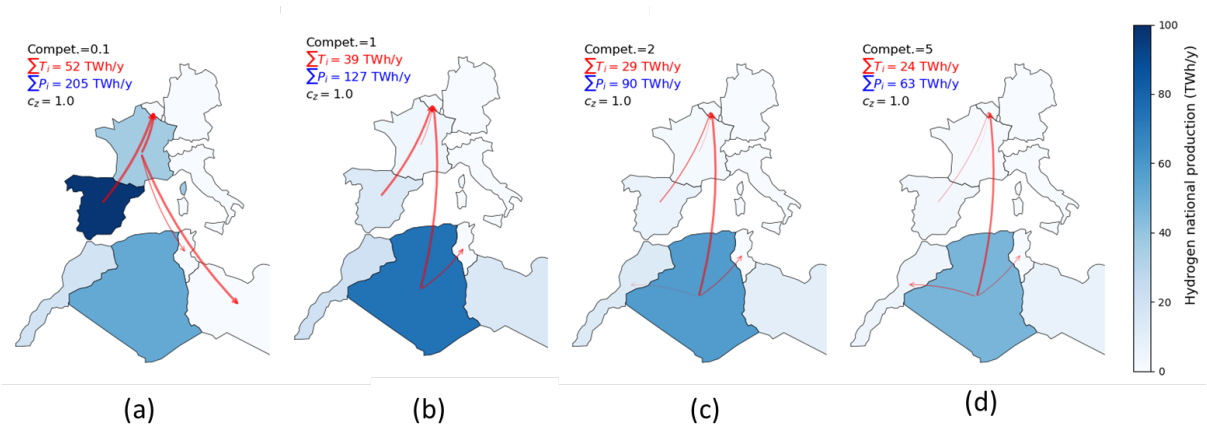


Figure 4.18: Market flows for balanced importance on the weight (c_z) for the cost compared to the competition aspect ($\sum G_i$)

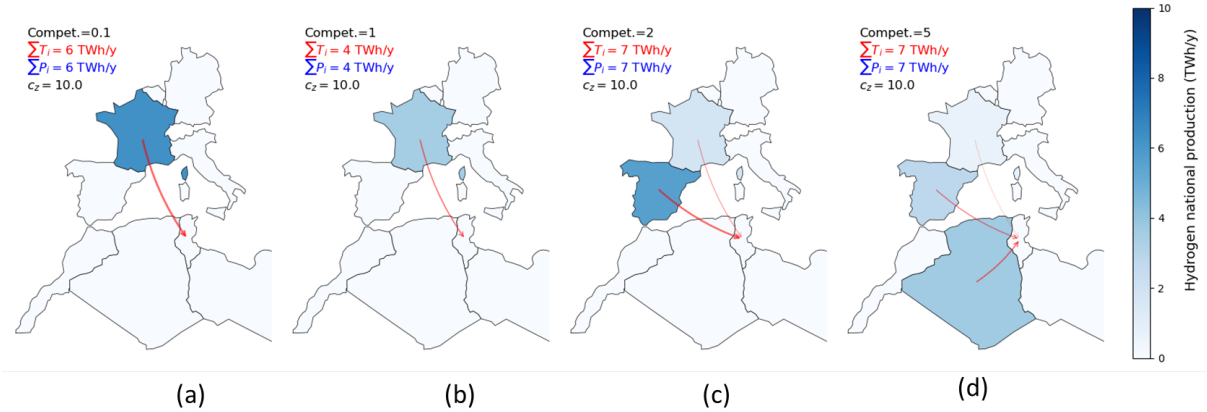


Figure 4.19: Market flows for high importance on the weight (c_z) for the cost compared to the competition aspect ($\sum G_i$)

These four maps provide insights into the dynamics of the green hydrogen market at different competitivity levels. They highlight the variations in production and export patterns between North Africa and Europe, shedding light on the complexities and trade-offs involved in resource allocation and market dynamics.

Chapter 5

Discussion

5.1 Models comparison

5.1.1 Game theory vs Global optimum

Two different models were developed: the global optimum model and the game theory approach. These models were refined to provide a more realistic view of market competition in the hydrogen sector.

The global optimum model focused on single or bi-objective optimization. In the single objective case, the model aimed to minimize the global price of hydrogen. In the bi-objective case, the goal was to minimize both the price and the unmet demand, which represents the shortfall between total demand and the produced units of hydrogen. This model provided a baseline for comparison and optimization in terms of price and demand fulfillment.

The game theory approach introduced additional elements to capture the dynamics of competition in resource allocation. In this approach, an additive model was developed with four penalty costs: under utilization, dissatisfaction, restrictions imposed on opponents, and conflicts created. These costs aimed to simulate the competition among different entities for resource allocation.

To further improve the realism of the game theory model, the monetization cost was integrated. This cost accounted for the production, transportation, and other associated expenses related to hydrogen production and distribution. By including these factors, the model was able to capture the economic aspects alongside the allocation competition penalties. The introduction of weights in the model also allowed for the consideration of different priorities and trade-offs between cost and allocation penalties.

Overall, the refinement of the models aimed to provide a more comprehensive and realistic representation of the market competition in the hydrogen sector. By incorporating game theory elements, allocation penalties, and economic considerations, the last model sought to capture the complex dynamics and trade-offs involved in decision-making processes related to hydrogen production, allocation, and pricing.

5.1.2 Allocation comparison

The Figure 5.1 showcases, on the left side, the allocation versus competitivity for different models: the global optimum (GO) model for both single and bi-objective cases with different weights for unmet demand, the game theory (GT) model focusing solely on allocation, and the GT model with the inclusion of monetization weight for $c_z = 1$.

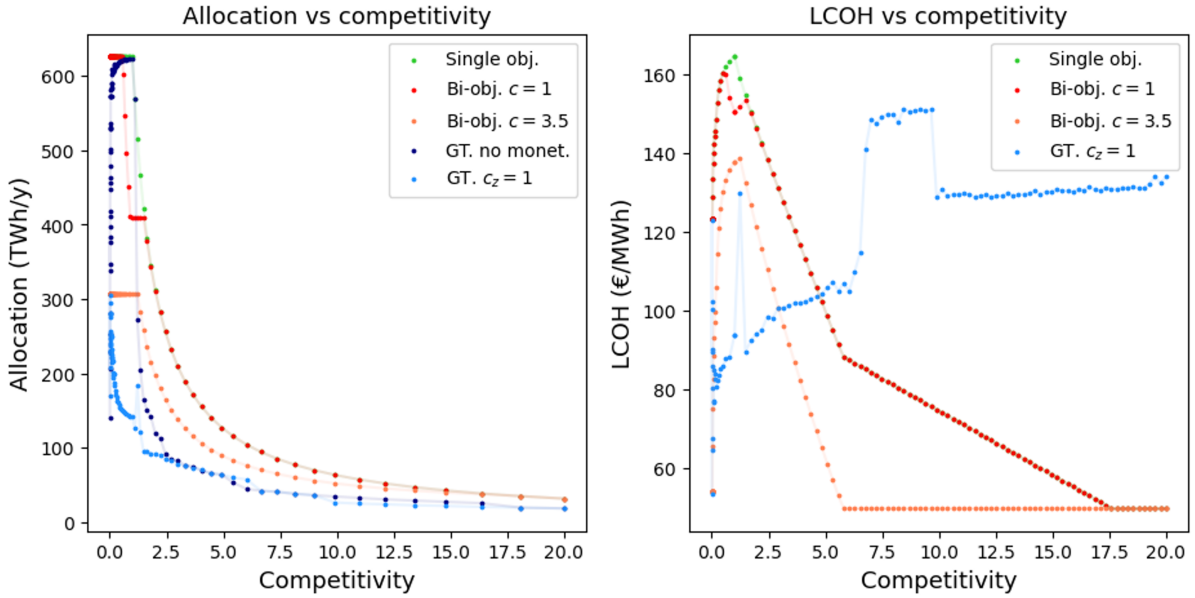


Figure 5.1: Models comparison for wide competitivity range. The difference between GO. and GT. is well marked and leads to more realism in monetization of GT.

In the single objective case, where the goal is to allocate everything available, the allocation remains constant regardless of competitivity . However, in the bi-objective case, as the weight of unmet demand increases, the allocation decreases. This suggests that when considering both price and demand fulfillment, allocating everything available is not the optimal strategy.

The GT model, which focuses solely on allocation, exhibits interesting behavior. At competitivity =1, it allocates everything available, reflecting its definition. As competitivity increases, the allocation decreases, indicating a more selective allocation strategy. This behavior aligns with the concept that higher competition necessitates more strategic resource allocation.

The GT model with monetization weight introduces an additional component to the allocation strategy. It starts with a minimum allocation of 20% at competitivity =1 and gradually increases with availability, reaching around 70% allocation in highly competitive markets. This model combines the strategic allocation of the GT approach with economic considerations. It avoids extreme allocation strategies and aims for a coherent allocation approach that balances competitivity and resource availability.

Based on the observations, we can draw several conclusions. The single objective approach, although naïve, emphasizes the importance of not solely focusing on allocating everything to achieve the best price. The bi-objective model initially performs well but

tends to converge to a single objective behavior in highly competitive markets, which is undesirable. The pure allocation approach of the GT model shows promise for competition but allocates everything in competitivity =1 by definition.

Finally, the GT model with monetization incorporates a coherent allocation strategy. By considering both competitivity and resource availability, it maintains a balanced allocation approach without reaching extremes. This model reflects the dynamics observed in real-world scenarios, where allocation strategies adapt to the level of competition and resource availability. In reality, these findings highlight the need for a nuanced approach to resource allocation. Simply allocating everything or solely focusing on competition may not yield the optimal outcomes. Instead, incorporating economic considerations and balancing the allocation strategy based on competitivity and resource availability can lead to more effective decision-making in the hydrogen market.

Now on the right in Figure 5.1 we observe that in the GO model, the LCOH exhibits a peak at competitivity level 1 and gradually decreases with increasing competitivity . This trend is driven by the availability of fewer resources, resulting in only the cheapest options remaining and a constant, minimum price, often around 50€/MWh for high competition cases. However, this simplistic focus on price alone does not capture the realistic dynamics of the market.

The GT model takes into account additional factors beyond price, including dissatisfaction, penalties for underutilization, restrictions, and conflicts. In markets with low competitivity , the LCOH is close to its minimum value, indicating minimal tension. The weightage of price and dissatisfaction plays a significant role in keeping the LCOH low. As competitivity increases, the LCOH experiences some instabilities around competitivity level 1. This can be attributed to the disruptive changes in strategies that occur during the transition from a non-competitive to a competitive market. During this phase, the LCOH tends to be higher as there may not be sufficient incentives for minimizing the global price, given the uncertainties and doubts surrounding the new competitive landscape.

Beyond a certain level of competitivity (around 10), the LCOH stabilizes, indicating a more settled market environment with a limited number of active participants. At this stage, the choices for buyers and sellers become constrained, reducing the need for drastic changes in allocation strategies. Notably, a step change in LCOH is observed between competitivity levels 7 and 10, with an increase from 100 to 150 €/MWh. This suggests that significant changes in allocation strategies are still possible within this range as countries become interdependent, where changes in strategies for some actors influence others, aligning with the concept of Nash equilibrium.

The comparison, in Figure 5.2, between the single objective and GT monetized models reveals distinct patterns in the allocation of green hydrogen production. In the single objective model, the focus is on maximizing production efficiency and minimizing costs. Consequently, Algeria, being a low-cost producer, allocates its resources to produce as much as possible. This results in Algeria being the primary producer in the region, exporting to various European countries.

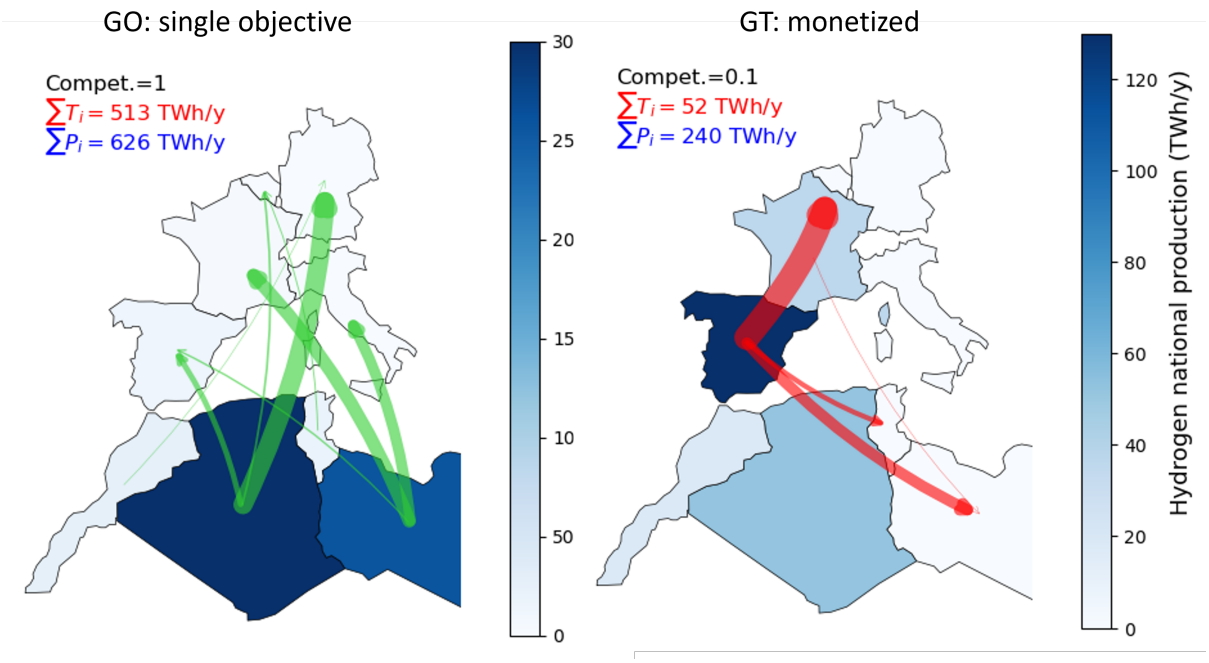


Figure 5.2: Flows comparison between single and GT model for competitivity=1.

On the other hand, in the GT monetized model, the allocation strategy is more centered on Europe. The influence of penalty costs becomes evident as countries consider not only production costs but also the economic dynamics of the market. The model shows interesting trade routes, such as exporting hydrogen from Spain to Tunisia and Libya. These allocations are driven by the consideration of penalty costs and the potential economic benefits derived from exporting hydrogen to neighboring countries.

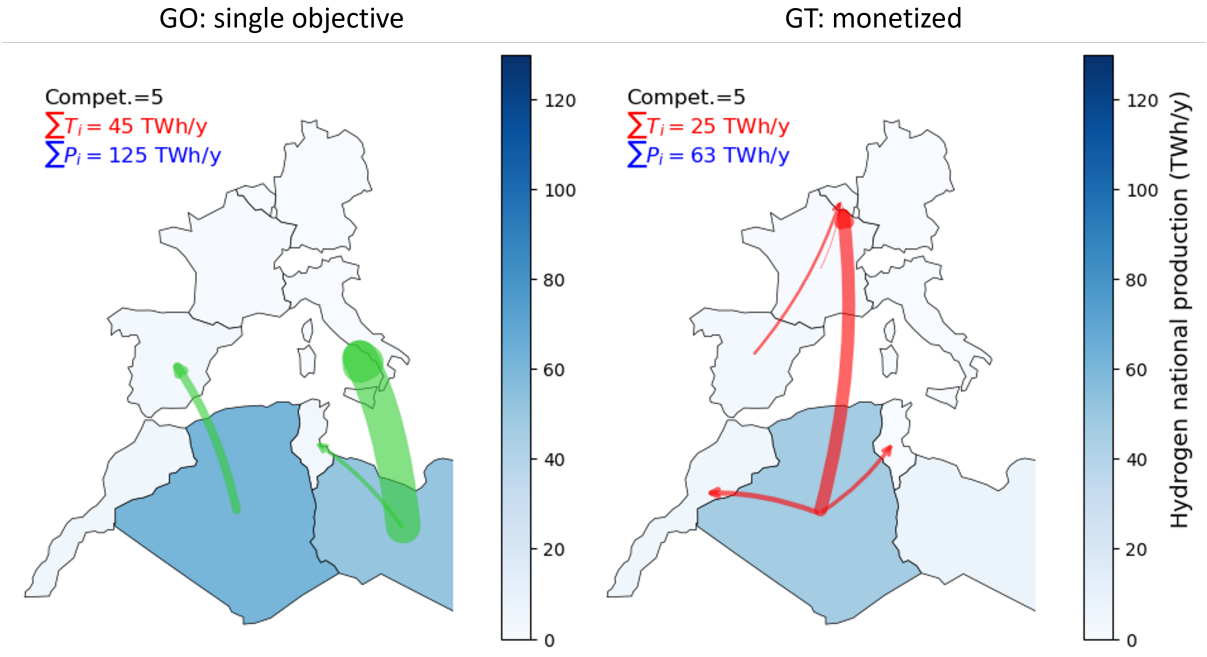


Figure 5.3: Flows comparison between single and GT model for competitivity=5.

As competitivity increases in Figure 5.3, we observe a convergence in the allocation of green hydrogen resources between North Africa and Europe in both the single objective and GT monetized models. The models predict an increase in the export of green hydrogen from North Africa to Europe as the competition intensifies. This convergence suggests that countries in North Africa become more competitive in the production and export of green hydrogen to meet the growing demand in Europe.

However, it is important to note that despite the convergence in allocation, there are still differences in behavior between the two models. In the GT monetized model, the weight of allocation plays a more significant role compared to the weight of price. This implies that countries may prioritize maximizing their allocation even if it results in higher costs. On the other hand, the single objective model tends to prioritize cost minimization, leading to a general decrease in the levelized cost of hydrogen.

Finally, the GT monetized model provides a more realistic representation of the market dynamics, considering the influence of both allocation and economic factors. The observed increase in LCOH in the GT monetized model aligns with the complexities and fluctuations of the real market, highlighting the importance of considering multiple factors in resource allocation.

5.2 Models limitations

Global Optimum (GO) model:

- Unrealistic allocation: The GO model assumes that all available resources can be allocated, which is not practical in real-world scenarios where resource limitations exist.
- Difficulty in assigning weights: The bi-objective nature of the model requires assigning weights to different objectives, which can be subjective and challenging to justify

. Game Theory (GT) model without monetization:

- Oversimplification of market behavior: The GT model without monetization simplifies the representation of the hydrogen market, failing to capture the specific behaviors and dynamics unique to the industry.
- Limited applicability: The model may not fully align with the complexities of the hydrogen market, limiting its usefulness in providing accurate insights and decision-making guidance.

Game Theory (GT) model with monetization:

- Challenges around competitivity equals to 1: The model faces difficulties in capturing the dynamics of the market when competitivity is at its lowest level. A small change in strategy can have significant impacts on the overall market, making it challenging to model accurately.

- Sensitivity to strategic changes: The model recognizes that even a slight change in strategy can lead to a substantial shift in the market dynamics, reflecting the inherent volatility and sensitivity of the hydrogen market.

These limitations highlight the complexities involved in modeling and analyzing the hydrogen market. While the GO and bi-objective models have their drawbacks, the GT model with monetization addresses some of the shortcomings by incorporating cost considerations and providing a more comprehensive representation of the market dynamics. However, the challenges around competitivity level 1 highlight the need for further refinement and understanding of the specific behaviors and dynamics of the hydrogen market in order to create more accurate and robust models.

Chapter 6

Conclusion and perspectives

6.1 Summary

The research question of this thesis is twofold: first, to model the competition in the green hydrogen market by analyzing production and transportation flows between North Africa and European countries; and second, to compare different modeling approaches to highlight the main characteristics of international trade in green hydrogen.

To fulfill the first aspect, we conducted a comprehensive analysis of production and transportation flows, considering factors such as resource availability, competitivity levels, and market dynamics. We utilized data on potential production capacities, demand, and infrastructure to model the competition accurately. This allowed us to identify key players, their roles in the market, and the potential for export and import relationships between North Africa and Europe.

For the second aspect, we compared different modeling approaches to gain insights into the international trade of green hydrogen. We evaluated the Global Optimum (GO) model, the Bi-Objective (Bi-Obj) model, and the Game Theory (GT) model. By examining their limitations and strengths, we were able to highlight the key characteristics of international trade in green hydrogen, including price optimization, resource allocation, strategic behavior, and the impact of competitivity .

The main findings of this thesis are presented here under:

- Maintaining balance: The concept of equilibrium is crucial in competitive scenarios. Participants in the market strive to achieve and maintain a balanced state, as it represents a desirable outcome for all parties involved. This balance ensures fair competition and efficient allocation of resources.

- Dissatisfaction increases with distance from equilibrium: As the market deviates further from the balanced state, dissatisfaction among participants tends to increase. This dissatisfaction arises from the challenges and uncertainties associated with imbalances, such as higher prices, limited availability of resources, and reduced market efficiency.

- Peak of conflicts: Imbalances that occur after a period of equilibrium often trigger a surge in conflicts among market participants. These conflicts emerge as stakeholders compete for resources, market share, and favorable positions. Resolving these

conflicts becomes essential for restoring equilibrium and achieving a more stable market environment.

- Scarce resources and restrictions: In scenarios where resources are scarce, the cost of imposing restrictions on resource allocation becomes more significant compared to other costs. This highlights the importance of efficient resource management and allocation strategies to mitigate the impact of limited availability.

- Under utilization and incentive: Under utilization of resources can act as a driving force in preventing market stagnation. When each country has the incentive to fulfill its own demand, it promotes market activity and dynamics. Efficient utilization of available resources is vital for maintaining competitivity and meeting the increasing demand for green hydrogen.

- Potential influence: In the context of low competitivity and a strong emphasis on price optimization, the conclusion is drawn that Europe is better positioned to produce green hydrogen due to its cost advantages. However, the potential in North Africa becomes a crucial asset for importing green hydrogen, as Europe's limited resources pose challenges for meeting the growing demand.

- Competition transition: Transitioning from sufficient resources to scarcity, around competitivity level one, causes a shock in resource allocation strategies. This instability arises as countries adjust their approaches to adapt to changing conditions. Maintaining stability while accommodating strategic shifts becomes crucial, emphasizing the delicate balance between resource scarcity and market dynamics.

- Cooperation in energy transport: such as utilizing intermediate countries like Morocco for transporting energy from Algeria to Europe, presents an opportunity to establish mutually beneficial partnerships. Leveraging existing infrastructure and fostering regional collaboration can enhance the efficiency and reliability of energy supply, facilitating the transition to a more sustainable and interconnected energy system.

- Bilateral agreements: it provides a crucial foundation for stability and reliability. These agreements act as safeguards against abrupt and drastic shifts in production and transportation flows. By establishing a certain level of commitment and collaboration between countries, bilateral agreements help maintain consistent import and export dynamics, ensuring a more predictable and manageable market environment.

- Additive model combination: The additive model, which incorporates various costs and penalties, provides a comprehensive framework for understanding the dynamics and trade-offs in resource allocation within the green hydrogen market. The incorporation of a cost component in the model captures the economic dynamics of the market aside of human decision-making behavior (penalty costs). This combination allows for a more comprehensive representation of the systemic and economic aspects.

Additionally, it is important to address the potential for cooperation and collaboration within the context of Nash equilibrium models. These models can provide insights into the strategic behaviors of countries and stakeholders, highlighting the potential for

mutually beneficial cooperation. In the case of the green hydrogen market, the high potential for hydrogen production in North Africa, combined with the high demand in the European Union, creates opportunities for cooperation and trade between these regions. Collaboration can lead to shared benefits, technological advancements, and the establishment of a sustainable and interconnected green hydrogen market.

In summary, the identified phenomena emphasize the significance of maintaining balance, managing conflicts, optimizing resource allocation, and fostering cooperation in the green hydrogen market. Understanding these dynamics and considering them in modeling efforts will contribute to the development of robust strategies and policies for a thriving and sustainable green hydrogen economy.

6.2 Perspectives

As we saw in the 5.2 To improve the GT model, several aspects need attention:
Firstly, enhancing the variety of coefficients used to model competition in allocation is crucial, particularly to address instability issues around competitivity =1. A more group-oriented approach should be adopted to model cooperation between countries, considering collaborative dynamics and agreements. Additionally, incorporating economic models to balance availability and demand, particularly for monetization purposes, would enhance the model's accuracy. Analyzing the model's evolution over time through time series analysis would also provide insights into its reliability and adaptability.

Apart from model-related considerations, revising solving techniques is essential, especially given the discrete set of possible solutions. Implementing more robust and efficient techniques would improve computational efficiency and accuracy in finding optimal solutions within the model.

It is important to recognize that a model can never fully capture real-world complexities. However, using historical data to test and validate the model in a similar market, such as the future green hydrogen market, offers an interesting path to enhance its consistency. By continuously refining and validating the model based on real-world data, there is potential to converge towards a more realistic and reliable representation of the dynamics and complexities of the green hydrogen market.

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Appendix

Appendix A

Game theory: EU27

In Figure A.1 are depicted 3 different scenarios at the EU27 scale.

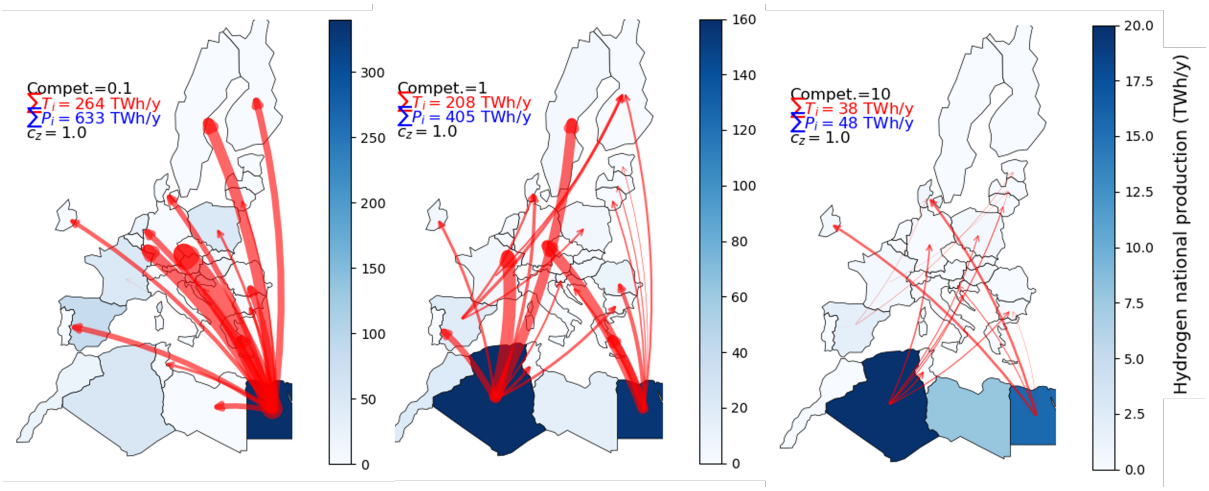


Figure A.1: Map of the EU27 countries production and transportation flows for different levels of competitivity.

In the scenario of low competitivity , Egypt emerges as the dominant producer due to its significant potential and exports to various European countries. The majority of European nations rely on imports from Egypt for their hydrogen supply.

When competitivity equals 1, indicating a balance between available resources and demand, we observe that France, Spain, Algeria, and Egypt become key producers and exporters to Northern Europe. These countries meet the demand for hydrogen in the region and play a crucial role in supplying hydrogen to Northern European countries.

However, as competitivity increases to 10, we observe a shift in the dynamics. Northern Europe becomes too distant for significant exportation, leading to reduced exports to that region. On the other hand, there is still a noticeable level of exportation to Southern Europe. Interestingly, importers from Algeria and Egypt show a tendency to change over time and do not remain consistent. For instance, in the case of competitivity equals 1, Germany imports from Egypt, but in the case of competitivity equals 10, Germany switches to importing from Algeria.

Appendix B

Game theory: World

In Figure B.1 are depicted 3 different scenarios at the world scale.



Figure B.1: Worldwide map of the countries production and transportation flows for different levels of competitivity.

The global market for green hydrogen extends beyond regional boundaries, with significant trade flows between Asia, South America, and Europe. Asia, known for its advancements in renewable energy technologies, serves as a major producer of green hydrogen. Countries like Japan, South Korea, and China have invested heavily in hydrogen infrastructure and are key exporters of green hydrogen to Europe.

Similarly, South America, with its abundant renewable energy resources, has emerged as a significant player in the global green hydrogen market. Countries like Chile and Brazil have favorable conditions for hydrogen production, including ample sunlight and access to water resources. They export green hydrogen to Europe to meet the growing demand for clean energy.

On the other hand, Europe, with its ambitious decarbonization goals, acts as a major importer of green hydrogen. European countries, including Germany, Netherlands, and France, have implemented policies to promote the use of green hydrogen in various sectors, such as transportation and industry. They rely on imports from Asia and South America to supplement their domestic production and meet the rising demand for clean hydrogen.

This interconnections between Asia, South America, and Europe creates a global market for green hydrogen, facilitating the exchange of technology, expertise, and resources to accelerate the transition towards a sustainable and low-carbon future.

Appendix C

Instabilities

When initially implementing the GT model, we encountered instabilities due to several sources of errors. One issue was the non-connectivity of Gurobi, the optimization solver used. This led to difficulties in finding optimal solutions and increased the likelihood of suboptimal outcomes. Another challenge arose from the existence of multiple Nash equilibria, which resulted in a multitude of local minima within the solution space. These multiple equilibria further contributed to the instability of the model. Additionally, the model itself was not well-constrained, meaning that certain parameters and constraints were not sufficiently defined or limited, leading to uncertainties in the results. Addressing these sources of errors is crucial to enhance the stability and accuracy of the GT model in analyzing the dynamics of the green hydrogen market.

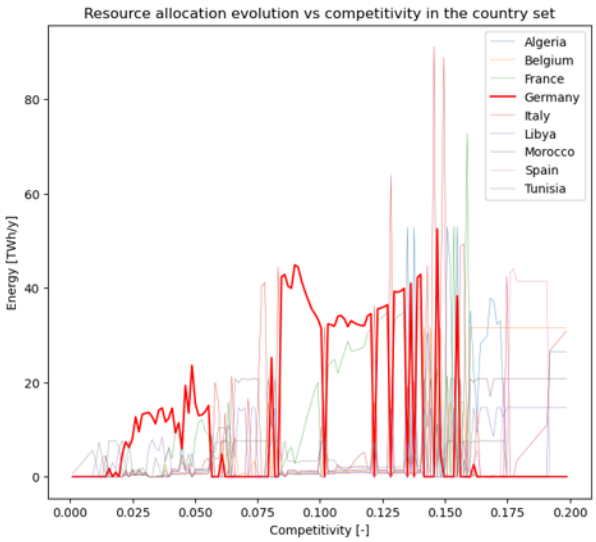


Figure C.1: Instabilities in the allocation for different competitivities with the focus on Germany (in red)