SUPPLY CHAIN ANALYSIS OF RENEWABLE ENERGY CARRIERS

Masterarbeit

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List of Abbreviations

LCOH	Levelized cost of hydrogen
CO2	Carbon Dioxide
EV	Electric vehicle
LP	Linear programming
GHG	Greenhouse Gas
H2	Hydrogen
EODB	Ease of doing business
CAPEX	Capital expenditures
OPEX	Operating expenses
SMR	Steam methane reforming
CCS	Carbon capture storage
PV	Photovoltaic
LH2	Liquefied hydrogen

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1 Introduction

Today, a large part of the energy we consume comes from fossil fuels, i.e. fuels that are partly made up of carbon molecules and which release so-called greenhouse gases during combustion with Oxygen. This is one of the main causes of global warming.

In 2019, 84.33% of the energy consumed worldwide came from fossil fuels: Oil 33.06%, Coal 27.04%, and Gas 24.23%, which indicates that today the percentage of renewable energies excluding nuclear energy is 11.42% [1]. These figures are far below the target that would be necessary to reverse the consequences of climate change.

But it is not all bad news, as the earth possesses a wealth of natural resources that can be harnessed for renewable energy production. These renewable resources are not equally abundant in all areas of the planet; we will have areas closer to the equator where the hours of sunshine will be greater, or areas where the wind blows more frequently and intensely.

This work will provide an analysis of the renewable energy supply chain, as the areas where the most renewable resources are available are not always the areas where the most energy is demanded. Therefore, the entire chain will be studied from production to energy transport, complying with a series of restrictions that will be discussed later.

In the following two sections belonging to the introduction, the motivations for carrying out this work, as well as the objective, will be developed in detail.

1.1 Motivation

The world as we know it today is unviable from the point of view of environmental sustainability. According to the latest estimates, 51 billion tonnes of greenhouse gases are released into the atmosphere [2], a large part of these emissions are generated by the energy sector [Fig.1], which is causing the average global temperature to rise considerably above 2 degrees Celsius by the end of the century if this trend continues.

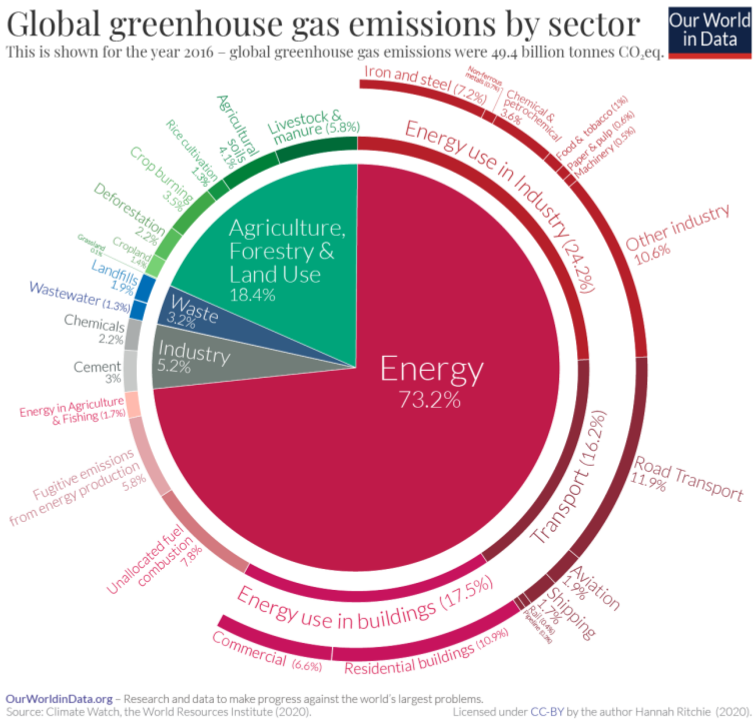


Figure 1: Global greenhouse gas emissions by sector

This temperature increase would have catastrophic consequences in the medium and long term, such as warmer temperatures, more natural disasters (Hurricanes, forest fires), melting of glaciers, the disappearance of animal species, more expensive food among others.

On 12 December 2015, a historic environmental agreement was reached at COP21 in Paris, where 195 signatories pledged to reduce greenhouse gas emissions to keep the global temperature rise this century below 2 degrees Celsius above pre-industrial levels, and to continue their efforts to further limit the temperature to 1.5 degrees Celsius [3].

To meet this ambitious goal, the solution lies in the global decarbonization of economies by transforming their current energy production model, mostly based on fossil fuels, towards a model where energy production is based on clean and renewable energies.

Within the great challenges of this energy transition, my master thesis focuses on this line of reducing GHG emissions, and more specifically on the analysis and design of the supply chain for the production and transport of hydrogen as renewable energy carrier between Africa and Europe. Thus, contributing to finding the best solution towards a fossil fuel free model.

The analysis and design of the supply chain will consider important aspects such as each country's energy consumption, renewable energy production potential, and paths of transport, analyzing all possibilities as a whole, and choosing the most cost-optimal and sustainable option (lowest GHG emissions).

1.2 Objective

The main objective of this work is to design a mathematical model to study the hydrogen supply chain where different forms of transport, as well as production technologies, will be taken into account.

To meet this objective, certain restrictions will be imposed that limit the model and make it fairer for the countries as a whole. The model does not only contemplate the transport of renewable energy from areas with greater renewable resources to more industrialized areas where energy consumption is higher, such as Central Europe but the energy demands of each country must first be covered before allowing energy exports to other countries.

This is what will happen in most North African countries, where production capacity far exceeds demand, so the surplus can be exported to countries where demand is much higher than their production capacity with renewable resources, such as in this case Central Europe.

It is also intended to give importance in this model to the political stability index of each country since the development of the infrastructures necessary for the development of renewable potential requires large investments that demand certain stability for their deployment.

The environmental factor is very important because depending on the technology used in hydrogen production, CO2 emissions vary. These emissions will therefore be taken into account in the model, incorporating the price per CO2 emission into the cost of hydrogen production.

2 Background

2.1 Renewable potential in Africa

As mentioned in the introduction, 73.2% of GHG emissions are caused by the energy sector, so a large part of the solution lies in decarbonizing this sector, which is the largest GHG emitter.

Renewable resources in Europe are very limited, for example, in Algeria normal direct solar irradiation (DNI) values reach about 2,200 kWh/(m2 a), but so far there are only 40MW of solar power installed in a country with a surface area of 2,382,000 km2. In contrast, Germany is characterized by relatively low irradiation values, typically below 1,000 kWh/(m2 a), but at least 39,800MW of PV capacity is already installed on 357,386 km2 [4].

These data indicate that North Africa has a great potential for electricity production through solar photovoltaic and wind energy that has not yet been developed.

A key factor to consider along with the potential of renewable resources is the area available for the construction of the necessary infrastructures for production. This is one of the great advantages of North Africa, where the population density values per km2 are 18 to 98 people/km2, whereas in Europe these values are much higher (16 to 414 people/km2), which makes the exploitation of renewable resources in this area viable [5].

To put the energy consumption of the area under study in context, the following picture shows the large differences between the energy consumption per km2 in Central European countries (4 to 86 TJ/(a km2)), with those in North African countries with a much lower consumption per surface area (1 to 4 TJ/(a km2))[5].

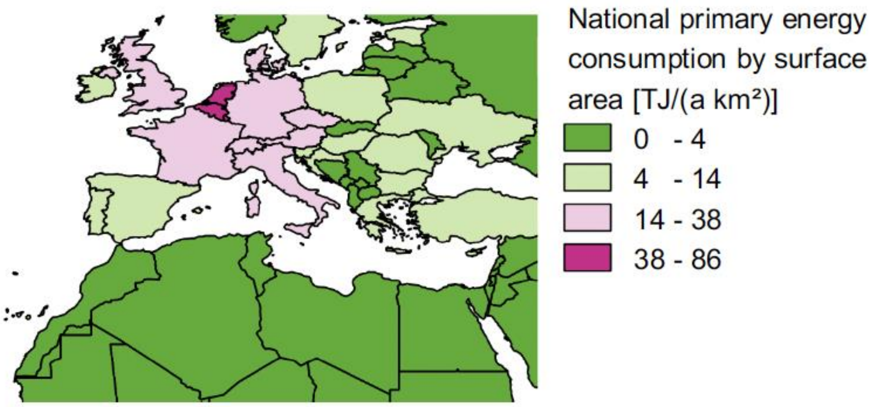


Figure 2: Energy consumption by surface area

With all the data collected, it is clear that a good alternative to decarbonize the Central European energy sector is to develop and exploit renewable resources in North African countries.

To transport this renewable energy to Europe, it is necessary to study different clean fuel alternatives and production technologies. In this work, we will focus on hydrogen, but we will also consider different production technologies from PV and wind energy.

The production of these fuels depends to a large extent on the development of technologies to produce solar and wind energy, since in the case of hydrogen, for example, the energy consumption of electrolyzers will come from solar and wind energy, and therefore the LCOE of these energies directly influences the LCOE of hydrogen. The following images from the IRENA database show this downward trend for the coming years [6]:

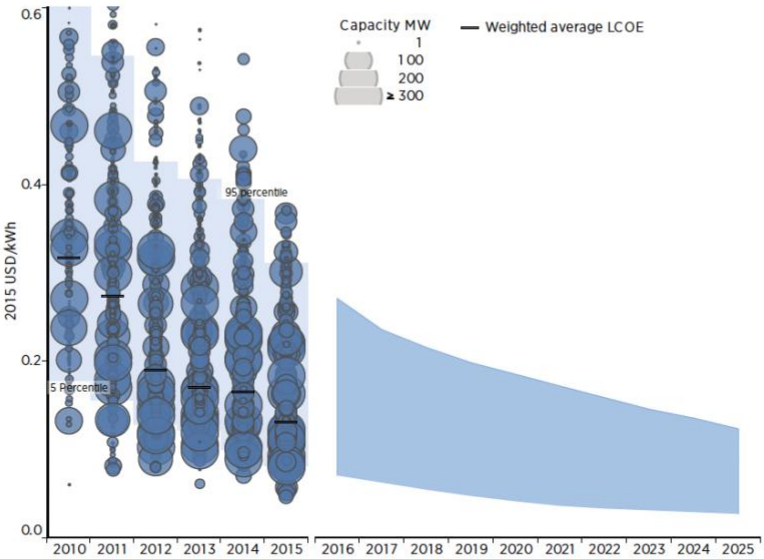


Figure 3: Global utility-scale solar PV LCOE range, 2010-2025

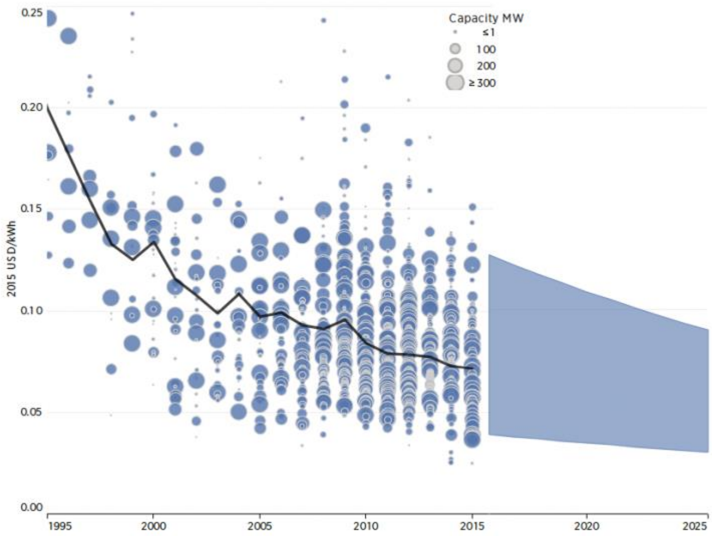


Figure 4: Levelized cost of electricity onshore wind, 1983-2025

2.2 Africa electricity access

If the current situation on the African continent in terms of access to electricity is put into context, the situation in terms of electrification of the continent is not very good, as despite the continent's great potential for renewable resources, according to recent trends, over 60% of Sub-Saharan Africans are still lack access to electricity in 2020 [7].

As mentioned above, this is not due to a lack of potential for development, but to the difficulty of obtaining the necessary funding and commitment of local governments to be able to deploy the infrastructures needed for its development.

Figure 5: Satellite image of Europe and Africa at night

Furthermore, according to the Sustainable Development Goals set by the United Nations, number 7 is to ensure access to affordable, secure, sustainable, and modern energy for all. Therefore, it is key to deploy the necessary resources for the development of Africa's renewable energy potential to achieve the construction of both the production centers of this renewable energy, focused on solar and wind energy, as well as the infrastructures for its transport and distribution both within and outside the continent.

This will make great progress in terms of access to electricity, as well as for Africa's economic development, generating a large number of jobs related to the energy sector.

Having put into context the serious situation in which Africa finds itself in terms of access to electricity for its inhabitants, the following section will define the energy carrier to be used in this model for the transport of renewable energy.

2.3 Hydrogen

Hydrogen has been considered as a fuel for storing renewable energy, since, according to the IEA, it will be key to the decarbonization of the planet. Unlike fossil fuels, the only emission that hydrogen produces when combusted with oxygen is water vapor, and there are various technologies for its production through renewable energies and its subsequent transport to the points of consumption. These characteristics make it a great candidate for the transport of renewable energy.

Today, 95% of hydrogen production comes from the use of fossil fuels such as natural gas, oil, and coal. The remaining 5% is produced through production technologies with low CO2 emissions, such as electrolysis and steam methane reforming with CO2 capture, technologies that will be studied within the scope of this work [8].

Furthermore, most of the hydrogen production is not used as a renewable energy carrier, but as a feedstock for the production of ammonia for fertilizers and the production of methanol [8].

Hydrogen can be classified into three colors depending on its origin. In this model, as only two production technologies are considered: Electrolysis and Steam Methane Reforming (SMR) with carbon capture, the production technologies will be defined and classified in the corresponding colour:

- Green: This will be the hydrogen that is produced by the separation of water in the electrolysis process, which only produces hydrogen and oxygen as a reaction product. Using this technique, the hydrogen can be stored, and the excess oxygen can be discharged into the atmosphere without any environmental impact.

Electricity is needed to achieve electrolysis, and what makes this hydrogen green is the fact that the electrolyzers that separate the water are powered by renewable energy sources, such as wind or solar energy. This makes the green hydrogen option the cleanest option with no GHG emissions, therefore, it will be the one that this work will use to analyze its large-scale supply chain as a renewable energy carrier.

- Blue: Blue hydrogen is produced by separating hydrogen and CO2 from natural gas, mainly by two technologies, Steam Methane Reforming (SMR) or Auto Thermal Reforming (ATR), but the excess CO2 is captured. By capturing the CO2 released by the process, mitigates the environmental impact that the process itself would have.

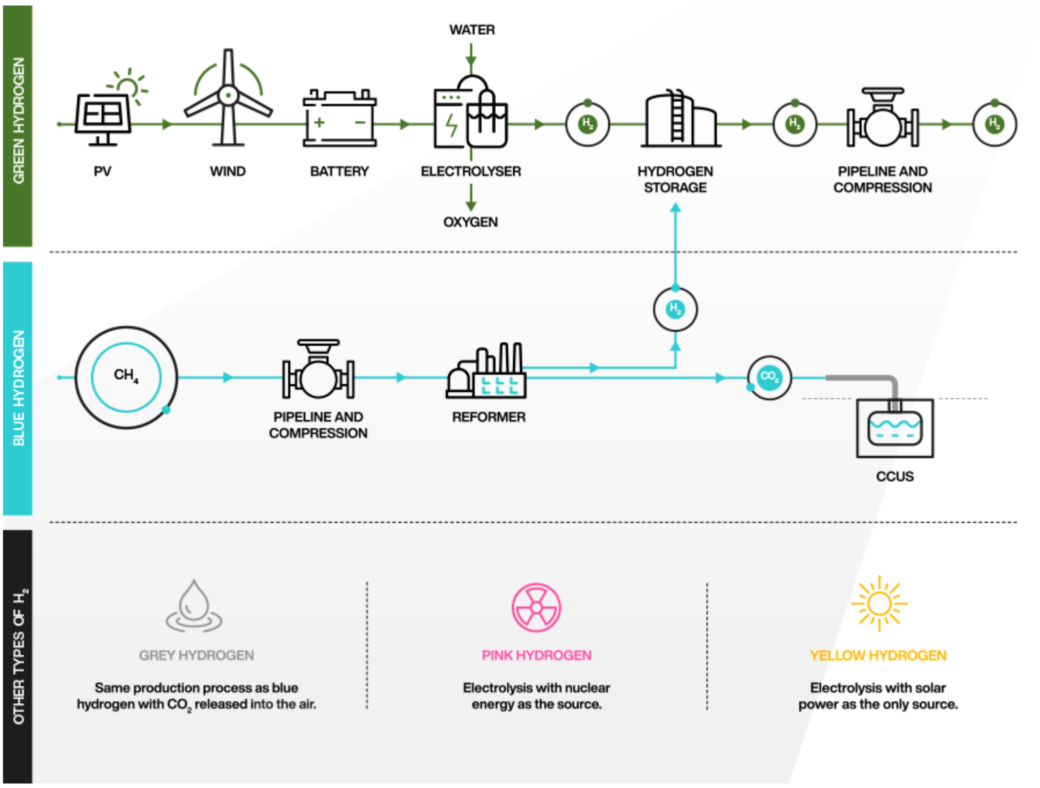


Figure 6: Types of hydrogen according to its production source

Having explained why hydrogen will be used as an energy carrier, in the next chapter it will be treated the methodology used to solve the model, as various tools are allowed to solving complex mathematical models, it is necessary to choose the best that fits with our proposals. It will be explained step by step which tools we have decided to choose, why and what mathematical methodology will be used to solve them.

3. Methodology

The problem that arises depends on many variables, including various hydrogen production technologies, different paths for transporting hydrogen, as well as different costs for its production, which in turn depend on other variables.

What is meant by this is that the problem is so complex that it is unfeasible to solve it manually, i.e. its solution is not evident at first sight, and therefore a mathematical model must be proposed that is capable not only of solving it and obtaining any solution to our problem but also meets a series of limitations that will be imposed by the limitations that exist today, such as the maximum amount of hydrogen that can be transported by pipeline, ship or truck. All of these will be discussed later when the full model is explained in detail.

It should also be noted that the solution, in addition to meeting the constraints imposed, model should be able to obtain a solution that optimizes the total cost of the hydrogen supply chain, i.e. the final solution of the model will be the one that meets all the constraints and is also the most economical.

In the following section, we will define the mathematical methodology used to design and solve the model. Among them is mathematical optimization, but more specifically we will define the pillars of linear optimization, as this is the one that will be used expressly in this work.

3.1 Mathematical optimization

Mathematical optimization is a science that studies the selection of the best element, concerning a defined criterion, from a set of available elements. Moreover, one of the fundamental pillars of operations research is precisely mathematical optimization [9].

A common mathematical optimization problem consists of maximizing or minimizing the values of a real function by choosing an initial input value, thus using different iterations of the model to arrive at the optimal solution with the minimum possible number of resources.

Within mathematical optimization there are several fields, the most studied are linear programming, non-linear programming, combinatorial optimization, and heuristics.

Linear programming will be the method chosen to solve the model since the variables, restrictions, and objective function contemplated by the model are linear, i.e. they follow the equation of a straight line and there are not multiple valid solutions for each variable, as occurs in non-linear programming models, where at least one variable of the objective function will have an exponent greater than one, which indicates that there is not a single solution for each variable and this multiplies the difficulty of finding an optimal solution for the model.

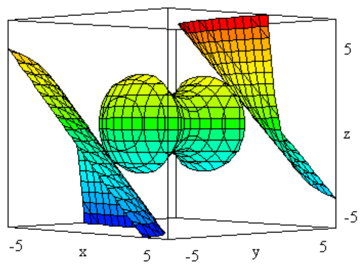


Figure 7: Example of non-linear optimization

3.2 Linear programming

Also called LP is a mathematical programming method that consists of optimizing the solution of a linear function or also called objective function, which, in the model section, will explain which variables have been decided to consider and their formulation.

The objective function is a key part of the model, as it must include the variables to be optimized, so its correct formulation is of vital importance.

It is equally important to formulate the restrictions correctly. In other words, each variable of the objective function must comply with a series of constraints, and these are defined as inequalities or equalities within the model.

To better visualize linear programming, an example can be seen in the following figure:

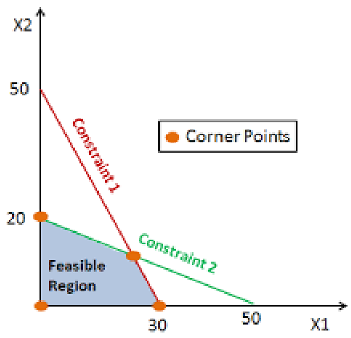


Figure 8: Example of linear programming model

As it shows the previous image, it is very important to define the constraints of the model, because these will limit the range of viable solutions.

Once the region where all the solutions of the model are found is delimited, the objective function will come into play, since depending on how this function is properly defined, the objective will oversee choosing the final solution, depending on whether the objective is to minimize or maximize.

The following chapter will discuss the software used for solving the mathematical model, as it will be important to use tools that facilitate data processing, model solving, and visualization of results.

3.3 Software used

First, Python will be discussed. This program will be the key tool used to write the mathematical model, including variable declaration, objective function, and constraints.

Python is a multi-paradigm programming language, as it partially supports object-orientation. But one of its most important features and the reason why it has been decided to use this software is that it is based on open source. This means that anyone can develop their tool for free and share their model with anyone who has the software installed.

Multiple libraries allow us to work more easily with data, such as Pandas, NumPy, etc. libraries.

The model will be written in Python with Spyder IDE, but when writing our model, we will adapt the model language to the Gurobi library, which expressly allows us to solve mathematical models of linear and non-linear programming.

To use this library, it has been necessary to obtain a license from Gurobi, which requires accessing its website and obtaining a code for activation [10].

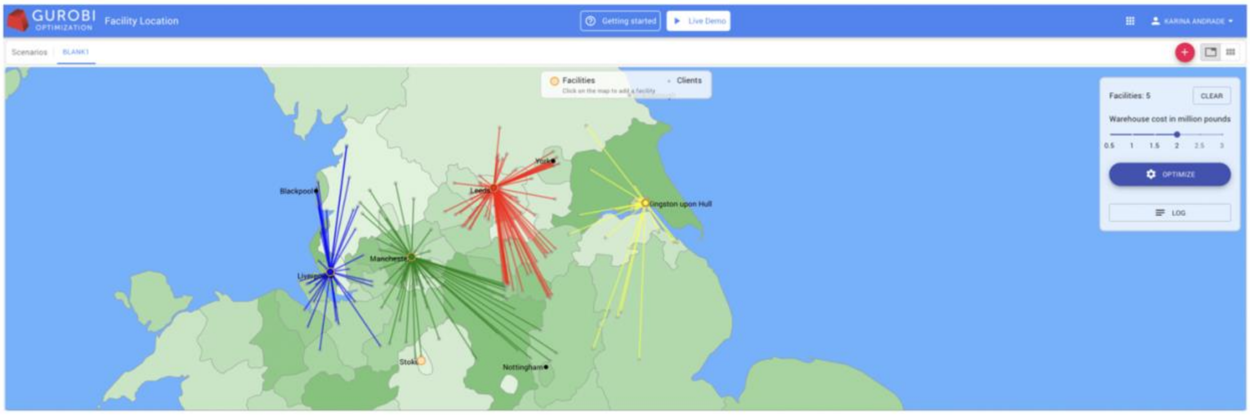


Figure 9: Example of mixed-integer programming (MIP) warehouse location

Gurobi is a widely used library for solving complex models. It has solved models of any industrial sector such as warehouse location problems, supply chain, energy...etc. In addition, there is a lot of documentation with example models, and this is a great advantage that makes it very accessible to any user who wants to solve any mathematical optimization model.

A major task of this work has been the analysis and search for information for the model. This has not been an easy task, as there is some information that is not as accessible as one might think at first.

Some of the information needed for our model was indeed in databases such as Eurostat for EU countries, but other data about hydrogen and its transport, such as for Africa, have been more difficult to find, and in some cases, it has been necessary to make some assumptions.

Therefore, the information needed by the model must be extracted from these databases, and in the worst cases, it must be extracted by hand from technical documentation in PDF. A tool that has been very useful to link the Python model and the information collected from different sources has been the Excel tool, and the creation of different sheets to structure the information and thus be able to import the necessary information into the model.

Also, the key will be the use of Excel to extract the model results from our Python IDE to .csv files, as the tool to be used for visualization, which will be defined below, only supports data in this widely used comma-separated format.

Once the model has been produced, it is necessary to extract the data for analysis and interpretation. As the model includes countries in both Europe and Africa, the simplest way to interpret it is to represent the results on a map.

Several tools allow the visualization of data on maps, one of the most widespread and which also allows its programming directly in Python is Geopandas. A priori we studied the possibility of using this library, but due to issues related to incompatibilities and the creation of virtual environments for its use in Python, we finally decided to look for other tools.

Finally, it was decided to choose the Kepler.gl tool. This tool allows the visualization of data in .csv files and is also visualized directly from the web browser. The configuration for the visualization of the data, depending on each variable to be represented, consists of different layers of colors that can be assigned to each column of the .csv file of the results.

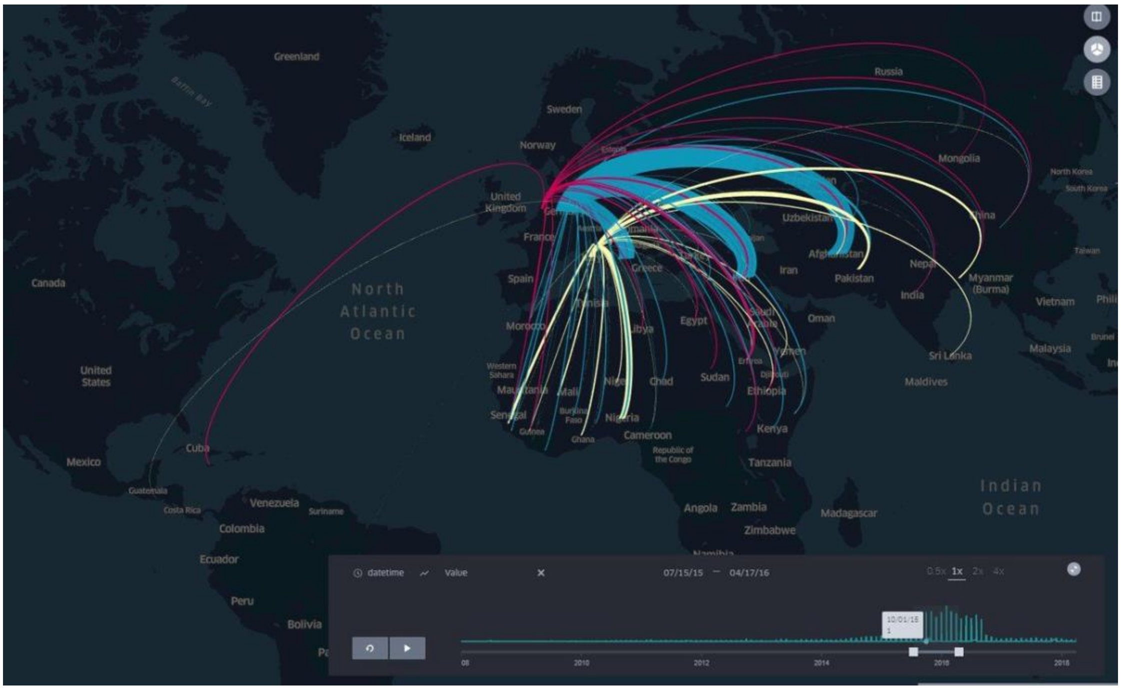


Figure 10: Example of data visualization in Kepler.gl

As can be seen in the visualization example with Kepler.gl, the data can be represented with different geometric shapes, in this case they are represented by arcs. This will be very useful, since in this model one of the variables to be solved is the transport of hydrogen between each country, and with this tool the arcs that will mark the transport between countries can be visualized.

This tool also allows the map to be shared with any user via a link. The user will be able to view it with any browser and use it interactively, i.e., by clicking on a line, the user will be able to see the path the hydrogen has taken, as well as the country of origin and destination.

Following the methodology explained and making use of the tools chosen for its resolution, each of the parts of the model will be defined in the next chapter.

4. Model

When designing a mathematical optimization model in which such a complex problem is modeled in which there in an infinite number of influencing variables, first of all, it is necessary to express the model in mathematical form, i.e. by defining variables, ranges, indices, subindices, and parameters.

This is the simplest way to model real problems, as it allows each variable to be identified one by one to structure the model. First of all, it will be defined the indexes that will be used in the model.

4.1 Indexes

Indexes are the first step to define a linear optimization model, as the variables, parameters, objective function and constraints for their analysis and resolution will be based on them.

In this model, all the variables and parameters depend on the countries that are being analyzed, therefore, there is an index that corresponds to countries that it is called suppliers, which are those countries that supply hydrogen to others, and another index called customers that corresponds to those countries who import hydrogen from others.

Although these indices will have the same value, which will be equal to the number of countries covered by the model, it is necessary to have two equal indexes in order to be able to go through the data in all their columns and rows.

It will also be necessary to define the number of hydrogen production technologies that the model will have. In this case there are two main technologies, corresponding to SMR and electrolysis.

Hydrogen can be transport in three different transport paths, that is why it is also mandatory to define paths as an index, otherwise, it could be confused the way of considering the quantity of hydrogen transported between countries, because it would not been possible to difference the way of transport chosen by the model.

It is key to explain this nuance, as it will not cost the same to transport a quantity of hydrogen by ship as by truck.

In order to calculate the distances between countries, their geographical coordinates will be needed, which are defined in the model as parameters, as it will be discuss in the next section. The geographical coordinates have two components: Latitude and longitude, therefore, for their treatment it will be necessary to add an index that allows to refer to the geographical coordinates of each country.

Below is a brief table which contains the indexes that are defined in the model:

Table 1: Model indexes

INDEX	DEFINITION	RANGE
i	Index which contains the number of countries as a range. This index represents Supplier's countries.	{0,1,2,3, 4,…,74}
j	Customer's countries index	{0,1,2,3, 4,…,74}
w	This index defines the two hydrogen production technologies used in this model	{0,1}
p	p corresponds to the different paths of transport available, in this case there are six main paths: Gaseous truck, liquefied truck, LOHC truck, liquefied ship, LOHC ship and pipelines	{0,1,2,3,4,5}
k	k refers to the two terms containing the geographical coordinates of a country, latitude and longitude.	{0,1}

Now that the indexes that will be used to traverse the data and structure the information in the model have been defined, it is time to define the parameters.

4.2 Input parameters

Parameters of a linear optimization model are defined as those values of the model that do not change, i.e. they are fixed and immovable values that are predefined by the nature of the problem.

In this model, an example of a parameter is the renewable energy demand of each country. This quantity is fixed according to the demands of each country, which vary according to the economic model and the energy needs of its population.

For better visualization of the parameters of the model, a table with each of the parameters and their meaning is attached in the appendix with the definition of each of them.

The parameters are a very important part of the model since it will be necessary to use them to define the constraints and they will define the consistency of the model.

4.3 Variables

The variables of a linear optimization model are those that have to be defined in the model beforehand, but their value is unknown. This value will be given by the final solution of the model.

In this case, the variables that need to be defined are the following:

Table 2: Model variables

VARIABLES	DEFINITION	UNIT
X_{ijp}	Hydrogen transported between country i to country j by transport path p	Kg of H2
SMR_PROD_i	Hydrogen produced in country i with SMR	Kg of H2
$ELECTROLYSIS\_PROD_i$	Hydrogen produced in country i with Electrolysis	Kg of H2

The value of these variables can be infinite, i.e. there will be infinite solutions to solve the model, but the objective function and the imposed constraints will be in charge of deciding which will be the optimal solution that in this case minimizes the global cost of the hydrogen supply chain.

4.4 Objective function

The objective function is the cornerstone of the model; it directly defines, through the incorporation of the variables and parameters previously defined, towards which solution space we want to guide the model.

The main challenge pursued with this model is to minimize the global cost of the hydrogen supply chain, therefore, it will be necessary to define the objective of reaching a minimum global cost.

In order to define the global cost, a large number of variables and parameters will have to be taken into account and, using mathematical tools such as sums and the indices defined at the beginning of the model, an equation will have to be created that includes all the costs of the supply chain.

Next, the objective function of the model is defined mathematically:

$$\boldsymbol{C} = \sum_{\boldsymbol{i}\in\boldsymbol{I}} \left(\boldsymbol{LCOE_{HYDROGEN_{i,1}}} * \boldsymbol{SMR_{PROD_i}}\right) + \left(\boldsymbol{LCOE_{HYDROGEN_{i,2}}} * \boldsymbol{ELECTROLYSIS_{PROD_i}}\right) + \sum_{\boldsymbol{i}\in\boldsymbol{I}} \sum_{\boldsymbol{j}\in\boldsymbol{J}} \sum_{\boldsymbol{p}\in\boldsymbol{P}} \boldsymbol{TRANS\_COSTS_{i,j,p}} * \boldsymbol{X_{i,j,p}}$$

The first summation defines what the cost of hydrogen production will be in each country, taking into account the two hydrogen production methods.

The second summation contains the global sum of the amount of hydrogen transported between countries times the transport cost according to the mode of transport.

In addition, this objective function will in turn be subject to the following constraint:

$$i \neq j$$

This restriction imposes that the global cost of the supply chain does not take into account the quantity of hydrogen produced in the same country, since, as will be explained in the following section on conditions, the variable $X_{i,j,p}$, when $i = j$, corresponds to the production of hydrogen in country i, and this quantity should not be included in the global supply chain costs, since it is assumed that the transport costs for the supply of hydrogen in the same country will be equal to zero.

The parameter $\boldsymbol{TRANS\_COSTS_{i,j,p}}$ is a three-dimensional matrix since all the transport costs associated with each path will be stored in it. It will not be an unknown variable, since its values come from the input parameters of the transport costs and depending on the distances between each country, which is why they have not been included in the table of variables [Tab 1].

The calculation of this parameter will be explained in detail in the data section.

4.5 Constraints

Constraints in a linear optimization model is the last step to formulate a model correctly. These constraints must be set after defining the objective function, since, if no constraints are defined, the model could have infinite solutions and be meaningless.

The objective function will try to arrive at variables that minimize the global cost by assuming the following restrictions that will be explained step by step.

1) $X_{i,j,p} = 0; \qquad \forall i \in I, j \in J, p \in P \quad ; \quad s.t \;\; ADJACENCY\_MATRIX_{i,j,p} = 0$

In the data chapter, we will go into detail on how to obtain the three-dimensional matrix where each of the adjacency sub-matrices will be stored as a function of the transportation path (p).

In short, with this constraint we are limiting that when the value in the adjacency matrix is zero, this directly implies that the amount of hydrogen transported by that path will be equal to zero, since the path is not available and therefore, no amount of hydrogen can be transported.

2) $DEMAND_i = \overbrace{\sum_{j\in J}\sum_{p\in P} \boldsymbol{X_{i,j,p}}}^{\text{HYDROGEN PRODUCTION}} + \overbrace{\sum_{j\in J}\sum_{p\in P}(\overset{\text{INPUTS}}{\boldsymbol{X_{j,i,p}}} - \overset{\text{OUTPUTS}}{\boldsymbol{X_{i,j,p}}})} \;\; ; \quad \text{s.t } \forall\, i \in I$

s.t $i = j$ s.t $i \neq j$

- The first term represents the hydrogen production in each country, and is therefore subject to the condition that *i*=*j*

- In the second summation, the INPUTS of hydrogen minus the OUTPUTS in country *i* shall be subtracted.

The definition of this constraint implies the free circulation of hydrogen between countries. It states that the hydrogen demand of country *i* (being a fixed parameter), must be equal to the sum of all production plus the subtraction of the amount of hydrogen coming in minus the amount of hydrogen going out.

In this way, the hydrogen material balance in each country is also ensured.

3) $SMR\_PROD_i \leq SMR\_CAPACITY_i \;\; ; \; \forall \, i \; \in I$

4) $ELECTROLYSIS\_PROD_i \leq ELECTROLYSIS\_CAPACITY_i \;\; ; \; \forall \, i \; \in I$

These two constraints limit each country's hydrogen production *i* according to two new variables that are calculated based on each country's capacity data; their calculation will be explained in detail in the data section.

5) $SMR\_PROD_i + ELECTROLYSIS\_PROD_i = \underbrace{\sum_{j \in J} \sum_{p \in P} \boldsymbol{X_{i,j,p}}}_{\boxed{\text{s.t } i = j}} \; ; \; \forall i \; \in I$

The amount of hydrogen $X_{i,j,p}$, where the indices *i*, *j* have the same value, indicates that this is the amount of hydrogen produced in country *i*. This variable of total amount of hydrogen produced in country *i* and does not distinguish between the two production technologies studied.

As this variable does not make any distinction, it is necessary to equal it to the sum of the production with each of the production methods, SMR and Electrolysis, by creating this constraint.

6) $X_{i,j,p} \geq 0 \qquad s.t \; \forall i \in I, j \in J, p \in P$

In all optimization problems it is necessary to constrain the range of solutions to only positive values. The constraint above performs this function, over the entire range of *i*, *j* and *p* make the values at least equal to or greater than zero.

In this model it has been assumed that there are no limitations on transportation paths, i.e. the amount of hydrogen that can for example be transported by truck or ship is unlimited, except for the case of pipeline transport.

The current infrastructure for hydrogen pipeline transport is very limited today, mainly due to the shortage of pipelines that are designed exclusively for hydrogen transport.

Despite this major limitation regarding the existence of pipelines working exclusively with hydrogen, several studies, among them the one by Dr. Ing. Sebastian Timmerberg from Hamburg University of Technology [5], indicates that hydrogen transport via natural gas pipelines is possible.

This study indicates that a safe value for its transport is 10% hydrogen and 90% methane. With this mixture it would be feasible to transport it through the same pipeline, although it would be necessary to increase the number of pumping stations to maintain a constant pressure.

Figure 11: Natural gas transport from North Africa to Europe

There are currently several pipelines transporting natural gas from North Africa to Europe. Specifically for this model, the Maghreb-Europe, Medgaz, Trans-Mediterranean and Greenstream pipelines will be used, all of which, except the Greenstream, start from the Hassi R'Mel operation located in Algeria. The Greenstream starts from Wafa in Libya and this pipeline connects to Italy.

The Trans-Mediterranean transports natural gas from Algeria to Italy, and Medgaz and Maghreb-Europe to Spain.

7) $X_{0,56,5} = 2{,}11 * 10^8$
8) $X_{0,59,5} = 3{,}57 * 10^8$
9) $X_{26,59,5} = 1{,}19 * 10^8$

The first constraint limits the amount of hydrogen transported between Algeria (*i=0*) and Spain (*j=56*), there is only one constraint for Spain because although Spain is served by two pipelines from Algeria, the limitation will be imposed by the sum of the limitation from Medgaz plus Maghreb-Europe.

As the two pipelines that reach Italy start from Libya and Algeria, which are different countries, these two constraints must be treated separately as shown in constraints 8) and 9).

How these values for limiting the amount of hydrogen transported through natural gas pipelines are obtained will be explained in the data section.

5. Data

For a linear optimization model to be well thought out, it is not enough for the mathematical formulation to be correct; it is also necessary to design a good data structure for its incorporation into the model. This transition from the acquisition of data until they are added to the model will be carried out with the Excel tool by creating several spreadsheets depending on each parameter to be incorporated.

Firstly, it will be briefly explained from which sources the different parameters have been extracted, as well as their nature. Secondly, their formulation will be defined to convert them into parameters which, once processed, will be used directly in the constraints and objective function of the model.

5.1 Demand

The aim of this work is to provide a model that is as economical and sustainable as possible, i.e., one that releases as little GHG into the atmosphere as possible. With this idea in mind, the possibility of covering the entire energy demand of countries with hydrogen was raised, with the aim of decarbonizing the economy 100%.

But this idea is somewhat utopian, due to the simple fact that there are energy consumptions that will be very difficult to replace directly with hydrogen.

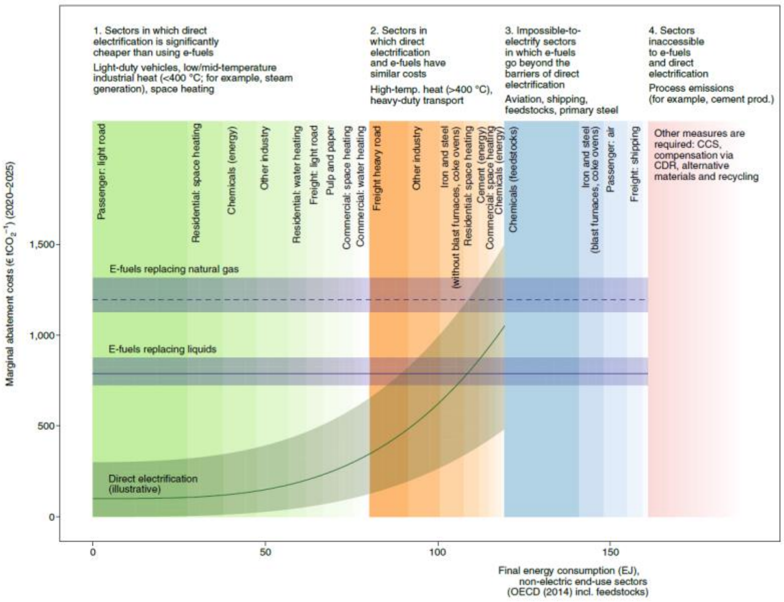


Figure 12: Sectors in which is cheaper to use e-fuels or electricity

The image above shows a classification of the sectors in which e-fuel substitution is feasible and the sectors in which the use of e-fuels is unfeasible, and the most economical solution is electrification.

A very clear case is that of household electricity consumption. This consumption is already electrified, and conversion to e-fuels would be so expensive that it is not worth converting. The use of hydrogen as an energy source for processes such as cement manufacturing is unfeasible due to the very nature of the manufacturing process, and the best solution is electrification.

In addition, processes such as cement manufacturing are major sources of GHG emissions. The process itself emits GHGs and there is no other way to avoid these emissions than by direct carbon capture.

The sectors where e-fuel substitution is feasible are the transport sector (Aviation, shipping...) and some industrial processes such as Ammonia manufacturing, Refinery natural gas and oil, and steel and iron production. These will be the sectors from which their hydrogen demand will be extracted to be treated in the model.

Although some of the products that are manufactured and whose manufacturing process is intended to be decarbonized emit GHG when used, such as the use of ammonia as fertilizer for the agricultural sector, this is a first step to at least decarbonize their manufacturing process and gradually make an energy transition towards the creation of products that in the future can replace the role of ammonia or fossil fuels such as gas, but whose use does not produce GHGs.

The demand that needs to be incorporated into the model that has been defined must be in Kg of hydrogen, but this information has not been easy to find in some cases, such as Africa, so some assumptions have had to be made to find this information.

5.1.1 Europe demand

In the case of hydrogen demand in Europe, this information was obtained directly from the report Analyzing future demand, and transport of hydrogen (European Hydrogen Backbone) [11].

In this report, hydrogen demand in European countries is classified according to the sector and the year in which demand is estimated.

As the demand is classified according to the years, this will allow the model to be analyzed with various possible scenarios and thus obtain different results that will be analyzed in the conclusions.

As can be seen in the following image extracted from the report, in this case the demand from the industrial sector is classified into different uses: Ammonia, Fuels & HVC, Steel, and Industrial heat.

Country	2030					2040					2050				
	Ammonia	Fuels & HVC	Steel	Industrial heat	Total 2030	Ammonia	Fuels & HVC	Steel	Industrial heat	Total 2040	Ammonia	Fuels & HVC	Steel	Industrial heat	Total 2050
Austria	0.23	2.39	3.30	1.59	**7.51**	1.20	6.74	11.78	4.67	**24.39**	1.50	9.39	11.96	6.16	**29.01**
Belgium	0.95	9.58	4.29	3.04	**17.86**	5.06	27.05	9.10	8.73	**49.94**	6.33	37.71	7.90	11.37	**63.31**
Bulgaria	0.00	2.39	0.00	0.69	**3.07**	0.75	6.74	0.00	1.95	**9.44**	5.03	9.39	0.00	2.52	**16.94**
Croatia	0.00	1.64	0.00	0.25	**1.89**	0.35	4.63	0.00	0.71	**5.69**	2.33	6.45	0.00	0.93	**9.71**
Cyprus	0.00	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00	0.00	**0.00**
Czech Republic	0.00	2.14	0.22	1.07	**3.44**	0.35	6.05	2.22	3.15	**11.78**	2.37	8.43	3.79	4.16	**18.75**
Denmark	0.00	2.20	0.00	0.38	**2.58**	0.00	6.22	0.00	1.13	**7.35**	0.00	8.67	0.00	1.51	**10.18**
Estonia	0.00	0.00	0.00	0.03	**0.03**	0.00	0.00	0.00	0.11	**0.11**	0.00	0.00	0.00	0.16	**0.16**
Finland	0.00	3.06	2.03	0.14	**5.22**	0.00	8.64	4.05	0.52	**13.20**	0.00	12.04	4.11	0.76	**16.91**
France	1.10	17.71	6.83	5.28	**30.92**	5.87	49.99	15.68	15.55	**87.09**	7.34	69.69	18.72	20.53	**116.28**
Germany	0.93	25.63	17.81	16.60	**60.98**	11.11	72.38	49.59	49.47	**182.55**	18.52	100.90	59.96	65.73	**245.11**
Greece	0.00	8.82	0.00	0.18	**9.00**	0.13	24.91	0.00	0.51	**25.54**	0.85	34.73	0.00	0.66	**36.24**
Hungary	0.00	2.02	0.15	0.76	**2.93**	0.58	5.70	1.53	2.17	**9.98**	3.85	7.95	2.61	2.83	**17.23**
Ireland	0.00	0.87	0.00	0.49	**1.36**	0.00	2.45	0.00	1.44	**3.90**	0.00	3.42	0.00	1.91	**5.33**
Italy	0.31	20.26	4.01	5.76	**30.35**	1.64	57.21	14.62	16.75	**90.22**	2.04	79.76	18.17	21.97	**121.94**
Latvia	0.00	0.00	0.00	0.04	**0.04**	0.00	0.00	0.00	0.12	**0.12**	0.00	0.00	0.00	0.15	**0.15**
Lithuania	0.00	2.32	0.00	0.21	**2.53**	0.89	6.56	0.00	0.58	**8.03**	5.91	9.15	0.00	0.74	**15.81**
Luxembourg	0.00	0.00	0.00	0.26	**0.26**	0.00	0.00	0.00	0.75	**0.75**	0.00	0.00	0.00	0.96	**0.96**
Malta	0.00	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00	0.00	**0.00**
Netherlands	1.90	16.15	3.21	3.77	**25.03**	10.13	45.61	3.41	10.93	**70.08**	12.66	63.58	11.85	14.33	**102.41**
Poland	0.00	6.99	2.14	2.82	**11.95**	2.24	19.73	5.03	8.20	**35.19**	14.91	27.50	7.90	10.76	**61.07**
Portugal	0.00	5.26	0.00	0.85	**6.11**	0.00	14.86	0.00	2.46	**17.31**	0.00	20.71	0.00	3.22	**23.93**
Romania	0.00	2.91	3.28	1.67	**7.87**	1.79	8.22	4.98	4.65	**19.64**	11.95	11.46	5.05	5.96	**34.42**
Slovakia	0.00	1.52	0.42	0.35	**2.29**	0.47	4.28	4.17	0.97	**9.89**	3.14	5.97	7.11	1.23	**17.45**
Slovenia	0.00	0.00	0.00	0.34	**0.34**	0.00	0.00	0.00	0.99	**0.99**	0.00	0.00	0.00	1.30	**1.30**
Spain	0.25	18.67	3.39	5.34	**27.65**	3.02	52.72	8.40	15.60	**79.74**	5.03	73.50	8.53	20.52	**107.58**
Sweden	0.00	5.10	2.70	0.06	**7.86**	0.00	14.41	6.07	0.17	**20.64**	0.00	20.08	6.16	0.22	**26.47**
UK	1.42	17.79	1.37	4.24	**24.82**	7.55	50.24	2.87	12.42	**73.07**	9.44	70.03	5.05	16.36	**100.88**
Total	**7.07**	**175.43**	**55.17**	**56.20**	**293.87**	**53.13**	**495.34**	**143.50**	**164.68**	**856.65**	**113.19**	**690.53**	**178.86**	**216.97**	**1,199.56**

Figure 13: Industrial hydrogen demand per country in (TWh/year)

The hydrogen demand is given in (TWh/year), in this model the quantities of hydrogen must be treated in kg, therefore, it will be converted by multiplying by the following conversion [12]:

$$1\ Kg\ of\ Hydrogen = 33{,}6\ KWh$$

This conversion to kg hydrogen is done because the parameters for calculating transport costs are given in $/kg hydrogen.

To calculate the total hydrogen demand for each country, the total demands of the industry, transport and power sector are added together.

5.1.2 Africa demand

In the demand for hydrogen in Africa, it has not been possible to find a source that estimates the demand for Africa in the coming years. In order to make an approximation of demand, it has been necessary to first look at the production of different African countries in sectors that can be decarbonized by using hydrogen.

For this model, the production of oil [13] and gasoline [14] has been considered, which in countries such as Algeria is a fairly significant amount, and whose extraction and refining processes produce a large amount of GHG, therefore, switching to e-fuels could mean a considerable saving in the carbon footprint of their production.

In Africa there are also steel producing countries Algeria or South Africa [15], where the energy consumption of their manufacturing process can also be substituted by hydrogen. Finally, the production of Ammonia [16] and the Jet Fuel consumption [17] will be considered.

As in the estimation of the hydrogen demand for Europe, it has also been necessary to convert the units to kg of hydrogen, as these energy consumptions are often in KWh or Thousand barrels per day in the case of jet fuel consumption.

In the appendix is attached the table with the demand of Kg of hydrogen in each European and African country, differentiating in blue the European countries and in brown the African ones.

5.2 Capacity

The proposed model will address two hydrogen production technologies. These two production technologies, SMR (with direct carbon capture) and PEM electrolysis have been chosen because they are the two technologies that emit the least GHG into the atmosphere and are the most efficient.

> According to the study, Life Cycle Assessment, and water footprint of Hydrogen production methods, "The numerical results show that hydrogen produced from non-fossil energy sources outperforms hydrogen produced from fossil sources (e.g., SMR and

grid electrolysis) in terms of life-cycle environmental performance. Electrolysis and reforming of bio-liquids present the opportunity for environment friendly hydrogen production using renewable resources. Electricity generation efficiency and the source will guide resource consumption, emissions, and corresponding overall life cycle impact results" [18].

The production process with each of the technologies is very different and requires different raw materials.

The following table [18] shows the different quantities of raw materials required for each of the methods:

Type	Thermo-Chemical				Electrolysis		Biological		
Conversion pathway	Steam methane reforming	Coal Gasification	Biomass Gasification	Biomass Reformation	Proton exchange membrane (PEM)	Solid oxide electrolysis cells (SOEC)	Dark fermentation + microbial electrolysis cell (MEC), w/out ER	Dark fermentation + microbial electrolysis cell (MEC), w/ER	Dark fermentation + microbial electrolysis cell (MEC), w/H_2 recovery
Abbreviation	SMR	CG	BMG	BDL-E	E-PEM	E-SOEC	DF-MEC w/out ER	DF-MEC w/ER	DF-MEC w/H_2 recovery
Feedstock	Natural gas	Coal	Corn Stover	Ethanol	Electricity	Electricity	Corn Stover	Corn Stover	Corn Stover
Natural gas (MJ/kg H_2)	165	-	6.228	-	-	50.76	22.9	-	-
Coal (kg/kg H_2)	-	7.8	-	-	-	-	-	-	-
Biomass (kg/kg H_2)	-	-	13.5	6.54	-	-	23.0	23.0	23.0
Electricity (kWh/kg H_2)	1.11	1.72	0.98	0.49	54.6	36.14	21.6	6.03	21.6
Water (kg/kg H_2) [1]	21.869	2.91	305.5	30.96	18.04	9.1	104.225	104.225	104.225
Ammonia (kg/kg H_2)	-	-	-	-	-	-	0.102	0.102	0.102
Sodium hydroxide (kg/kg H_2)	-	-	-	-	-	-	0.389	0.389	0.389
Sulfuric acid (kg/kg H_2)	-	-	-	-	-	-	0.207	0.207	0.207
Glucose (kg/kg H_2)	-	-	-	-	-	-	0.335	0.335	0.335
Corn liquor (kg/kg H_2)	-	-	-	-	-	-	0.008	0.008	0.008
Diammonium phosphate (kg/kg H_2)	-	-	-	-	-	-	0.015	0.015	0.015
Reference	[27]	[28]	[29]	[30]	[31,32]	[25,33]	[25]		

[1] For SMR, PEM, and SOEC water flow is water, deionized; For BMG and DF-MEC is water completely softened; for coal gasification and ethanol reforming is tap water.

Figure 14: Technology-specific feedstocks for hydrogen production

Once the raw materials needed to produce hydrogen with each of the technologies are known, the next step is to search in the literature for the quantities of resources needed in each country in order to calculate the production capacity.

For SMR hydrogen production, three raw materials are needed: Natural gas, water, and electricity. For PEM Electrolysis, however, only water and electricity are needed.

As explained above in the Model section, water availability, electricity and natural gas sources are input parameters of the model, but the way to calculate the production capacity in kg of hydrogen is done in a different way by the following formulation which is directly implemented in the model code in Python.

- PEM Electrolysis capacity

$$ELECTROLYSIS\_CAPACITY_i = Min\left[\frac{ELECTRICITY\_POTENTIAL_i\ (Kwh\ )}{54{,}6(\frac{Kwh}{Kg\ H_2})}; \frac{WATER\_AVAILABILITY_i\ (kg\ H_2O)}{18{,}04(\frac{kg\ H_2O}{kg\ H_2})}\right]$$

- SMR capacity:

$$SMR_{CAPACITY\,i}$$

$$= Min\left[\frac{ELECTRICITY\_POTENTIAL_i\ (Kwh\ )}{1{,}11(\frac{Kwh}{Kg\ H_2})}; \frac{WATER\_AVAILABILITY_i\ (kg\ H_2O)}{21{,}87(\frac{kg\ H_2O}{kg\ H_2})}; \frac{NATURAL\_GAS\_RESERVES_i\ (kg\ H_2O)}{165(\frac{MJ\ CH_4}{kg\ H_2})}\right]$$

The capacity of each country will be restricted by the minimum value of the quotient between the available amount of feedstock and the amount of feedstock needed to produce one kg of hydrogen.

Both technologies require electricity and water as feedstock. These two resources are often produced or extracted by fossil fuels or exploited in an environmentally unsustainable way.

In the case of water, it has been decided to consider according to the database from AQUASTAT, the total renewable water resources, which are calculated as follows [19]:

[Total renewable water resources] = [Total renewable surface water]+

[Total renewable groundwater]-[Overlap between surface water and groundwater]

Total renewable water resources will be the amount of water that can be sustainably extracted in each country, as this amount is naturally renewed annually.

As for the electricity available for hydrogen production, the model designed only considers the use of electricity from renewable resources, to keep the supply chain carbon-free. PV solar and Wind energy will be the two sources that the model will consider for the calculation of hydrogen production capacity, therefore, it can be said that it will be a green hydrogen.

For the estimation of PV solar and wind energy in Europe, data will be obtained from the JRC report "An EU energy outlook to 2050" [20]. This report estimates the differences in installed capacities for PV solar and wind energy between 2050 and 2015.

This is a good approximation, as it only considers new installed capacity, which is assumed to be used to produce green hydrogen. In this way, the use of pre-2015 installed capacity in this model is omitted, as this capacity has already been allocated today, and it would not make sense to have it.

In Africa, part of the renewable energy produced is used for the country's electricity consumption or in other industrial processes, as in Europe. Therefore, the renewable energy capacity currently installed on the continent cannot be considered.

Therefore, the way to calculate the available capacity for hydrogen production will be as follows:

$$Renewable\ capacity\ installed = Wind\ installed\ capacity + PV\ installed\ capacity$$

$$Potential\ renewable\ capacity = Renewable\ projections - Renewable\ capacity\ installed$$

The renewable capacity installed in Africa is taken from the IRENA database [21], [22]. In contrast, the renewable energy potential in Africa is taken from the report by IRENA in collaboration with KTH: Estimating the Renewable Energy Potential in Africa [23].

The data for PV Solar and Wind capacities are given in GW or MW. For conversion to energy, a capacity factor must be used depending on the type of energy involved. For Wind energy, the capacity factor is given as a function of three values: 20, 30 and 40%, these values depend on the intensity with which the wind blows and its frequency.

On the other hand, to estimate the energy that a solar plant can produce, its capacity factor is needed, which in this case is not given in the literature. A typical capacity factor for solar PV is 16,1 % and this depends on the geographical area in which the plant is installed.

As we do not have the capacity factor for each of the countries studied, an average capacity factor for solar PV of 16,1% is assumed.

$$ELECTRICITY\_POTENTIAL_i(MWh) = Potential\ renewable\ capacity_i(MW) * 24\left(\frac{hours}{day}\right) * 365\ (days) * Capacity\ Factor$$

The way in which the electricity potential in country *i* parameter is obtained is with the formula shown above, in which the capacity factor of each type of energy and its potential capacity is used.

The last element needed for hydrogen production with the SMR method is natural gas. This information is taken from the World Population review database where the natural gas reserves still available in 2021 are shown [24].

All the data needed to calculate the hydrogen production capacity by SMR and PEM Electrolysis by country is now available. This capacity will be limited by the amount of water, renewable electricity, and natural gas available in each country.

The following section will explain what the LCOE of hydrogen is and from which sources it is obtained. This parameter will set the price of production, depending on the technology used, and will have a major impact on the overall cost of the supply chain.

5.3 Levelized Cost of Hydrogen

The levelized cost of hydrogen is a way of calculating how much hydrogen production will cost in $/kg over the lifetime of the production plants. This price will vary depending on several factors such as the lifetime of the plant, hydrogen produced during the lifetime years, investment costs, operation and maintenance costs and a discount rate [25].

$$LCOH = \frac{sum\ of\ cost\ over\ lifetime}{sum\ of\ hydrogen\ produced\ over\ lifetime}$$

$$sum\ of\ cost\ over\ lifetime = \sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}$$

$$sum\ of\ hydrogen\ produced\ over\ lifetime = \sum_{t=1}^{n} \frac{H_t}{(1+r)^t}$$

I_t: *Investment costs in year t*

M_t: *Operations and maintenance costs in year t*

F_t: *Fuel costs in year t*

H_t: *Hydrogen produced in Kg in year t*

r: *discount rate*

n: *expected lifetime year of the power station*

This is the most widespread way of calculating the cost of hydrogen production in each country with the highest accuracy, depending on the technology used. In this project, two ways of calculating the levelised hydrogen costs will be used, firstly it has been decided to assume an average LCOH for all countries, depending on the technology. An attempt has been made to differentiate prices by taking into account the "ease of doing business" index, which indicates on a scale from 0 to 100 the ease of doing business in a country, with 100 being the maximum possible [26].

Therefore, two different LCOH scenarios will be considered. One scenario will modify the "ease of doing business index" to multiply it by the average LCOH to obtain different prices for each country, considering that the lower the "ease of doing business index", the higher the LCOH will be proportionally. The other scenario is to manually estimate the LCOH to obtain a differentiation between countries based on the cost of electricity and their potential for renewable electricity generation, as will be discussed in the next chapters, the manually calculated LCOH is the one to use and the one that is closest to reality. For the adaptation of the ease of doing business index, the value of Germany has been chosen as the standard. In this way, the indices of each country will be obtained by dividing its index by the standard. In the case of Germany by dividing its index by the same amount, its modified index will be equal to 1, therefore, by multiplying this index by the average LCOH in SMR or Electrolysis, the prices are going to be the same for Germany.

This is because Germany is a country that has been taken as the standard for ease of doing business and it is assumed that prices will not vary there. They will change in the case the ease of doing business was different.

How is it calculated the index for another country as Argelia?

Algeria's ease of doing business index: 48,60

Standard ease of doing business index (Germany): 79,70

If we divide these values: $\frac{48,60}{79,70} = 0,609$;

Which means that to approach the hydrogen production German costs, Argelia needs to improve its ease of doing business:

$$(1 - 0,609) * 100 = 39\%$$

As Argelia needs to improve his index in 39%, the hydrogen production costs will be 39% higher than in Germany. That's why the ease of doing business modified index for Argelia will be 1,39.

Then to calculate the prices for Argelia:

$$SMR\ production\ cost\ in\ Argelia = 1,39 * Average\ SMR\ production\ cost = 3,284$$

Prices for LCOH average are taken from the report, Hydrogen: A renewable energy perspective from IRENA [27]. This report estimates the costs of hydrogen production by SMR+CCS at 2.2 $/kg. In the case of electrolysis using energy from Solar PV, with an average-cost of 85$/MWh the LCOH would be 6.8$/Kg, for electricity from Wind with an average-cost of 55$/MWh the LCOH would be 4.3$/Kg.

$$\boldsymbol{Average\ SMR\ LCOH = 2,2\ \$/KG}$$

$$\boldsymbol{Average\ ELECTROLYSIS\ LCOH} = \frac{6,8 + 4,3}{2} = \boldsymbol{5,5\ \$/KG}$$

The following values will be taken as LCOH for each technology and from these values the production costs are estimated.

To penalize the method that emits the most GHG into the atmosphere, the cost of its emissions will be added to the average LCOH. It is known that the emissions caused by each production technology are as follows:

$$SMR + CCS\ GHG\ emissions = 5520\ \frac{g\ CO2}{KG\ H2}$$

$$Electrolysis\ GHG\ emissions = 360\ \frac{g\ CO2}{KG\ H2}$$

Multiplying the GHG emissions of each technology by the emissions price and adding this amount to the average LCOH will give the total hydrogen production price for each technology. Adding the emissions price to the model will allow the study of various scenarios varying the emissions price, using different emissions prices depending on their estimates for the coming years.

The next chapter will now discuss the final parameters defining the model and used to calculate the transport costs of the hydrogen supply chain, before moving on to discuss the model results and their discussion.

5.4 Transport costs

The transport costs together with the production costs will form the total cost of the supply chain, and it will be of vital importance to analyse in detail the literature that has been considered to obtain each parameter that defines the transport costs.

This model will consider several transport paths, among them are Truck, Ship, and natural gas pipelines. In addition, within them there will be several variants that will also be considered and that will have different limitations and costs. All this will be explained in detail in the following sections.

5.4.1 Adjacency matrix

Before calculating the actual transport costs for each pathway, the model will need information as to what constraints exist on each pathway. There will be paths in which it will be unfeasible to transport hydrogen for some countries.

A very illustrative example could be the case in which we want to transport hydrogen by truck between Algeria and Spain. In this case it is not possible because the only way to transport hydrogen by sea is by ship or natural gas pipelines.

A very widespread method for this type of problem is the adjacency matrix. These matrices are made up of *n* rows and *n* columns, where *n* is the number of countries studied in the model, in this model the adjacency matrix will be 75x75.

The adjacency matrix method consists of filling the cell in which a hydrogen exchange between the countries is physically possible with the value 1. In the opposite case, in which the exchange is unfeasible, the cell value will be 0.

The idea is to fill in all the adjacency matrices and create a three-dimensional matrix, where, depending on the exchange countries and the transport path *p*, we have the limitations of the paths.

	Algeria	Angola	Benin	Botswana	Burkina Fas	Burundi	Cameroon	Central Africar	Chad	Congo	Côte d'Ivoir	Djibouti	DR Congo	Egypt
Algeria	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Angola	0	0	0	0	0	0	0	0	0	1	0	0	1	0
Benin	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Botswana	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Burkina Faso	0	0	1	0	0	0	0	0	0	0	1	0	0	0
Burundi	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Cameroon	0	0	0	0	0	0	0	1	1	1	0	0	0	0
Central African Republic	0	0	0	0	0	0	1	0	1	1	0	0	1	0
Chad	0	0	0	0	0	0	1	1	0	0	0	0	0	0
Congo	0	1	0	0	0	0	1	1	0	0	0	0	1	0
Côte d'Ivoire	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Djibouti	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DR Congo	0	1	0	0	0	1	0	1	0	1	0	0	0	0
Egypt	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Equatorial Guinea	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Eritrea	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Eswatini	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ethiopia	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Gabon	0	0	0	0	0	0	1	0	0	1	0	0	0	0
Gambia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ghana	0	0	0	0	1	0	0	0	0	0	1	0	0	0
Guinea	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Guinea-Bissau	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kenya	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lesotho	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Liberia	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Libya	1	0	0	0	0	0	0	0	1	0	0	0	0	1
Malawi	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mali	1	0	0	0	1	0	0	0	0	0	1	0	0	0
Mauritania	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Morocco	1	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 15: Extract from Adjacency matrix truck

This information will be used in one of the constraints. As explained above with constraint *(1)*, the amount of hydrogen transported between countries *i* and *j* with path *p* equal to zero will be fixed when the element of the adjacency in question is also zero.

It is necessary to make some clarifications regarding the elaboration of the adjacency matrix. In the case of the Adjacency Matrix Truck, the assumption will be made that only countries that share a land border will have a matrix value of 1. This ensures that the calculation of the distance is more accurate, because as will be seen in the following section, the distance between countries is calculated with the Haversine function between the geographical centres of each country.

Therefore, if the final solution of the model considers transporting hydrogen by truck between South Africa and Morocco, the distance that the truck will travel in this transport will not be a straight line as the Haversine function would calculate, the real distance will be the distance that the truck travels between the different countries that it travels through.

By limiting the transport between bordering countries, the model is forced to consider the set of distances between each country separately and not a straight line between the two countries. This limitation also makes the transport cost as realistic as possible since, as we will see in later sections, part of the transport cost is a function of the kilometres travelled.

In the Adjacency Matrix Ship a simplification will be made in the model, since it was not possible to obtain the information on distances between countries with coastline, it is assumed that for the transport of hydrogen by ship between Africa and Europe it is only possible to transport it between all African countries with coastline and The Netherlands.

It has been decided to establish the connection point for the transport of hydrogen by ship in The Netherlands because the port of Rotterdam is the largest in Europe and is a great candidate as a future hub for the transport of green hydrogen between Africa and Europe.

For the supply of Cyprus, the option of transport by ship with Egypt has been enabled, as it is the closest country and has great renewable potential. In the case of Ireland, the possibility of transport by ship from The Netherlands has also been enabled.

Finally, in the adjacency matrix pipelines, there is only the possibility of transport between Algeria-Spain, Libya-Italy, and Algeria-Italy, using the infrastructure currently available in these countries.

The calculation of the distances is a parameter that has not been easy to obtain from the available literature and its calculation will be important for the transport cost, therefore, it is worth devoting the following section to its explanation.

5.4.2 Distances

The distances between countries are strictly necessary parameters to calculate the total transport costs for each transport path. Calculating the distances manually would be a rather time-consuming process, therefore, the option of using the haversine function [28] has been chosen.

This is an important equation for astronomical navigation. It is widely used for the calculation of the distance between two points on the surface of a sphere. These points will be given by geographical coordinates, latitude, and longitude.

$$haversin(\theta) = sin^2(\frac{\theta}{2})$$

$$haversin\left(\frac{d}{R}\right) = haversin(\varphi_1 - \varphi_{\mathbf{2}}) + \cos(\varphi_1)\cos(\varphi_{\mathbf{2}})\, haversin(\Delta\lambda)$$

In this model the sphere of the equation will be the earth, where:

- d is the distance between the two points along the earth.
- r is the radius of the earth.
- φ1, φ2 are the latitude of point 1 and latitude of point 2 (in radians).
- λ1, λ2 are the longitude of point 1 and longitude of point 2 (in radians).

For the automated calculation of the distance between countries, a Python function is defined where the Haversine equation is introduced and from two points the function returns the distance. To store these values, a distance matrix will be created named $Matrix\_haversine_{ij}$, which will later be used for the calculation of transport costs.

A great advantage of using the Haversine equation for the calculation of distances between countries is that this equation considers the radius of curvature of the earth, so the calculation error will be minimal.

Land distances would already be ready to be used in the model, but what about maritime distances?

The maritime routes do not follow a pattern compared to the distances calculated using the Haversine function, since the Haversine function calculates the distance as the minimum distance, which in all cases is a straight line, but in maritime transport it is strictly necessary to consider the coastlines, therefore, the distance in maritime route will not be the minimum distance.

This restriction has meant that for this model it has not been possible to consider all countries that have a coastline for their maritime transport. The model had to be simplified by establishing a connection point with Europe in The Netherlands but considering all the countries of the African continent with a coastline.

The calculation of the maritime distances had to be done manually using the online tool: https://www.searates.com/es/services/distances-time/.

These distances have been added to an Excel sheet and an input parameter has been created for use in the model named $SHIP\_DISTANCES_{ij}$.

5.4.3 Truck

In hydrogen transport by truck, there are several ways in which hydrogen can be transported, each of which will be discussed in this model and at different costs depending on the physical state in which it is transported.

Within hydrogen transport by truck, hydrogen can be transported in gaseous form in gas cylinders or gas tubes at pressures between 200 and 500 bar. Recently a jumbo trailer was released that can carry 13,000 m3 of hydrogen compressed with 500 bar (Linde Group, 2013), which amounts to a transported hydrogen weight of about 1100 kg [29].

Given the lack of pipeline infrastructures dedicated to the transport of exclusive hydrogen, this transport route is promising because, as mentioned in the previous study, there are already trucks equipped for hydrogen transport, and this technology will undoubtedly advance in the coming years in terms of greater transport capacity and lower carbon footprint in transport by truck, changing the consumption of fossil fuels in trucks for e-fuels.

According to the report, Path to hydrogen competitiveness [30], the compression cost is 0.8\$/Kg H2 and the transport cost per 400 km is 1\$/Kg H2. With these values we could already calculate the transport costs for gaseous truck, with the input of the following parameters to the model:

$$TRUCKING\_COMP = 0{,}8\ (\frac{\$}{Kg})$$

$$TRUCKING\_GAS\_DIST = \frac{1}{400} = 0{,}0025\ (\frac{\$}{Kg * Km})$$

The following formula is used to calculate the transport costs between each country considering the associated costs:

$$TRANS\_COSTS_{i,j,0} = TRUCKING\_COMP + (TRUCKING\_GAS\_DIST * Matrix\_haversine_{ij})$$

The transport costs for gaseous truck will be stored in the parameter $TRANS\_COSTS_{i,j,p}$ which will be used in the objective function to extract the transport costs for each path. In this case, the costs are stored at p=0 since the first subscript of the path corresponds to the gaseous truck mode.

The second way of transporting hydrogen by truck is in liquid form. Hydrogen in liquid form has a higher energy density than in its gaseous form, so it is possible to transport more hydrogen in liquid form than in gaseous form, but the disadvantage is that to liquefy the hydrogen it is necessary to lower its temperature to -253ºC and store it at a pressure between 350-700 bar [31].

The way to calculate its total cost is very similar to that of the gaseous truck, but changing its parameters:

$$TRUCKING\_LIQUEF = 1{,}6\ (\frac{\$}{Kg})$$

$$TRUCKING\_LIQUEF\_DIST = \frac{0{,}4}{400} = 0{,}001\ (\frac{\$}{Kg * Km})$$

$$TRANS\_COSTS_{i,j,1} = TRUCKING\_LIQUEF + (TRUCKING\_LIQUEF\_DIST * Matrix\_haversine_{ij})$$

The last way in which hydrogen can be transported by truck is by Liquid organic hydrogen carriers (LOHC). These organic compounds can absorb hydrogen through an exothermic hydrogenation reaction. When the organic compound together with the hydrogen reaches its destination, it is also necessary to perform another endothermic reaction to purify the mixture to separate the hydrogen from the organic compound, called dehydrogenation. A great advantage of using LOHC is that they can be transported under ambient conditions, therefore, no large pressurized or refrigerated tanks are needed for transport.

Although transport can be performed under ambient conditions, the hydrogenation reaction occurs at pressures of 30-50 bar and 150-200°C in the presence of a catalyst. The dehydrogenation reaction also occurs at higher temperatures of 250-320ºC, so these are factors that must be considered when designing the supply chain.

The way of calculating the transport costs associated with LOHC by truck is somewhat different from the above. In this case, we have not found a report that will calculate an exact figure for each stage of transport, so we have chosen to extract the information from the following study, Techno-economic feasibility of road transport of hydrogen using liquid organic hydrogen carriers [32].

According to this study, the price in (€/kg H2) depends on two variables: distance travelled, and kilos of hydrogen transported. Therefore, to estimate the costs for any given distance and amount of hydrogen transported, an approximation will be made according to the data of this study, by performing a linear interpolation.

		GH2 (composite) most feasible										LOHC (low CAPEX) most feasible	
Hydrogen demand		One-way transport distance											
kg/day	MW	25 km	50 km	75 km	100 km	125 km	150 km	175 km	200 km	225 km	250 km	275 km	300 km
1800	2.5	0.98	1.03	1.09	1.14	1.19	1.24	1.30	1.34	1.37	1.41	1.44	1.48
3600	5	0.72	0.78	0.83	0.97	1.01	1.04	1.08	1.12	1.19	1.23	1.26	1.30
5400	7.5	0.62	0.78	0.83	0.88	0.94	0.98	1.01	1.05	1.08	1.12	1.15	1.18
7200	10	0.65	0.70	0.75	0.84	0.88	0.91	0.95	0.98	1.04	1.07	1.11	1.14
9000	12.5	0.60	0.65	0.76	0.80	0.84	0.89	0.92	0.96	0.99	1.03	1.08	1.11
10800	15	0.56	0.66	0.71	0.77	0.82	0.85	0.89	0.92	0.97	1.01	1.04	1.07
12600	17.5	0.58	0.63	0.71	0.76	0.79	0.83	0.88	0.91	0.94	0.99	1.03	1.06
14400	20	0.55	0.60	0.69	0.74	0.77	0.82	0.85	0.89	0.93	0.97	1.00	1.05
16200	22.5	0.53	0.61	0.67	0.72	0.77	0.80	0.85	0.88	0.91	0.96	0.99	1.02
18000	25	0.51	0.59	0.67	0.72	0.75	0.79	0.83	0.86	0.91	0.94	0.98	1.02
19800	27.5	0.52	0.60	0.65	0.70	0.75	0.78	0.81	0.86	0.89	0.93	0.97	1.01
21600	30	0.51	0.59	0.66	0.69	0.73	0.77	0.81	0.84	0.89	0.92	0.96	0.99

Figure 16: LOHC truck transport cost depending on the distance

The following values shall be taken as data for linear interpolation:

- For 100 km the values of 3600 and 21600 kg/day will be taken.
- For 300 km the same amounts of hydrogen will be taken, thus covering most of the values and giving a value as close as possible.

In the next table, the yellow cells contain the changing values, distance in kilometers and kg/day transported between each country. In this example, the cost of hydrogen transport is calculated for 431 km and 600 kg H2/day.

In green is the price value (€/kg H2) calculated with linear interpolation, according to the distance and the amount of hydrogen transported in each case.

Table 3: Interpolation values for LOHC truck transport costs

(kg/day)/km	100	300	431
3600	0,97	1,3	1,51615
21600	0,69	0,99	1,1865
600			1,57109167

This way of calculating the transport cost is implemented in Python so that its calculation is automated according to the distance and quantity of hydrogen transported.

In this pathway, as in the following section on transport by ship, there will be no limitations on the amount of hydrogen transported; it is assumed that the necessary trucks and ships will be available depending on the transport demand.

5.4.4 Ship

The methods for transporting hydrogen by ship are very similar to the solutions currently available for transport by ship. There are two forms of transport by ship that are currently the most feasible, firstly, transport via liquefied hydrogen tanks refrigerated to -253ºC.

Figure 17: Suiso Frontier, the first LH2 carrier ship

The picture above shows the Suiso Frontier, the first LH2 carrier ship to transport liquefied hydrogen from Australia to Japan. This indicates that this type of transport is a reality and that as new, more efficient ship models with higher cargo capacities are developed, the cost of transport will be reduced. This will also allow the increased use of this path for new large-scale supply chains.

The estimated prices for LH2 ship carrier are 1$/Kg for the liquefaction process, 1.2$/Kg for transport over a route of 8700 km and the last item would be the port import costs of 0.2$/Kg [33].

$$SHIPPING\_LIQUEF = 1\ (\frac{\$}{Kg})$$

$$SHIPPING\_LIQUEF\_DIST = \frac{1{,}2}{8700} = 0{,}0001379\ (\frac{\$}{Kg * Km})$$

$$SHIPPING\_IMP\_TER = 0{,}2(\$/Kg)$$

$$TRANS\_COSTS_{i,j,3} = TRUCKING\_LIQUEF + (TRUCKING\_LIQUEF\_DIST * Matrix_{haversine_{ij}}) + SHIPPING\_IMP\_TER$$

The above formulas show how the cost is calculated for this type of transport, very similar to those previously seen, but with an additional cost term corresponding to the import costs at the port.

The second and last transport path by ship is the well-known LOHC. One of the great advantages of this path is that, unlike LOHC by truck, the amount of hydrogen to be transported by ship is much greater than by truck, as the tanks on these ships have much larger capacities than a truck. Therefore, it is a good option when transporting hydrogen over long distances (transcontinental).

The costs for transport are as follows: For the initial hydrogenation process the cost is 0,5$/Kg, for the case of a maritime route of 7000 Km the cost is 0,4$/Kg, and the last cost concept corresponds to the dehydrogenation process once at destination which would be 1,8$/Kg.

Having seen the concepts that make up the transport cost for LOHC by ship, the following formulas are implemented in the Python code to obtain the costs between each country:

$$SHIPPING\_HYDROG = 0{,}5\ (\frac{\$}{Kg})$$

$$SHIPPING\_LOHC\_DIST = \frac{0{,}4}{7000} = 5{,}71 * 10^{-5}\ (\frac{\$}{Kg * Km})$$

$$SHIPPING\_DEHYDROG = 1{,}8(\$/Kg)$$

$$TRANS\_COSTS_{i,j,4} = SHIPPING\_HYDROG + (SHIPPING\_LOHC\_DIST * Matrix_{haversine_{ij}}) + SHIPPING\_DEHYDROG$$

These two paths will be considered by the model if hydrogen transport by sea is necessary. The following section will explain the last path considered, which will be by means of the current natural gas pipelines, as there are currently very few pipelines exclusively for the transport of hydrogen.

5.4.5 Pipelines

As mentioned in section 4.5 constraints, pipeline transport will consider the existing gas pipelines between North Africa and Europe. To calculate the cost of transporting hydrogen through pipelines transporting natural gas, it is first necessary to know the hydrogen transport capacities of the pipelines.

Table 4: Hydrogen capacity by natural gas pipelines

PIPELINES	Capacity (Bcm) of Natrual gas	H2 (KWh)	H2 (Kg)
Maghreb-Europe	11,5	4200000000	1,25E+08
Medgaz	8	2900000000	8,63E+07
Trans-Mediterranean	33	12000000000	3,57E+08
Greenstream	11	4000000000	1,19E+08

These data are taken from the study, Supply from North Africa to Central Europe as blend in existing pipelines [4]. The Maghreb-Europe and Medgaz would transport hydrogen directly from Algeria to Spain, therefore, the hydrogen transport capacities of the two pipelines will be added together to calculate the price of transport between Algeria and Spain. In contrast, the Trans-Mediterranean and the Greenstream would transport to Italy, from Algeria and Libya respectively, therefore, their capacities will be treated separately when calculating the cost of transport between each country.

When calculating the transport cost, it is necessary to differentiate whether the pipeline sections are onshore or offshore, as the costs will be very different if the pipeline is at sea or on land. In the case of offshore pipeline sections, the costs will be higher since access to these sections will be more expensive in the case of repairs in pumping stations or in any section of the pipeline.

The costs for onshore transport have a cost that varies between 1-2.2 €/GJ and for offshore sections will be between 1.2-2.6 €/GJ, for a section of 1000 km. Therefore, the costs for each type would be 0.000192 €/Kg*Km for onshore sections and 0.000228 €/Kg*Km for offshore sections.

Table 5: Onshore and offshore pipelines distances

Distances (Km)				
Onshore	Offshore	Onshore %	Offshore %	Price ($)
1385	45	0,96853147	0,03146853	3,80E+07
547	200	0,73226238	0,26773762	9,08E+06
1275	155	0,89160839	0,10839161	9,36E+07
540	520	0,50943396	0,49056604	1,56E+07

Depending on the distances travelled, the quantities transported and the type of section, we obtain weighted prices for transport. This gives the total transport costs for natural gas pipelines:

Table 6: Transport cost by pipelines

	Price ($)	Transport cost ($/kg)
Algeria-Spain	4,71E+07	0,22
Algeria-Italy	9,36E+07	0,26
Lybia-Italy	1,56E+07	0,13

The transport of hydrogen through natural gas pipelines is the cheapest among those considered in this model, but a major disadvantage of this pathway is that it is very limited by the transport of natural gas to Europe. These limitations, as discussed in the constraints section, will be considered in the model.

Having explained in detail the nature of the parameters, all the parts of the model and how the data have been obtained, the following chapter will analyze the results of the different scenarios to be studied.

6. Output

This chapter will analyze the results obtained by the model but analyzing it from several possible scenarios. It is essential to study a model from several scenarios, as this way it is possible to check that the model works correctly and meets the initial objectives of the work.

Within the different scenarios to be studied, both the computational results and the quantitative results of the global cost of the supply chain will be analyzed. It is important to analyze these two aspects, since in this case the computational costs of solving the model will not be taken into account, but when solving a model in a real situation for a company, the computational costs of solving large mathematical models are very important.

In total, 4 scenarios will be analyzed. In the first scenario, the model will be analyzed in which the same cost for all countries has been used to calculate the LCOH but multiplying this by a modified index that takes into account the ease of doing business, in order to have different costs for each country. In the second scenario, LCOHs will be calculated manually in order to have a price differentiation between each country, also taking into account the ease of doing business index as a rate of discount. In the third scenario, the manually calculated LCOH will be maintained, but this time a modification will be made to the LCOH for electrolysis, varying its CAPEX. Finally, a future scenario will be studied in which the price of GHG emissions in the coming years will be taken into account, and it will be analyzed how the results vary according to the increase in the price of these emissions, which are harmful to climate change.

6.1 Scenario I- Average LCOH

In this first scenario, the LCOH has been extracted directly from the literature [27], assuming costs of 5.5 $/kg for electrolysis and 2.2 $/kg for SMR with CCS. As explained in the LCOH section, these average costs are multiplied by a modified index that takes into account the ease of doing business index of each country, in order to have a differentiation in the LCOH. Although this scenario takes into account the modified ease of doing business index, a scenario that was considered at the beginning in order to simplify the model was to consider the same LCOH for all countries.

It is worth showing the computational results in these two cases:

- Average LCOH:

When the LCOH for all countries are equal, the Gurobi library is able to solve the model in 0.86 seconds after 23 iterations. The following graph shows the different optimal values reached by the model in each iteration.

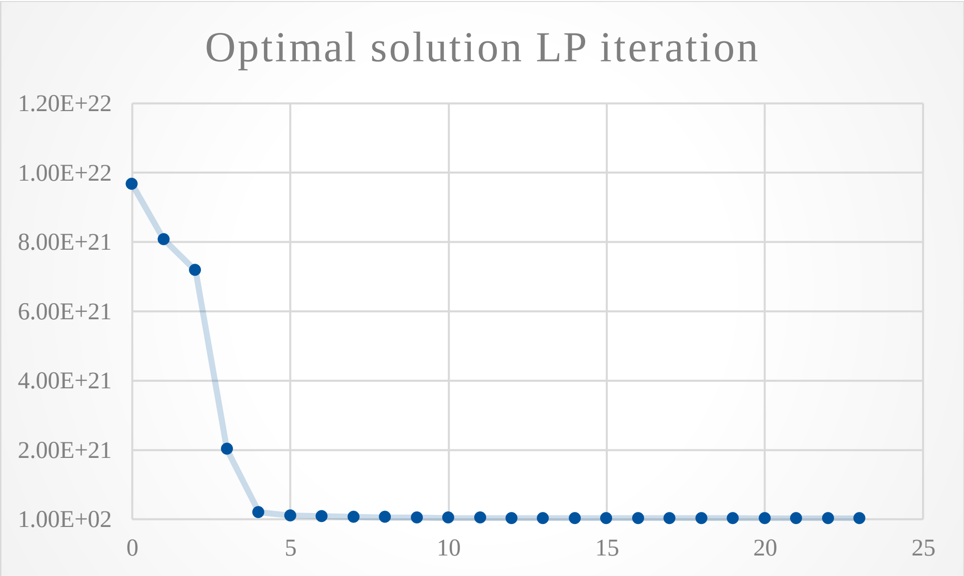


Figure 18: Optimal solution LP iteration scenario I

In the fourth iteration the model is already able to approach a solution very close to the final optimal solution. The final solution arrived at by the model is that the supply chain will have an overall cost of $2{,}229 * 10^{11}\$$

- Average LCOH with EODB:

However, when the ease of doing business index is taken into account, the LCOH for each country changes, and this complicates the model.

Table 7: Computacional results scenario I

Iterations	164
Seconds	1,67
Optimal objective	2,38E+11

The number of iterations increases and the optimal objective increases by 6.34%. The results of the model for the latter case are shown below, in which the variables of both the quantity of hydrogen produced in each country with each production technology, as well as the hydrogen transport flows between countries, are represented on a map.

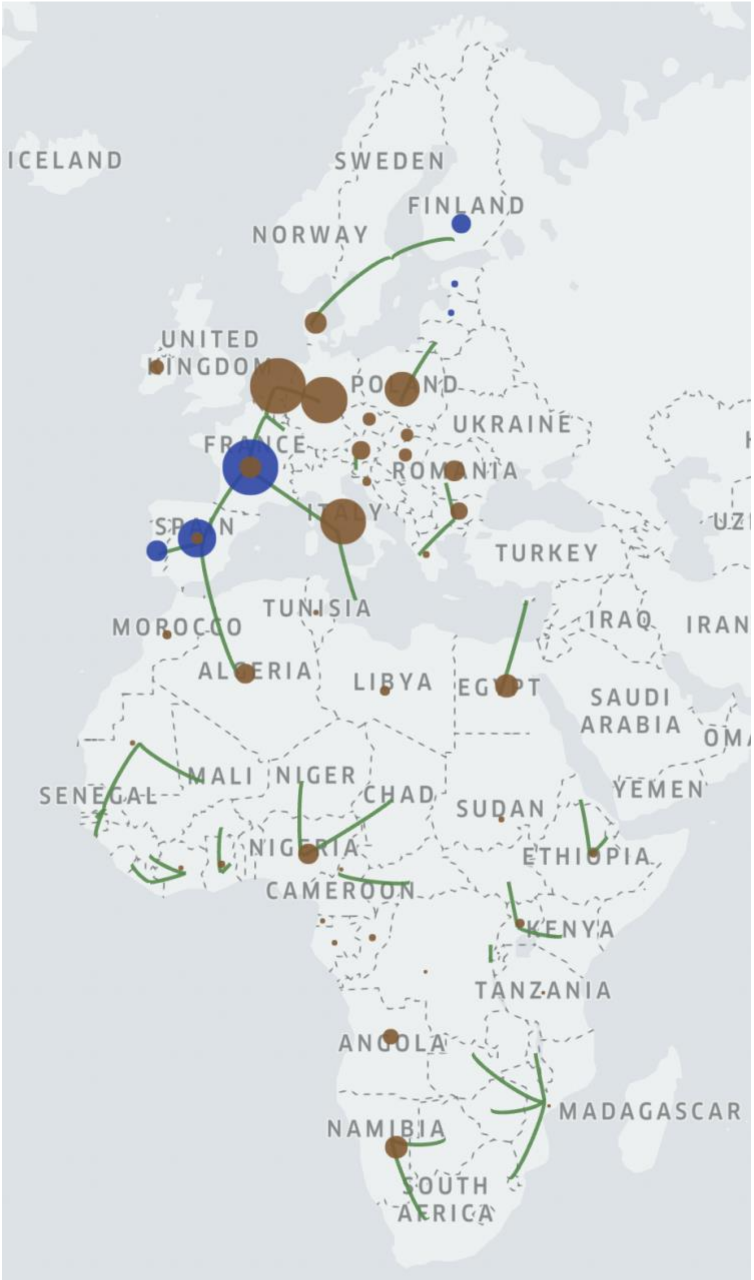


Figure 19: Production and transport of hydrogen in scenario I

The brown circles represent hydrogen production by SMR with CCS technology, and the blue circles represent hydrogen production by electrolysis. The radius of the circles will be proportional to the quantities of hydrogen produced in each case. The green lines represent the hydrogen transport flows between countries. It has not been decided to finally represent the width of the lines of the hydrogen transport flow as a function of the quantity transported, because there are exchanges where they are quite small compared to some transport flows in Europe, where the demand for hydrogen is higher, therefore, the transport flows in some African countries where the quantity transported was lower were not correctly appreciated.

In order to be able to appreciate the difference numerically, the results have been added in tables in the appendix at the end of the document.

A priori, there is a large number of countries where hydrogen is produced, but the large number of brown circles indicating the presence of a large amount of hydrogen from SMR with CCS stands out, this is due to the fact that the average LCOH for this type of technology is 150% lower than that of electrolysis. Furthermore, despite introducing a variation in LCOH according to the ease of doing business index, there are a large number of hydrogen producing countries in countries where the ease of doing business is relatively low compared to European countries with higher stability, indicating that the ease of doing business is not so detrimental to the final cost of the supply chain as to shift production to countries with a better ease of doing business index.

The large number of producing countries indicates that it pays to produce hydrogen in as many countries as possible because of the cost of transporting it, which in many cases does not compensate for the difference in EODB. The way in which the EODB is multiplied directly by the average LCOH does not accurately represent the price differentiation between countries with more potential for renewable hydrogen generation through clean energies such as solar PV or wind, as making this assumption is equivalent to penalizing countries with a low EODB in the LCOH regardless of their potential and the cost of energy, therefore, it is necessary to study a new scenario where LCOH will be calculated manually taking into account both the price of electricity and the renewable potential. Furthermore, the EODB will only be used as a rate of discount in the LCOH formula.

6.2 Scenario II – LCOH Manually with EODB as a rate of discount

This second scenario already considers, as mentioned above, the price of electricity and natural gas in each country, in order to have a much more realistic LCOH than the one contemplated in scenario I, where an average LCOH taken directly from the literature has been used.

In addition, the EODB concept is introduced in the LCOH calculation in a more correct way, where it will be considered as a rate of discount. The computational results of the resolution of the model with the new LCOH are shown below.

Table 8: Computacional results scenario II

Iterations	116
Seconds	1,95
Optimal objective	5,45E+11

In this second scenario, the number of iterations is lower, but the computational time in which the model is solved is somewhat longer than in the first scenario. On the other hand, the optimal cost of the supply chain increases by 129% with respect to scenario 1, due to the significant increase in the new manual calculation of the LCOH. The following image shows the results of the model visualized on the map.

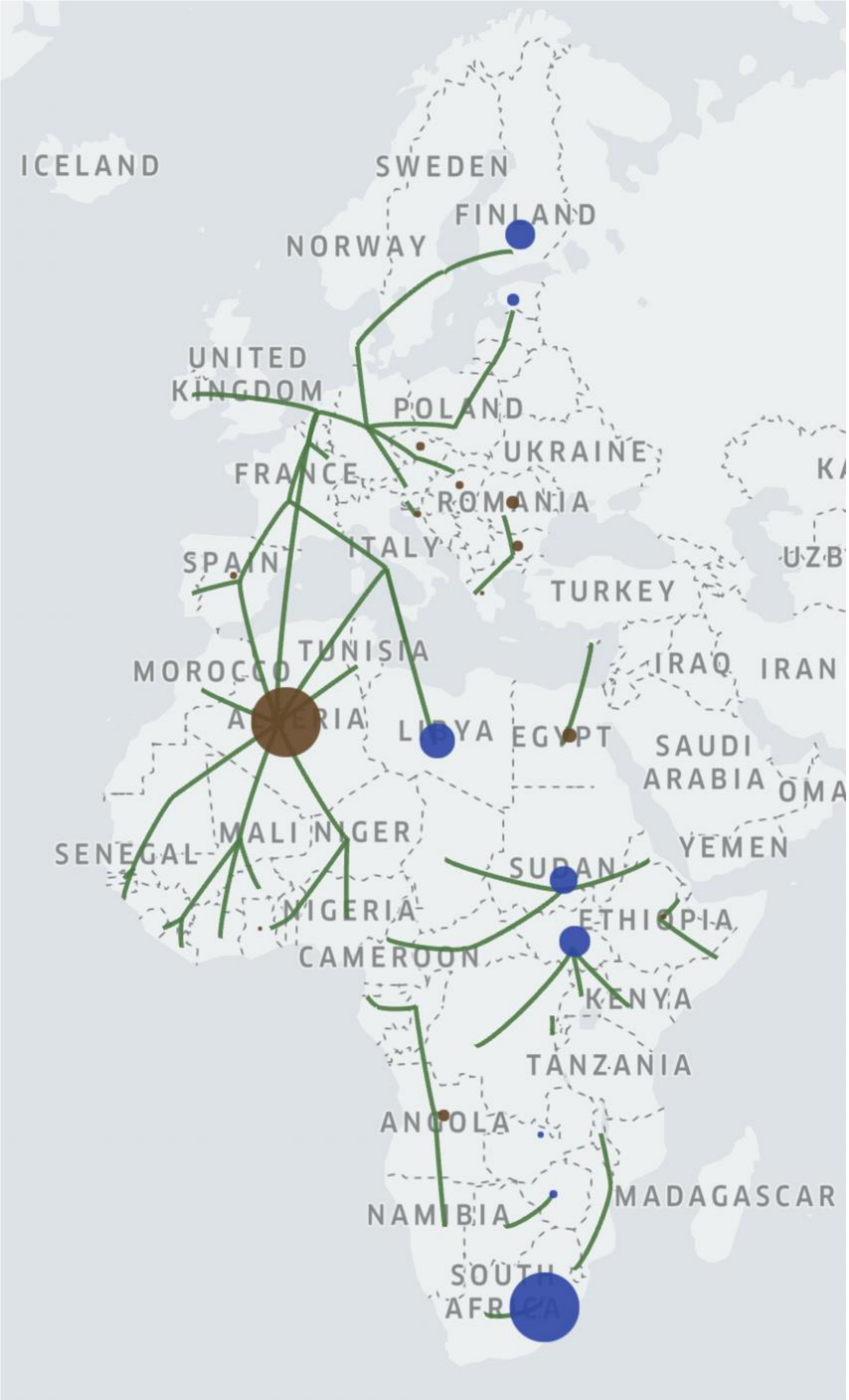


Figure 20: Production and transport of hydrogen in scenario II

The number of hydrogen exchanges between countries increases considerably in this second scenario, which leads to a decrease in the number of producer countries, creating large production centers in countries where LCOH is cheaper.

Furthermore, as can be seen in the annex where the numerical results of hydrogen exchanges between countries are presented, the hydrogen transport flow from Africa to Europe increases. In the first scenario, the quantity of hydrogen transported between Algeria and Spain is the maximum permitted quantity imposed by the capacity constraint. This is also the case in the second scenario, but unlike the first scenario, for the first time hydrogen transport between Algeria and The Netherlands by liquefied ship is observed. This and other remarkable results will be explained in more detail in the discussion section.

6.3 Scenario III – Long term CAPEX and OPEX

The results obtained in scenario II are very orientative, in that the final solution of the real model today is very much in the direction of this solution, but it is also important to be able to know the possible variations that the results may experience, based on the reduction in the prices of renewable energy generation, which would directly affect the LCOH in the case of using renewable energy sources for hydrogen production, as this model effectively contemplates. The following two scenarios aim to study precisely some of the possible variations that may occur in the near future.

The first of these is to study what results would be obtained by varying the CAPEX and OPEX for SMR with CCS and electrolysis. According to all the reports carried out both by consultancies specialized in renewable energy and by the International Energy Agency, the investment costs of electrolysis equipment are going to be drastically reduced in the coming years, as the prices of renewable energy production (solar PV and wind) are also reduced.

According to the IEA, the CAPEX for electrolysers in the long term will be 450 $/KW [34]. In scenario II current costs of 1100 $/KW have been assumed, this reduction in CAPEX for long term will be close to 60% compared to current costs. The CAPEX significantly influences the LCOH, therefore, the LCOH for electrolysis in this case will be drastically reduced. As well as the investment costs (CAPEX), the operation and maintenance costs will also be affected, which typically range between 1 and 3% of the CAPEX, equivalent to an operation and maintenance cost of 13.5 $/KW [35].

Just as this drastic reduction is estimated for hydrogen production by electrolysis, the IEA also estimates a long-term reduction in costs for SMR with CCS. The CAPEX in this case would drop from 1680 $/KW to 1280 $/KW, a reduction of 23.8%.

The computational results of this third scenario are shown below with the above-mentioned changes:

Table 9: Computacional results scenario III

Iterations	180
Seconds	1,14
Optimal objective	4,90E+11

The number of iterations increases, but the resolution time is shorter than in scenario II. As for the optimal target cost, the value is reduced by 10.09%, which a priori is not so remarkable considering the drastic reduction in the LOCH for electrolysis.

The results for hydrogen transport and production are shown in the map below.

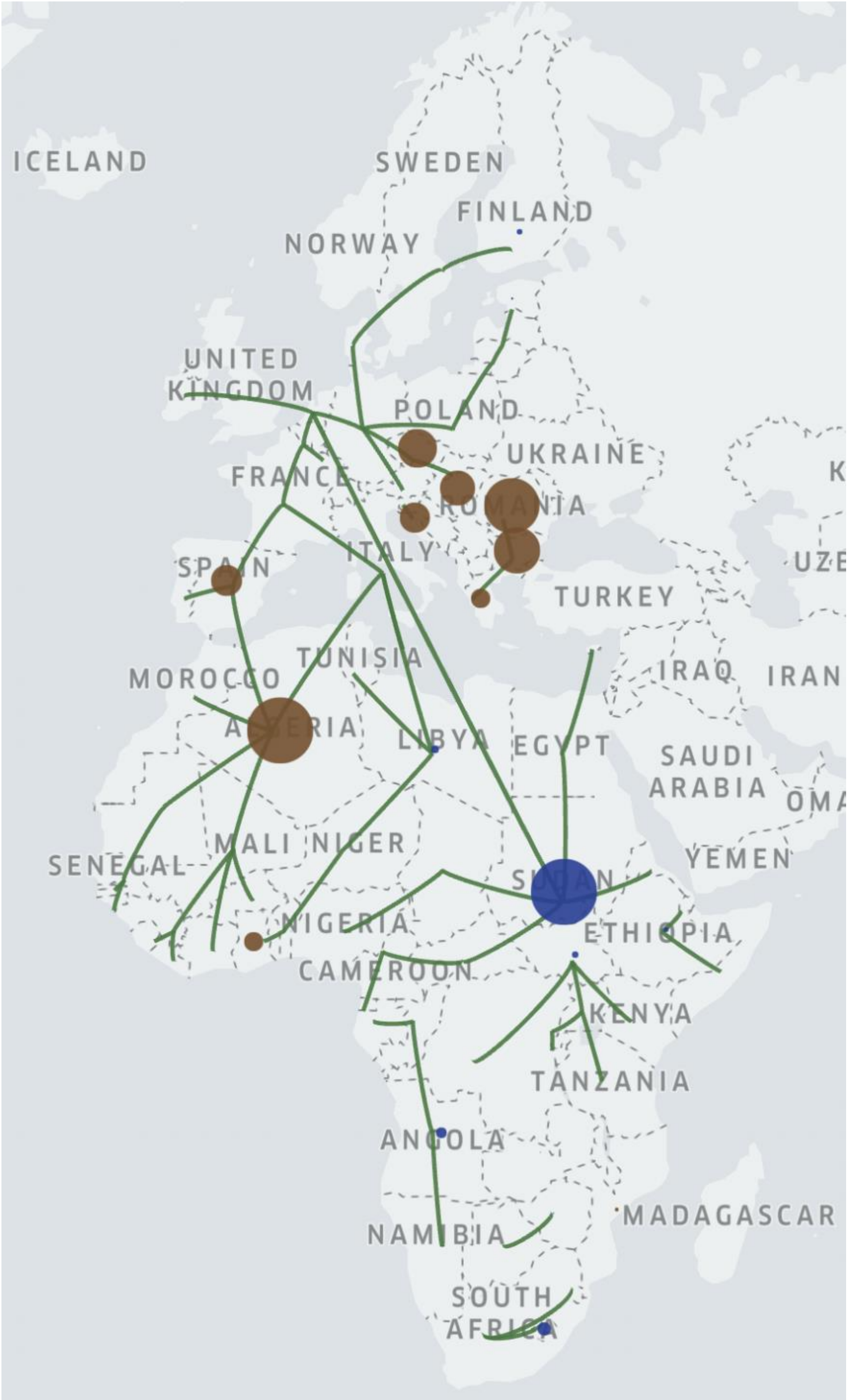


Figure 21: Production and transport of hydrogen in scenario III

In the map we can see briefly that the countries producing hydrogen by electrolysis are increasing. This is largely due to the fact that the reduction in LCOH for electrolysis is greater than for SMR with CCS. In addition, the amount of hydrogen produced by electrolysis increases in countries that already had such production in scenario II.

This can be observed in countries such as Sudan, where the amount of hydrogen produced by electrolysis increases and, in contrast to scenario II, hydrogen is transported directly from Sudan to the Netherlands by liquefied ship.

The results of this scenario show that the reduction of CAPEX and OPEX for the two production technologies studied benefit electrolysis to a greater extent, as its costs will be reduced to a greater extent compared to those of SMR with CCS and will also be accompanied by a reduction in the costs of producing renewable electricity in the long term.

The two production technologies considered in this model are the least environmentally damaging, as their GHG emissions to the atmosphere are minimal, but in the last scenario the results will be analyzed taking a long-term view, where the lower production costs and the price of emissions in the long term will be taken into account.

6.4 Scenario IV – CO2 emissions price long term

When calculating the LCOH for each technology, no terms corresponding to the cost of GHG emissions are taken into account. In 2020, the average price of CO2 emissions was €24.75/Tn, this cost is assumable today by most energy producing companies, but the price paid for the rights to emit CO2 into the atmosphere increases every year, until the time comes when it is no longer profitable to emit CO2 and many companies will have to opt for investment in clean energy production methods.

In this scenario, the aim is to study how an increase in the price of CO2 emissions would affect the results of the model. Electrolysis is a 100% clean production method that does not produce CO2, whereas SMR with CCS, although it is one of the cleanest production methods for hydrogen production, is not completely clean. Although SMR uses carbon capture storage, this storage has an efficiency of around 90%, so some of this CO2 will be emitted.

SMR with CCS produces emissions of 1 kg CO2 per kg of hydrogen, which means that at the current emission price of 0.029 $/Kg H2 will be paid. This additional cost hardly influences if we compare the price difference between producing with electrolysis or with SMR, therefore, it is necessary to study a long-term scenario where the price for emissions is much higher and can affect the LCOH. To this end, a very restrictive scenario will be studied in which the price for emissions is 1000 €/Tn CO2.

This would mean an additional cost of 1.19 $/kg for SMR with CCS, which could significantly affect the decision to produce with this technology or with electrolysis, where prices would be maintained as it is a clean method.

The computational results of the model are shown below:

Table 10: Computacional results scenario IV

Iterations	182
Seconds	2,23
Optimal objective	4,98E+11

The resolution time increases, although the target cost increases by 1.63% compared to scenario III, because the LCOH for SMR with CCS increases due to the additional cost of a scenario in which the price per CO2 emissions is 1000 €/Tn. Despite an increase in the emissions price of 4040% over the average price in 2020, the increase in the optimal supply chain cost increases by only 1.63%. The transport and production results represented on the map are shown below in order to be able to fully analyze the results:

Figure 22: Production and transport of hydrogen in scenario IV

According to the representation of the results on the map, the reduction in hydrogen production through SMR with CCS in several countries can be observed, in Europe there are fewer countries that produce with this type of technology, as an extra cost is added due to the price of CO2 emissions.

At first glance, the results shown on the map do not seem to show major differences with respect to scenario III, but in the following discussion section, the results of the four scenarios will be analyzed in detail and a comparison will be made between them.

6.5 Discussion

This section of the discussion aims to give a contrasted view of the results in the different scenarios, making some comparisons of hydrogen production by technology, paths transportation and costs of the objective function.

First of all, the aim is to compare the amount of hydrogen produced in each region, differentiating between the two continents, Europe and Africa, and according to production technology. The following bar charts show the percentages of hydrogen produced in each continent according to the production technology and the different scenarios studied.

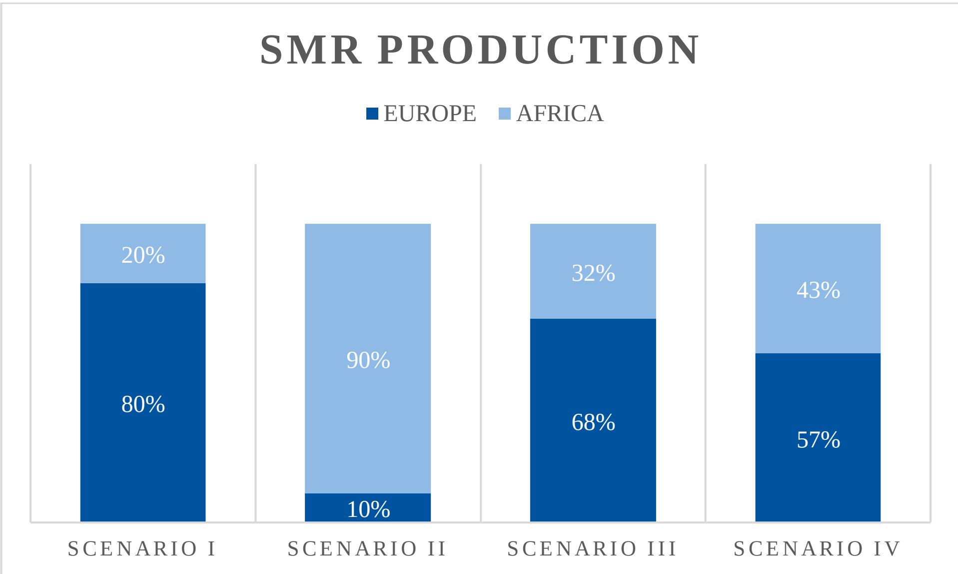
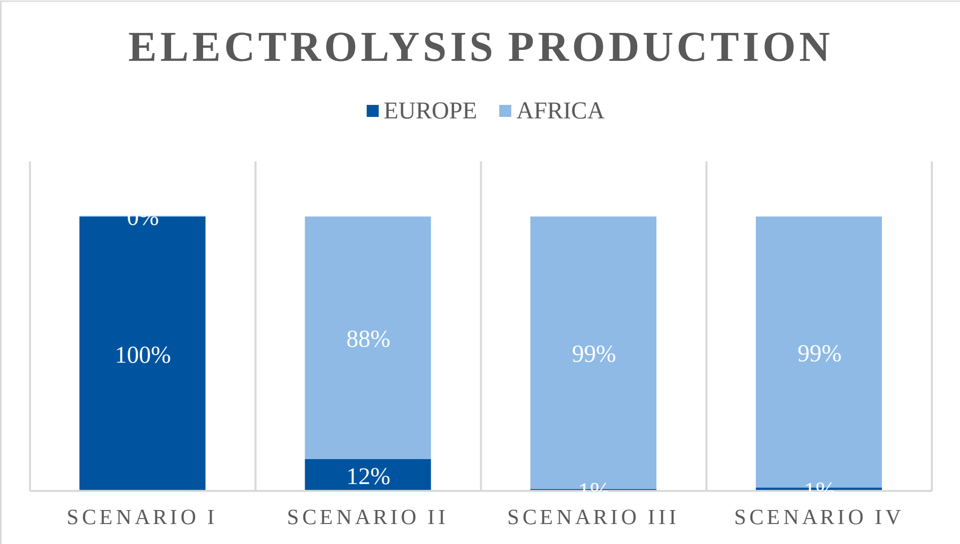


Figure 23: SMR production in different scenarios



Figures 24: Electrolysis production in different scenarios

In the first diagram it can be seen how, when moving from the first to the second scenario, production for both electrolysis and SMR with CCS goes from being mostly in Europe, to being in scenario II, 90% SMR with CCS and 88% electrolysis in Africa, This happens because in the second scenario the LCOH are calculated manually taking into account the potential of renewable energies, therefore, the price of renewable electricity in these African countries with greater potential is reduced and at the same time their LCOH, this is what causes the change of trend in the production areas.

This indicates that we move from centralized production closer to demand in Scenario I, to production much more decentralized to the demand found in Europe. In the model, 82% of the hydrogen demanded in the model is concentrated in European countries, while only 18% of the hydrogen demand comes from Africa. Despite this, in scenarios II, III and IV, hydrogen production by electrolysis in Africa is 88%, 99% and 99% respectively. It is very striking that even though European demand is much higher, most of the hydrogen is produced in Africa, due to its more advantageous LCOH compared to most European countries. For SMR with CCS production, the results are very different, although in Scenario II 90% of production is in Africa, in Scenario III production in Africa decreases to 32%.

The LCOH is a key factor that will influence the decision to produce in one area or another, this large change in influence on the geography of production must be related to the change in the LCOH, below, we will analyze the changes in the LCOH for SMR with CCS in European countries where production increases.

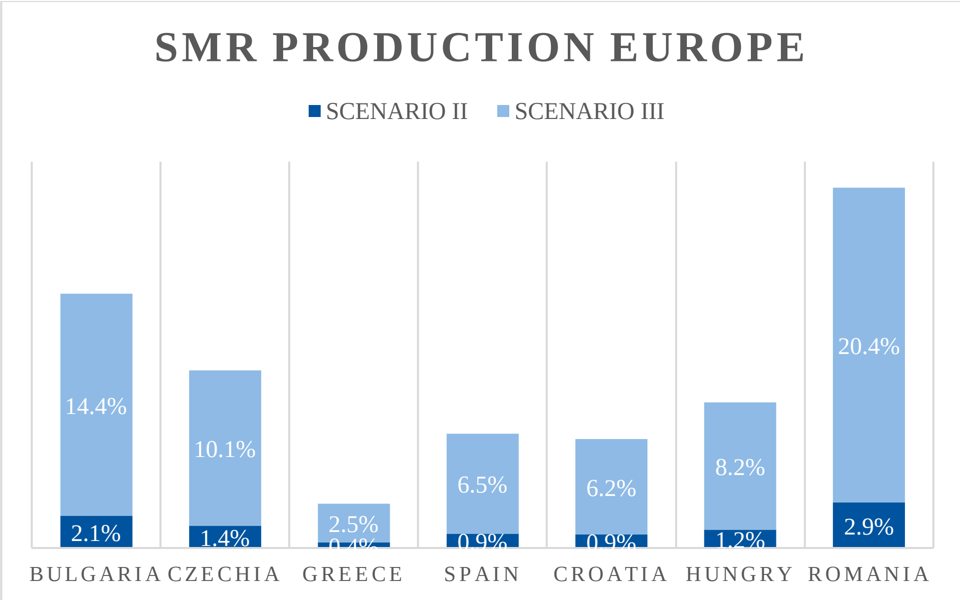


Figure 25: SMR production in Europe

The increases in the production of SMR with CCS between scenarios II and III are very notable in Europe, especially in Romania and Bulgaria, where the increases in production are 20.4% and 14.4% in scenario III. It is necessary to stop and analyze what is really happening with the quantity produced, as the representation on the maps can be confusing and represent a proportion, but not really the quantity produced.

What happens between scenario II and III is very curious, since according to the production data with SMR with CCS the quantities of hydrogen produced with this technology are the same even though the bar graphs represent an increase, but this happens because although production in Europe remains constant, in Africa there are several countries that stop producing hydrogen with SMR with CCS.

Table 11: Differences of SMR production between scenario II and III

	SMR production (Kg H2)	
	SCENARIO II	SCENARIO III
Algeria	5,3E+10	2,7E+09
Angola	1,6E+09	0,00
Egypt	2,3E+09	0,00
Ethiopia	3,4E+08	0,00
Ghana	2,3E+08	2,3E+08

Mozambique	1,3E+07	1,0E+07
Rwanda	2,7E+07	0,00
Tanzania	7,1E+07	0,00
Bulgaria	1,3E+09	1,3E+09
Czechia	9,2E+08	9,2E+08
Greece	2,3E+08	2,3E+08
Spain	5,9E+08	5,9E+08
Croatia	5,6E+08	5,6E+08
Hungary	7,5E+08	7,5E+08
Romania	1,9E+09	1,9E+09

Scenario III envisages a greater long-term decrease in CAPEX and OPEX for electrolysis than for SMR with CCS, therefore, there are countries that do not want to continue producing with SMR with CCS, such as Angola, Egypt, Ethiopia, Rwanda, and Tanzania.

Table 12: Differences of electrolysis production between scenario II and III

	Electrolysis production (Kg H2)	
	SCENARIO II	SCENARIO III
Algeria	0,00	0,00
Angola	0,00	1,4E+09
Egypt	0,00	0,00
Ethiopia	0,00	3,4E+08
Ghana	0,00	0,00
Mozambique	0,00	0,00
Rwanda	0,00	0,00
Tanzania	0,00	0,00
Bulgaria	0,00	0,00
Czechia	0,00	0,00
Greece	0,00	0,00
Spain	0,00	0,00
Croatia	0,00	0,00
Hungary	0,00	0,00
Romania	0,00	0,00

As can be seen in the above table of electrolysis production, Angola and Ethiopia switch from SMR to electrolysis hydrogen production. The following diagram shows the SMR producing countries in the different scenarios.

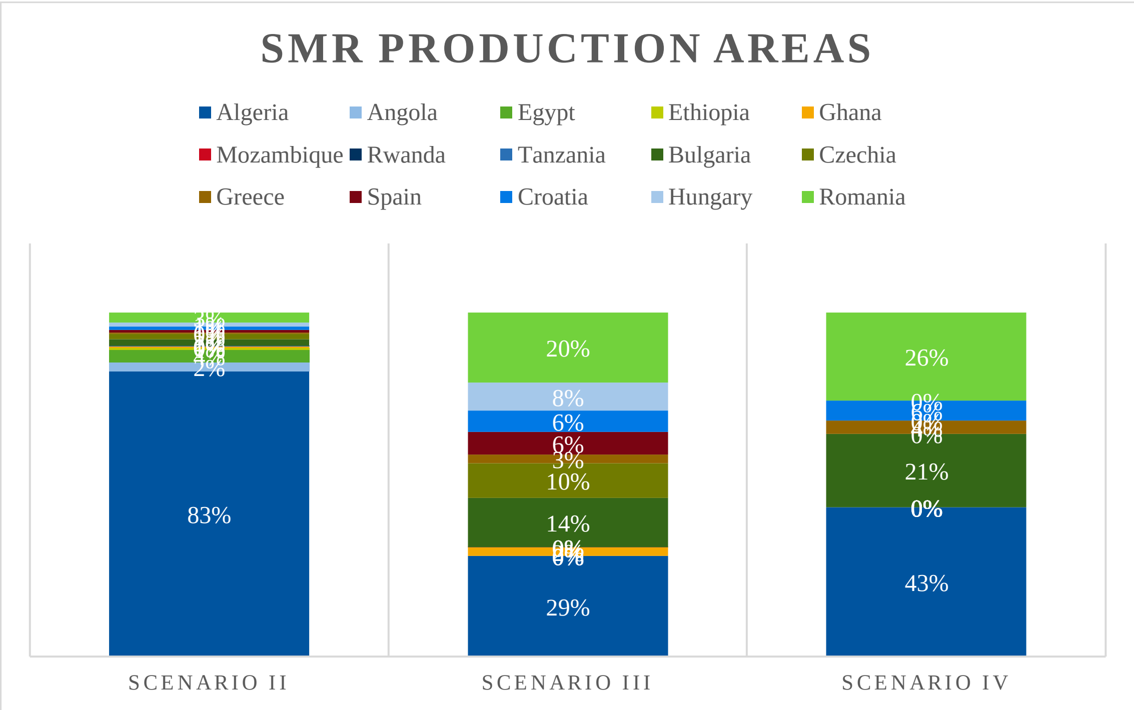


Figure 26: SMR production areas

Despite the reduction in CAPEX and OPEX, as well as the increase in the price for emissions, Algeria remains the largest producer of hydrogen through SMR. This is due to the fact that Algeria has one of the largest natural gas reserves in the world, its price is so competitive that few countries can compete with it, and its high renewable potential has a great impact on the reduction of the LCOH. Its geographical location is also remarkable as it has 1200 km of Mediterranean coastline, which makes it very favorable for the transport of hydrogen by ship.

In the same way that the previous analysis differentiated the amount of hydrogen according to each technology depending on the geographical area, it is also worth analyzing how the type of technology used varies independently of the geographical area.

Table 13: Rate of hydrogen produced with SMR and electrolysis

	SMR production	ELECTROLYSIS production
SCENARIO I	91%	9%
SCENARIO II	94%	6%
SCENARIO III	14%	86%
SCENARIO IV	9%	91%

Up to scenario II, most hydrogen is produced by SMR, but from scenario III onwards, the situation changes radically, and electrolysis becomes the dominant production method in the long term after reducing CAPEX and OPEX and adding CO2 emission penalties. Hydrogen production by electrolysis also undergoes major changes depending on the scenario studied.

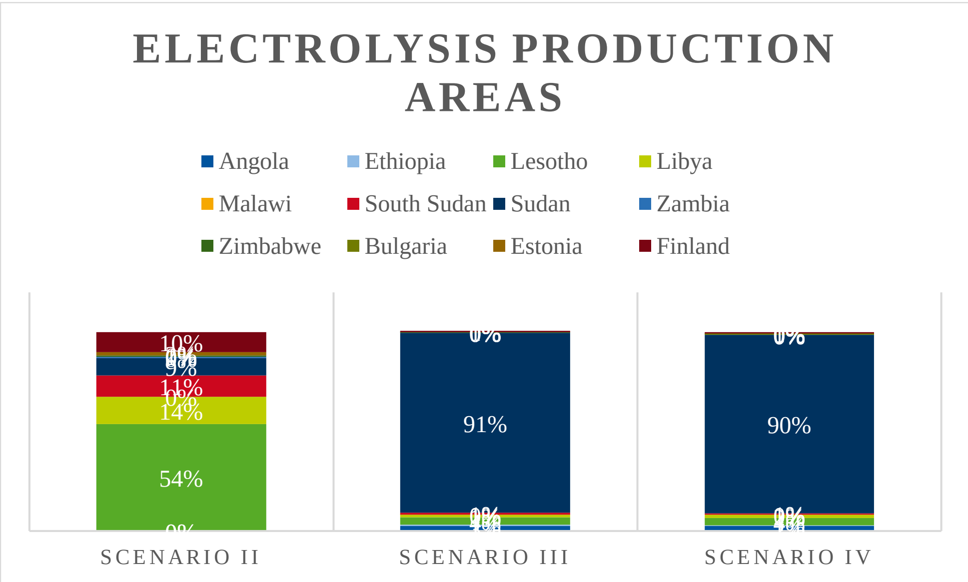


Figure 27: Electrolysis production areas

In Scenario II, 54% of electrolysis production takes place in Lesotho, but as CAPEX and OPEX are reduced and the emissions penalty is introduced, Sudan becomes the dominant producer of hydrogen by electrolysis with around 90% of total production.

Once the trends in production technology have been analyzed in terms of the scenario envisaged, it is necessary to analyze what will happen to the transport part of the supply chain.

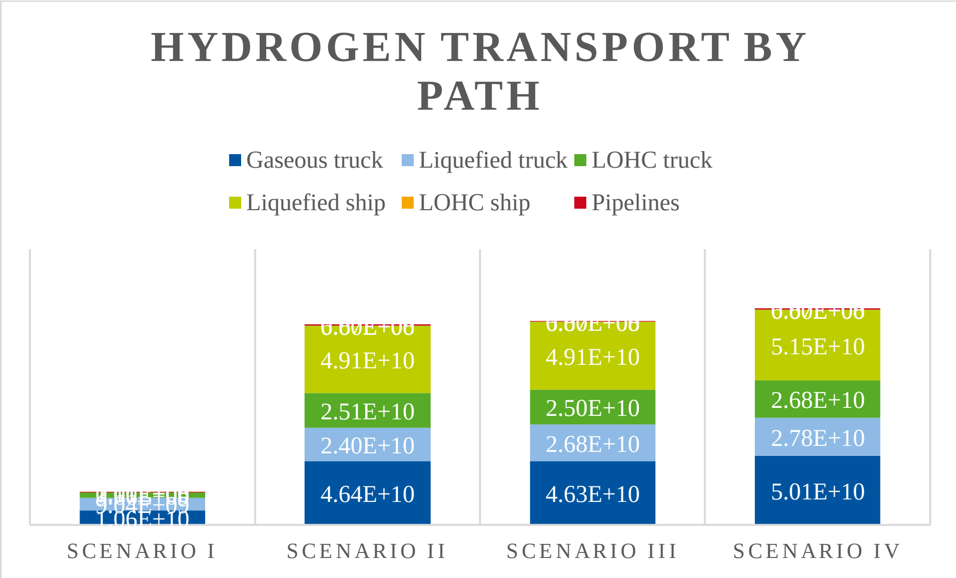


Figure 28: Hydrogen transport by path

In the diagram above, it can be seen how transport increases significantly from scenario I to the following scenarios studied. As mentioned above, this happens because the difference in the LCOH between countries does not compensate for the transport costs, therefore, production is centralized closer to the points of demand. On the other hand, for scenario II and subsequent scenarios, transport increases considerably, due to the fact that production costs in countries far from the countries that demand the most hydrogen are lower, as in the case of Sudan, where, thanks to its advantageous position in terms of renewable resources, it is a major hydrogen producing center due to its low LCOH, and from there it is worth transporting the hydrogen to Europe by liquefied ship.

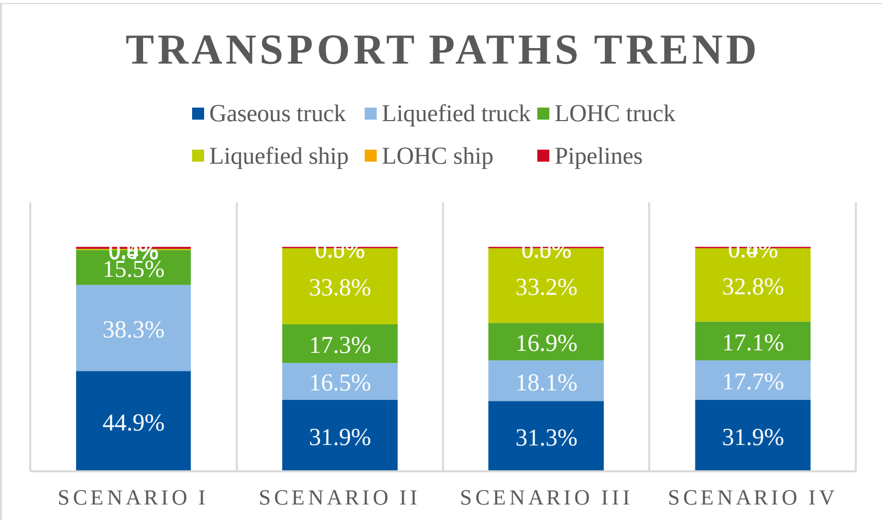


Figure 29: Transport path trend

This graph shows how from scenario II onwards, the trend in transport paths stabilizes, tending towards 33% of maritime transport by liquefied ship, and the rest of the transport is shared between trucks, with the most demand for truck transport being gaseous truck transport, with a percentage of around 32%. In comparison with transport by ship and trucks, transport by pipelines is very limited, given its limitations in terms of the current network of gas pipelines in Africa. Therefore, the transport that exists by this means is in the gas pipelines between North Africa and Europe, representing barely 0.5% of total transport, even though transport by pipelines is the most economical. Finally, the results of the objective function will be analyzed according to the different scenarios.

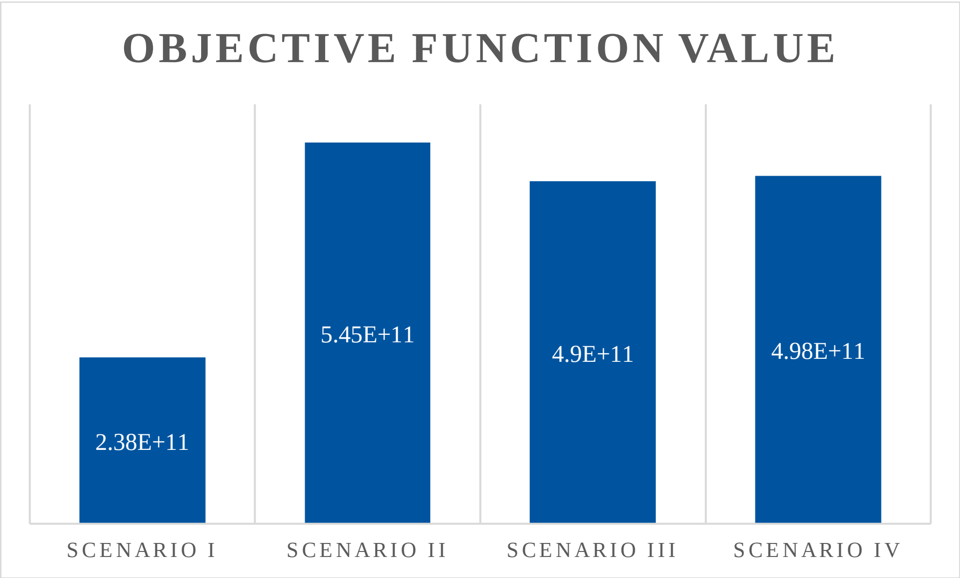


Figure 30: Objective function value

The value of the objective function of scenario I is not comparable with the subsequent scenarios, as the way of obtaining the LCOH is very different, being much lower in all countries for scenario I. From scenario II onwards, we would already have more representative values in terms of the cost of the entire hydrogen supply chain, from production to transport to the points of consumption. In future scenarios II and III, there is a 10% reduction in the target value compared to the current situation (scenario II). This is a significant reduction, as the total cost of the supply chain amounts to a total of 545 billion dollars, so the savings between a scenario such as the current one and a long-term scenario are estimated at 47 billion dollars.

In this section, all the results have been analyzed, comparisons have been made with all the scenarios studied, and an attempt has also been made to interpret the numerical results to find out why the changes in trends in production, transport and geographical areas are actually occurring. The following section will conclude this work with a conclusion and outlook.

7. Conclusion and outlook

As a final point for this project, the limitations and possible improvements of the model presented will be addressed, as well as an informed opinion on the results obtained.

The four scenarios dealt with in this work, despite having notable differences, have several aspects in common. Firstly, scenario number 1 is not entirely representative of reality, since an average LCOH is chosen for all countries and multiplied by the EODB index in order to obtain a price differentiation. This is not entirely correct, as a large part of the LCOH depends on the renewable potential and the price paid to produce the renewable electricity consumed by the hydrogen production technology, in this case SMR with CCS and electrolysis.

As can be seen in scenarios III and IV, between 86 and 91% of the total hydrogen production will originate from electrolysis, therefore, it can be stated that electrolysis will be positioned as the dominant hydrogen production technology, as it requires a larger amount of electricity than SMR.

Having a wrong view on the use of EODB for the calculation of LCOH, it is decided, in the subsequent scenarios, to introduce manual calculation of LCOH, using EODB as a rate of discount. In this way, countries with a lower EODB will be penalised, although most of the LCOH is defined by the hydrogen generation potential through renewable energies (PV solar and wind). The LCOH is also defined by CAPEX and OPEX, but these will be assumed to be constant in all countries.

In the case of further development of this model, as a possible improvement, capacity factors could be used depending on each country. In the current model, no such information was available, so a capacity factor has been assumed depending on whether it was solar or renewable energy.

For example, a solar plant in a country like Algeria, which enjoys a large number of hours of sunshine per year, will have a higher yield and produce more electricity than if the same plant with the same capacity were located in Germany. For this reason, it is advisable to consider different capacity factors depending on the country, which, in turn, will introduce greater differentiation in the LCOH and achieve greater profitability if hydrogen is produced in countries with greater renewable potential.

Another aspect to take into account is that in scenarios II, III and IV, when calculating the LCOH for each production technology, the cost of electricity has been introduced based on current prices for 2020, but also for future scenarios. Long-term electricity prices will change, especially in those countries with a high renewable potential and where currently the infrastructure for energy production is very limited, as is the case in most African countries.

In the absence of information on the change in electricity prices, current prices have had to be assumed. As a result, there are countries in this model with high renewable potential, but with very high current electricity prices. This is due to the fact that a large part of the population has no access to any kind of electricity and the electricity that can be purchased is mostly produced with fossil fuels.

As has been discussed throughout the project, the cost of electricity is entered manually in the LCOH calculation, but if the electricity price can somehow be unbundled from the LCOH, it would be further reduced and hydrogen production in countries with high renewable potential, such as most African countries, would be more profitable.

In this model, hydrogen transport has certain limitations that will have to be addressed as an improvement to further optimise the supply chain.

As for transport by ship, it has not been possible to consider transport between all countries that have a coastline, as there is no function to automatically create a matrix of maritime distances between countries. Unlike transport by truck or by pipelines, where it was assumed that the distances were straight with the haversine function, the maritime routes are irregular and go along the coast, which is why it was considered to treat transport by ship only between the African countries with a coastline and a point in Europe established in The Netherlands. This assumption, although it allows the connection between Africa and Europe, limits the transport by ship between European countries and between African countries with a coastline. A major improvement, which was not part of the objectives of this work, is to create a function that calculates the distances of all possible combinations of maritime routes and thus expand the possibilities for by ship transport.

In terms of the results obtained, certain trends can be observed in the geographical areas that cannot be ignored. Sudan is positioned as the largest producer of hydrogen by electrolysis, influenced by its low energy costs and high renewable potential.

In addition, its geographical characteristics make it an ideal country for transporting hydrogen by liquefied ship to Europe and a potential supplier of hydrogen within Africa. Sudan's share of total hydrogen production by electrolysis in the model is 90%, which is a very high percentage if the purpose of the model was a balanced design, where one country would not have such a high percentage of production to avoid problems of supply to other countries in the event of a problem.

This issue of energy dependence has not been addressed in this project, but it is an important issue that needs to be addressed before the design of a multi-location supply chain can be carried out, and it opens up a debate for future designs. Algeria, with its large natural gas reserves and low prices, is positioned as the leading producer of hydrogen through SMR with CCS. This is in spite of the very restrictive increase in the price of CO2 emissions added in scenario IV.

Hydrogen transport by pipeline has great potential and its very low price makes it the future of large-scale hydrogen transport. In all the scenarios studied in this work, pipeline transport is at its maximum capacity and limited by natural gas transport. Therefore, it would be appropriate to open a debate on whether it would be more profitable to invest in hydrogen pipelines for large-scale transport as opposed to more traditional means of transport, such as ship or truck.

The limitations of this model are to be found in points such as the data on hydrogen demand, especially in Africa, which are not yet estimated, or the estimate of the price of electricity is not available in many countries where the energy mix will change in the coming years. However, the study of different scenarios, changing certain parameters that are known to change in the future, gives an insight into what would be the most favourable hydrogen supply chains in Europe and Africa.

There is still much work to be done in terms of developing energy production infrastructures to facilitate universal access to electricity, especially in central African countries where, despite the great potential for renewable energy generation, access to electricity is very limited.

This work has made it clear that the future decarbonisation of the economy is possible and that it must also involve covering the energy demands of less developed countries and doing so by means of clean energy vectors, as in this case has been studied with hydrogen.

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Appendix

Table 14: SMR production scenario I

Countries	SMR production (Kg)
Algeria	1,68E+09
Angola	1,06E+09
Benin	1,15E+07
Cameroon	8,62E+07
Congo	2,31E+08
Côte d'Ivoire	1,22E+08
DR Congo	6,83E+07
Egypt	2,33E+09
Equatorial Guinea	1,28E+08
Ethiopia	3,24E+08
Gabon	1,46E+08
Ghana	2,59E+08
Libya	4,40E+08
Mauritania	1,33E+08
Morocco	3,66E+08
Mozambique	6,01E+07
Namibia	2,20E+09
Nigeria	1,80E+09
Rwanda	2,70E+07
Somalia	1,61E+07
Sudan	1,69E+08
Tanzania	7,06E+07
Tunisia	1,41E+08
Uganda	3,69E+08
Bulgaria	1,31E+09
Czechia	7,57E+08
Denmark	2,07E+09
Germany	9,17E+09

Ireland	9,09E+08
Greece	2,30E+08
Spain	5,92E+08
France	1,95E+09
Croatia	3,57E+08
Italy	8,84E+09
Hungary	7,54E+08
Netherlands	1,32E+10
Austria	1,50E+09
Poland	5,20E+09
Romania	1,86E+09
Slovakia	7,01E+08

Table 15: Electrolysis production scenario I

Countries	**ELECTROLYSIS production (Kg)**
Lesotho	1,53E+05
Estonia	5,54E+07
Spain	1,55E+09
France	3,29E+09
Latvia	4,91E+07
Portugal	4,68E+08
Finland	4,03E+08

Table 16: Hydrogen transport scenario I

FROM	TO	Path	Hydrogen transported (Kg)
Algeria	Spain	Pipelines	2,11E+08
Cameroon	Central African Republic	Liquefied truck	1,26E+07
Côte d'Ivoire	Guinea	LOHC truck	6,22E+06
Côte d'Ivoire	Liberia	LOHC truck	6,52E+06
Egypt	Cyprus	Liquefied ship	3,57E+07
Ethiopia	Djibouti	Gaseous truck	3,06E+07

Ethiopia	Eritrea	Liquefied truck	3,83E+06
Ghana	Burkina Faso	LOHC truck	8,47E+06
Ghana	Togo	Gaseous truck	2,38E+07
Liberia	Sierra Leone	Gaseous truck	2,30E+06
Mauritania	Mali	Liquefied truck	1,76E+07
Mauritania	Senegal	Liquefied truck	9,37E+07
Mozambique	Eswatini	Liquefied truck	3,83E+05
Mozambique	Malawi	Liquefied truck	2,74E+06
Mozambique	Zambia	Liquefied truck	1,96E+07
Mozambique	Zimbabwe	Liquefied truck	2,70E+07
Namibia	Botswana	Liquefied truck	4,60E+06
Namibia	South Africa	Liquefied truck	2,18E+09
Nigeria	Chad	Liquefied truck	9,40E+07
Nigeria	Niger	Liquefied truck	3,85E+07
Rwanda	Burundi	Gaseous truck	5,79E+05
Senegal	Gambia	Gaseous truck	5,37E+06
Senegal	Guinea-Bissau	Gaseous truck	4,79E+06
Uganda	Kenya	Liquefied truck	2,86E+08
Uganda	South Sudan	Liquefied truck	4,23E+07
Belgium	France	LOHC truck	1,54E+09
Belgium	Luxembourg	Gaseous truck	8,51E+07
Bulgaria	Greece	LOHC truck	1,08E+09
Denmark	Sweden	Liquefied truck	1,42E+09
Spain	Portugal	Gaseous truck	5,15E+08
France	Spain	Liquefied truck	3,08E+09
Italy	France	Liquefied truck	1,71E+09
Italy	Malta	Liquefied ship	6,55E+07
Latvia	Latvia	Pipelines	4,91E+07
Netherlands	Belgium	Gaseous truck	4,44E+09
Netherlands	Germany	Gaseous truck	4,81E+09
Austria	Slovenia	Gaseous truck	2,05E+08
Poland	Lithuania	LOHC truck	6,25E+08
Romania	Bulgaria	Gaseous truck	4,76E+08

Sweden	Finland	LOHC truck	3,92E+08

Table 17: SMR production scenario II

Countries	**SMR production (Kg)**
Algeria	5,26E+10
Angola	1,58E+09
Egypt	2,33E+09
Ethiopia	3,37E+08
Ghana	2,26E+08
Mozambique	1,35E+07
Rwanda	2,70E+07
Tanzania	7,06E+07
Bulgaria	1,31E+09
Czechia	9,19E+08
Greece	2,30E+08
Spain	5,92E+08
Croatia	5,63E+08
Hungary	7,54E+08
Romania	1,86E+09

Table 18: Electrolysis production scenario II

Countries	**ELECTROLYSIS production (Kg)**
Lesotho	2,18E+09
Libya	5,59E+08
South Sudan	4,37E+08

Sudan	3,53E+08
Zambia	1,96E+07
Zimbabwe	3,16E+07
Estonia	7,08E+07
Finland	4,03E+08

Table 19: Hydrogen transport scenario II

FROM	TO	Path	Hydrogen transported (Kg)
Algeria	Mali	Liquefied truck	1,48E+08
Algeria	Mauritania	Liquefied truck	1,15E+08
Algeria	Morocco	Liquefied truck	3,66E+08
Algeria	Niger	Liquefied truck	1,74E+09
Algeria	Tunisia	Liquefied truck	1,41E+08
Algeria	Spain	Pipelines	2,11E+08
Algeria	Italy	Pipelines	3,57E+08
Algeria	Netherlands	Liquefied ship	4,80E+10
Angola	Congo	Liquefied truck	5,05E+08
Angola	Namibia	Liquefied truck	1,53E+07
Benin	Togo	Gaseous truck	2,38E+07
Central African Republic	Cameroon	Liquefied truck	7,36E+07
Congo	Gabon	LOHC truck	2,74E+08
Egypt	Cyprus	Liquefied ship	3,57E+07
Ethiopia	Djibouti	Gaseous truck	3,06E+07
Ethiopia	Somalia	Liquefied truck	1,61E+07
Gabon	Equatorial Guinea	Gaseous truck	1,28E+08
Guinea	Liberia	Gaseous truck	4,22E+06
Guinea	Sierra Leone	Gaseous truck	2,30E+06
Lesotho	South Africa	LOHC truck	2,18E+09
Libya	Italy	Pipelines	1,19E+08
Mali	Burkina Faso	Liquefied truck	8,47E+06

Mali	Côte d'Ivoire	Liquefied truck	1,09E+08
Mali	Guinea	Liquefied truck	1,27E+07
Mauritania	Senegal	Liquefied truck	9,37E+07
Mozambique	Eswatini	Liquefied truck	3,83E+05
Mozambique	Malawi	Liquefied truck	2,74E+06
Niger	Benin	Liquefied truck	3,53E+07
Niger	Nigeria	Liquefied truck	1,67E+09
Rwanda	Burundi	Gaseous truck	5,79E+05
Senegal	Gambia	Gaseous truck	5,37E+06
Senegal	Guinea-Bissau	Gaseous truck	4,79E+06
South Sudan	DR Congo	Liquefied truck	6,83E+07
South Sudan	Kenya	Liquefied truck	2,86E+08
South Sudan	Uganda	Liquefied truck	4,09E+07
Sudan	Central African Republic	Liquefied truck	8,62E+07
Sudan	Chad	Liquefied truck	9,40E+07
Sudan	Eritrea	Liquefied truck	3,83E+06
Zimbabwe	Botswana	LOHC truck	4,60E+06
Belgium	France	LOHC truck	1,72E+10
Belgium	Luxembourg	Gaseous truck	8,51E+07
Bulgaria	Greece	LOHC truck	1,08E+09
Czechia	Slovakia	Gaseous truck	7,01E+08
Denmark	Sweden	Liquefied truck	1,42E+09
Germany	Czechia	Gaseous truck	5,39E+08
Germany	Denmark	LOHC truck	2,07E+09
Germany	Austria	LOHC truck	1,30E+09
Germany	Poland	Liquefied truck	5,23E+09
Estonia	Latvia	Gaseous truck	1,54E+07
Spain	Portugal	Gaseous truck	9,83E+08
France	Spain	Liquefied truck	5,10E+09
France	Italy	Liquefied truck	6,65E+09
Croatia	Slovenia	Gaseous truck	2,05E+08

Italy	Malta	Liquefied ship	6,55E+07
Lithuania	Latvia	Gaseous truck	3,37E+07
Netherlands	Belgium	Gaseous truck	2,01E+10
Netherlands	Germany	Gaseous truck	2,31E+10
Netherlands	Ireland	Liquefied ship	9,09E+08
Poland	Lithuania	LOHC truck	6,59E+08
Romania	Bulgaria	Gaseous truck	4,76E+08
Sweden	Finland	LOHC truck	3,92E+08

Table 20: SMR production scenario III

Countries	**SMR production (Kg)**
Algeria	2,67E+09
Ghana	2,26E+08
Mozambique	1,03E+07
Bulgaria	1,31E+09
Czechia	9,19E+08
Greece	2,30E+08
Spain	5,92E+08
Croatia	5,63E+08
Hungary	7,54E+08
Romania	1,86E+09

Table 21: Electrolysis production scenario III

Countries	**ELECTROLYSIS production (Kg)**

Angola	1,45E+09
Ethiopia	3,37E+08
Lesotho	2,18E+09
Libya	7,74E+08
Malawi	2,74E+06
South Sudan	5,35E+08
Sudan	5,25E+10
Zambia	1,96E+07
Zimbabwe	3,16E+07
Estonia	7,08E+07
Finland	4,03E+08

Table 22: Hydrogen transport scenario III

FROM	TO	Path	Hydrogen transported (Kg)
Algeria	Mali	Liquefied truck	1,48E+08
Algeria	Mauritania	Liquefied truck	1,15E+08
Algeria	Morocco	Liquefied truck	3,66E+08
Algeria	Spain	Pipelines	2,11E+08
Algeria	Italy	Pipelines	3,57E+08
Angola	Congo	Liquefied truck	3,77E+08
Angola	Namibia	Liquefied truck	1,53E+07
Benin	Togo	Gaseous truck	2,38E+07
Cameroon	Equatorial Guinea	Liquefied truck	1,28E+08
Central African Republic	Cameroon	Liquefied truck	2,02E+08
Chad	Nigeria	Liquefied truck	1,67E+09
Congo	Gabon	LOHC truck	1,46E+08
Egypt	Cyprus	Liquefied ship	3,57E+07
Ethiopia	Djibouti	Gaseous truck	3,06E+07
Ethiopia	Somalia	Liquefied truck	1,61E+07

Guinea	Liberia	Gaseous truck	4,22E+06
Guinea	Sierra Leone	Gaseous truck	2,30E+06
Lesotho	South Africa	LOHC truck	2,18E+09
Libya	Niger	Liquefied truck	7,38E+07
Libya	Tunisia	Liquefied truck	1,41E+08
Libya	Italy	Pipelines	1,19E+08
Mali	Burkina Faso	Liquefied truck	8,47E+06
Mali	Côte d'Ivoire	Liquefied truck	1,09E+08
Mali	Guinea	Liquefied truck	1,27E+07
Mauritania	Senegal	Liquefied truck	9,37E+07
Niger	Benin	Liquefied truck	3,53E+07
Rwanda	Burundi	Gaseous truck	5,79E+05
Senegal	Gambia	Gaseous truck	5,37E+06
Senegal	Guinea-Bissau	Gaseous truck	4,79E+06
South Africa	Eswatini	Liquefied truck	3,83E+05
South Sudan	DR Congo	Liquefied truck	6,83E+07
South Sudan	Kenya	Liquefied truck	2,86E+08
South Sudan	Uganda	Liquefied truck	1,39E+08
Sudan	Central African Republic	Liquefied truck	2,14E+08
Sudan	Chad	Liquefied truck	1,76E+09
Sudan	Egypt	Liquefied truck	2,33E+09
Sudan	Eritrea	Liquefied truck	3,83E+06
Sudan	Netherlands	Liquefied ship	4,80E+10
Uganda	Rwanda	LOHC truck	2,70E+07
Uganda	Tanzania	Liquefied truck	7,06E+07
Zimbabwe	Botswana	LOHC truck	4,60E+06
Belgium	France	LOHC truck	1,72E+10
Belgium	Luxembourg	Gaseous truck	8,51E+07
Bulgaria	Greece	LOHC truck	1,08E+09
Czechia	Slovakia	Gaseous truck	7,01E+08
Denmark	Sweden	Liquefied truck	1,42E+09
Germany	Czechia	Gaseous truck	5,39E+08
Germany	Denmark	LOHC truck	2,07E+09

Germany	Austria	LOHC truck	1,30E+09
Germany	Poland	Liquefied truck	5,23E+09
Estonia	Latvia	Gaseous truck	1,54E+07
Spain	Portugal	Gaseous truck	9,83E+08
France	Spain	Liquefied truck	5,10E+09
France	Italy	Liquefied truck	6,65E+09
Croatia	Slovenia	Gaseous truck	2,05E+08
Italy	Malta	Liquefied ship	6,55E+07
Lithuania	Latvia	Gaseous truck	3,37E+07
Netherlands	Belgium	Gaseous truck	2,01E+10
Netherlands	Germany	Gaseous truck	2,31E+10
Netherlands	Ireland	Liquefied ship	9,09E+08
Poland	Lithuania	LOHC truck	6,59E+08
Romania	Bulgaria	Gaseous truck	4,76E+08
Sweden	Finland	LOHC truck	3,92E+08

Table 23: SMR production scenario IV

Countries	**SMR production (Kg)**
Algeria	2,66E+09
Bulgaria	1,31E+09
Greece	2,30E+08
Croatia	3,57E+08
Romania	1,58E+09

Table 24: Electrolysis production scenario IV

Countries	ELECTROLYSIS production (Kg)
Angola	1,45E+09
Ethiopia	3,37E+08
Lesotho	2,18E+09
Libya	1,01E+09
Malawi	2,74E+06
South Sudan	5,35E+08
Sudan	5,50E+10
Zambia	1,96E+07
Zimbabwe	4,19E+07
Bulgaria	2,86E+08
Estonia	7,08E+07
Finland	4,03E+08

Table 25: Hydrogen transport scenario IV

FROM	TO	Path	Hydrogen transported (Kg)
Algeria	Mali	Liquefied truck	1,40E+08
Algeria	Mauritania	Liquefied truck	1,15E+08
Algeria	Morocco	Liquefied truck	3,66E+08
Algeria	Spain	Pipelines	2,11E+08
Algeria	Italy	Pipelines	3,57E+08
Angola	Congo	Liquefied truck	3,77E+08
Angola	Namibia	Liquefied truck	1,53E+07
Benin	Togo	Gaseous truck	2,38E+07
Burkina Faso	Ghana	LOHC truck	2,26E+08
Cameroon	Equatorial Guinea	Liquefied truck	1,28E+08
Central African Republic	Cameroon	Liquefied truck	2,02E+08
Chad	Nigeria	Liquefied truck	1,67E+09
Congo	Gabon	LOHC truck	1,46E+08

Egypt	Cyprus	Liquefied ship	3,57E+07
Ethiopia	Djibouti	Gaseous truck	3,06E+07
Ethiopia	Somalia	Liquefied truck	1,61E+07
Guinea	Liberia	Gaseous truck	4,22E+06
Guinea	Sierra Leone	Gaseous truck	2,30E+06
Lesotho	South Africa	LOHC truck	2,18E+09
Libya	Niger	Liquefied truck	3,08E+08
Libya	Tunisia	Liquefied truck	1,41E+08
Libya	Italy	Pipelines	1,19E+08
Mali	Côte d'Ivoire	Liquefied truck	1,09E+08
Mali	Guinea	Liquefied truck	1,27E+07
Mauritania	Senegal	Liquefied truck	9,37E+07
Niger	Benin	Liquefied truck	3,53E+07
Niger	Burkina Faso	Liquefied truck	2,35E+08
Rwanda	Burundi	Gaseous truck	5,79E+05
Senegal	Gambia	Gaseous truck	5,37E+06
Senegal	Guinea-Bissau	Gaseous truck	4,79E+06
South Africa	Eswatini	Liquefied truck	3,83E+05
South Sudan	DR Congo	Liquefied truck	6,83E+07
South Sudan	Kenya	Liquefied truck	2,86E+08
South Sudan	Uganda	Liquefied truck	1,39E+08
Sudan	Central African Republic	Liquefied truck	2,14E+08
Sudan	Chad	Liquefied truck	1,76E+09
Sudan	Egypt	Liquefied truck	2,33E+09
Sudan	Eritrea	Liquefied truck	3,83E+06
Sudan	Netherlands	Liquefied ship	5,05E+10
Uganda	Rwanda	LOHC truck	2,70E+07
Uganda	Tanzania	Liquefied truck	7,06E+07
Zimbabwe	Botswana	LOHC truck	4,60E+06
Zimbabwe	Mozambique	Liquefied truck	1,03E+07
Belgium	France	LOHC truck	1,78E+10

Belgium	Luxembourg	Gaseous truck	8,51E+07
Bulgaria	Greece	LOHC truck	1,08E+09
Czechia	Slovakia	Gaseous truck	7,01E+08
Denmark	Sweden	Liquefied truck	1,42E+09
Germany	Czechia	Gaseous truck	1,46E+09
Germany	Denmark	LOHC truck	2,07E+09
Germany	Austria	LOHC truck	2,26E+09
Germany	Poland	Liquefied truck	5,23E+09
Estonia	Latvia	Gaseous truck	1,54E+07
Spain	Portugal	Gaseous truck	9,83E+08
France	Spain	Liquefied truck	5,69E+09
France	Italy	Liquefied truck	6,65E+09
Italy	Malta	Liquefied ship	6,55E+07
Lithuania	Latvia	Gaseous truck	3,37E+07
Netherlands	Belgium	Gaseous truck	2,07E+10
Netherlands	Germany	Gaseous truck	2,50E+10
Netherlands	Ireland	Liquefied ship	9,09E+08
Austria	Hungary	Gaseous truck	7,54E+08
Austria	Slovenia	Gaseous truck	2,05E+08
Poland	Lithuania	LOHC truck	6,59E+08
Romania	Bulgaria	Gaseous truck	1,91E+08
Sweden	Finland	LOHC truck	3,92E+08