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D2.3 “Socio-techno-economic analysis of identified scenarios”

WP2 “Modelling the identified scenarios”

WP leader: JULICH

T2.3 “Techno-economic modelling”

T2.3.1 Socio-economic modelling approach”

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EXECUTIVE SUMMARY

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This document is the Deliverable D2.3 “Socio-techno-economic analysis of identified scenarios” as main result of activities driven by UNIGE in the framework of T2.3 “Techno-economic modelling” developed within WP2 “Modelling the identified scenarios” of the JUST GREEN-AFRH2ICA project.

The report provides an assessment of performances from a techno-economic point of view of production of green hydrogen in Africa, duly coupling renewable power plants (wind – solar – geothermal) with PEM Electrolysers evaluating their performances via specific KPIs (LCOH, CAPEX, Equivalent Operating Hours etc.). The report focuses its attention on the key hubs identified in WP1 across different regions: **North Africa**, **West Africa**, **East/Central Africa**, and **Southern Africa.** Such assessment is performed via UNIGE WECoMP tool, duly updated with specific cost functions related to water supply/treatment technologies (D2.1).

Taking into account the “HYDROGEN HUB” vision promoted by JUST GREEN AFRH2ICA project as key approach to facilitate the first green hydrogen production plant in Africa around relevant industrial site that can guarantee a reliable and continuous Hydrogen demand (thus making the projects more bankable), the study explores not only the green hydrogen production potential at local level, but it also assesses the techno-economic viability of using the locally produced green hydrogen for the production of products/goods in local hard-to-abate industrial hubs according to the cost of manufacturing and transport of each goods and the related cost of hydrogen production. Such assessment is performed also in order to compare green hydrogen production/export and production/export of such products leveraging the already existing value chain

The findings indicate that Africa has significant opportunities to become a global leader in green hydrogen production with LCOH that lands around 4÷6 €/kg more or less all around the continent. Furthermore, it shows how the “HYDROGEN HUB” approach proposed by the project can be a relevant opportunity not only to demonstrate the first electrolysis plants in Africa, but also to facilitate the export of enhanced value proposition and “cleaner” products leveraging the already existing logistic value chain.

In details, it contains:

- INTRODUCTION (Chapter 1)
- PRESENTATION OF THE HYDROGEN HUBS APPROACH (Chapter 2)
- GENERAL OVERVIEW AND METHODOLOGY (Chapter 3)
- GREEN HYDROGEN PRODUCTION ASSESSMENT IN THE DIFFERENT USE CASES (Chapter 4)
- TECHNO-ECONOMIC ASSESSMENT OF GREEN PRODUCTS PRODUCED EXPLOITING LOCALLY PRODUCED GREEN HYDROGEN (Chapter 5)

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1. INTRODUCTION

In the framework of Task 2.3, UNIGE used its WECoMP techno-economic modelling and optimization tool (https://tpg.unige.eu/w-ecomp/) to study the techno-economic viability of green hydrogen production plants (evaluated via KPIs like LCOH or Payback Period - PBP) in the different Use Cases identified in D1.3. In concert with T2.2, UNIGE updated its model to be able to operate with African scenario, also foreseeing the evaluation of water supply costs in terms of CAPEX and OPEX (as well as of energy consumptions) of different options like ground water pumping, desalination etc. Such costs and performance curves/equations were derived from literature and market research, developing a new module dedicated to water supply.

Using WECoMP tool, UNIGE performed two analysis, in order to investigate the techno-economic viability of the “HYDROGEN HUB” approach promoted by JGA project:

A first analysis in which, per each identified use case, UNIGE calculated LCOH supposing the realization of a 1 MW PEM Electrolysis plant, coupled to an off-grid local RES supply (that could be wind, solar or geothermal depending on the location) as well as with a Li-On battery whose size has been optimized by WECoMP Tool.

Starting from these values of LCOH and considering the different products manufactured in the different hubs as reported in picture below, UNIGE estimated the cost of production of such “Green products”. Generally speaking two categories of products were foreseen:
COMBUSTION PRODUCTS (like cement, steel..): in whose manufacturing process Hydrogen is used instead of Natural Gas
SYNTHESIS PRODUCTS (like methanol, urea, ammonia…): in whose manufacturing process Hydrogen is based as chemical building block

Thanks to a literature review cost function for the transport (via both trucks and ships) of aforementioned products were developed and then the possibility of producing green hydrogen in Africa (to be then exported to Europe even for manufacturing the assessed products) to be then transported to EU (via ships, trucks and NG pipelines) was evaluated and benchmarked against the costs of production and transportation (the ports of Genova and Rotterdam were used as references arrival hubs for both Hydrogen and products) of the “finite products” exploiting the existing value chains. Report results drove relevant outcomes about the JUST GREEN AFRH2ICA “Hydrogen Hubs” approach that will be valorised in WP3 in project roadmaps drafting.

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It is relevant to highlight that, in accordance with WP leader, despite its title, this report did not include any input about social aspects derivable from the results of the techno-economic analysis. Results of T2.3.1 " Socio-economic modelling approach" were indeed included by JULICH in D2.2

1.1 Structure of the Deliverable

Chapter 2 presents the JUST GREEN AFRH2ICA hydrogen hubs proposed approach and a brief description of the identified use cases (as presented in D1.3).
Chapter 3 presents the general overview and methodology of the methodology used for techno-economic assessment of green hydrogen production (presented in Chapter 4) and of green products (presented in Chapter 5) as well as the updated models integrated in the UNIGE techno-economic tools.
Chapter 4 and Chapter 5 presents the key results of such assessments with a focus in Chapter 5 also in the benchmarking of the production/export approaches, while Chapter 6 presents the deliverable's conclusions.

1.2 Relation to Other Tasks and Deliverables

This Deliverable D2.3 is based on Task 2.3 and it provides relevant inputs to T2.2-T2.5, towards the final goal of WP2: model the identified scenarios and propose sustainable hydrogen value chains for the different scenarios. The outputs of this deliverable will also be used in WP3, which aims to assess the impact of modelled scenarios and to develop the roadmaps to develop the transition to green hydrogen in Africa.

The report has been mostly realized by UNIGE with support of STRATH, NWU, and IRESEN in the identification of information to properly model project scenarios to be analysed and for some data sharing needed by the modelling approach.

It is relevant to highlight that:

- Ghana/Mali Use case was not considered as a not specific location was identified (by more a regional use case) thus making more complex the use of UNIGE tools
- Some specific cost and performance functions used by UNIGE in its analysis and presented in this report could slightly differ from functions used by JULICH (T2.2) and IME (T2.5) in their assessments.

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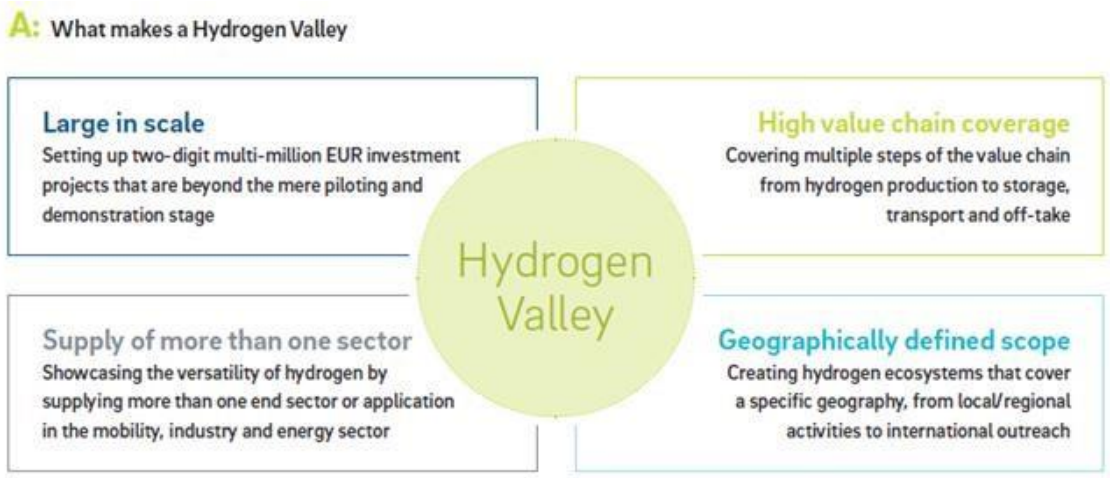
2. HYDROGEN HUBS APPROACH

The REPowerEU plan promoted the concept of Hydrogen Valleys as key approach to facilitate the hydrogen widespread in the European society and Economy. The concept of Hydrogen Valleys is summarized in the following figure.



Large in scale
Setting up two-digit multi-million EUR investment projects that are beyond the mere piloting and demonstration stage

High value chain coverage
Covering multiple steps of the value chain from hydrogen production to storage, transport and off-take

Supply of more than one sector
Showcasing the versatility of hydrogen by supplying more than one end sector or application in the mobility, industry and energy sector

Geographically defined scope
Creating hydrogen ecosystems that cover a specific geography, from local/regional activities to international outreach

Figure 1: The concept of Hydrogen Valley

Hydrogen Valleys have been identified in the RePowerEU plan as an essential feature in order to scale up Europe's hydrogen economy. This is the case because they bring together clean hydrogen production, storage of hydrogen and distribution to end-uses while creating regional value chains in a geographically constrained area, thus reducing investments in terms of infrastructure.

To accelerate EU and global transition to a sustainable hydrogen economy, EU Commission aspires to deploy over than 100 Hydrogen Valleys world-wide before 2030.

In this context, JUST GREEN AFRH2ICA (JGA) team interrogated itself since the beginning of the project to understand if the Hydrogen Valley approach can be replicated in Africa.

Due to different reasons (mainly the lack of energy and civil infrastructure that could facilitate the transportation of hydrogen even in limited areas as well as the lack of public transport structured organizations or the lack/impossibility to setup potential incentives for hydrogen production) JGA consortium decided to "adapt" the H2Valley approach to the African context, promoting the "Hydrogen Hub" (or "Hydrogen Hotspot") approach, where off-grid RES driven green hydrogen production plants should be located close to large H2 off-takers, like industrial use.

At this purpose, some use cases have been identified by the project in Morocco (Dakhla, Jorf Lasfar and Tangers), Kenya (Mombasa, Nairobi and Olkaria) and South Africa (Boegoebaai Bay, Coega and Saldanha Bay) to evaluate the techno-economic viability of this approach in such contexts, starting from the relevant RES potential (present in different forms at local level).

Along this report, techno-economic analysis will be performed to evaluate the viability of Green Hydrogen Hotspot approach and understand the “impact” of RES variability on the techno-economic feasibility of the projects, also looking at the possibility of using the produced hydrogen to manufacture green goods/products from locally produced hydrogen.

2.1 Hydrogen hotspot approach

As reported in D1.3, JGA Uses Cases were identified mostly looking at locally available RES potential and local off-taking opportunities, as well as taking into account availability of water. During the scouting of the potential Hydrogen Hotspots areas these parameters have been considered:

- geographic location and local drivers and barriers for the setting up of a “hydrogen hub”, presence;
- assessment of local energy and civil infrastructures;
- existing renewable power plants presence and local renewable energy sources potential;
- ➢ current and potential hydrogen demand at local level (e.g. current natural gas demand);
- local water sources assessment;
- potential export infrastructures availability;
- local stakeholders;
- local energy/Hydrogen demand and available RES production.

In accordance with these parameters, some potential areas have been identified as representative Project uses cases for the African continent. These selected areas could exploit a large scale local renewable current and potential production, have access to sustainable and manageable water sources and rely on significant potential hydrogen off-takers.

The selected African Uses Cases (as reported in Fig.2) per each Project Region are:

- Dakhla-Laayoune, Jorf Lasfar and Tangiers areas in Morocco for Northern Africa
- Mombasa Borders area, Olkaria and Nairobi areas in Kenya for Eastern Africa
- Coega, Saldanha Bay, Boegoebaai Bay and Namibia Borders/Swakopmund areas for Southern Africa.

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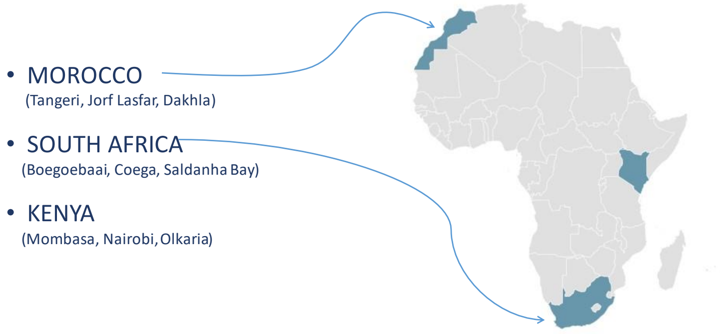

Figure 2: Selected African countries and related use cases

3.1.1. Moroccan Use Case

Morocco is a great candidate for green hydrogen production and export due to the high renewable potential and a strategic geographical location between Africa and Europe. In fact, the country benefits from an average level of solar irradiation around 5 kWh/m^2/day and, adding a likely high average wind speed from 6 to 10 m/s and hydropower plants, has an installed capacity of 4067 MW of renewables. In addition to that, the extended coastal provides access to seawater resources overcoming the water availability issue by using desalination.

Moreover, in 2021, Morocco has adopted a National Roadmap for Green Hydrogen and eight actions have been identified to boost green hydrogen production in the Country.

1. Cost reduction. Morocco will need to reduce the cost of green hydrogen production by improving the efficiency of solar and wind power plants, developing innovative technologies for hydrogen production, and increasing the scale of production.
2. Research and innovation. Morocco will need to invest in research and development to improve the efficiency of green hydrogen production and develop new applications for the gas.
3. Local content. Morocco will need to increase the local content of green hydrogen production by developing domestic manufacturing capacity for electrolyzers and other equipment.
4. Industrial cluster. Morocco will need to develop an industrial cluster for green hydrogen production, which would bring together companies from different sectors to share resources and expertise.
5. Domestic markets. Morocco will need to create domestic markets for green hydrogen by developing new applications for gas, such as in the transportation and industrial sectors.
6. Technological development and cost savings. Morocco will need to invest in research and development to improve the efficiency of green hydrogen production and reduce its cost.

7. Investment and procurement. the government will need to attract investment in green hydrogen projects and develop the necessary infrastructure.
8. Market and demand. Morocco will need to create demand for green hydrogen by developing new applications for the gas, such as in the transportation and industrial sectors.

Furthermore, Morocco is engaged in many low carbon hydrogen projects and is cooperating with many European international partners such as Germany, Portugal and Netherlands to develop the existing pipelines infrastructures in order to facilitate export to European market. In Morocco IRESEN identified three "Hydrogen Hotspots":

- **Tanger**. It has been selected for its high renewable energy potential but, especially, for its potential import and export opportunities due to the port infrastructure and NG pipelines in addition to land availability for renewable energy plants.
- **Jorf Lasfar-Casablanca**. It has been selected for the high industrial demand (e.g. steel, refinery products), in particular the Ammonia/ fertilizer production by the Office Chérifien des Phosphates (OCP) company and a well-developed transportation network.
- **Dakhla-Laayoune**. It has been selected due to the huge RES potential and land availability that could foster solar farms and wind turbines deployment.

Figure 3: Selected Moroccan "Hydrogen Hotspots"

3.1.2. South Africa Use Case

South Africa has abundant solar and wind resources. In addition to that, the Country has a strategic geographical location that facilitates access to sub-Saharan African markets.

Furthermore, the country is already investing in hydrogen projects and hydrogen-based technologies aiming to decarbonize hard-to-abate sectors such as transport, steel, mining and cement.

The Hydrogen Society Roadmap (HSRM) developed by South Africa government outlines several targets, including the creation of an export market for low carbon hydrogen and ammonia, the implementation of a Center of Excellence in manufacturing for hydrogen products, the development of domestic hydrogen supply chains, the production of 500 kilotons of green hydrogen by 2030, and a long-term target of 15 GW power generation based on hydrogen by 2040. Further targets include a 1 MW small-scale electrolysis facility operated by 2025, and the deployment of 10 GW electrolyzers in the Northern Cape and 1.7 GW electrolyzers in the Hydrogen Valley by 2030.

The implementation of the HSRM is expected to contribute to the goal of a just and inclusive net-zero carbon economic growth for societal wellbeing by 2050 through the following highlevel outcomes:

- Decarbonization of heavy-duty transport
- Decarbonization of energy-intensive industry (cement, steel, mining, refineries)
- Enhanced and green power sector (main and micro-grids)
- Centre of Excellence in Manufacturing for hydrogen products and fuel cell components
- Creating an export market for South African green hydrogen
- Increase the role of hydrogen (grey, blue, turquoise and green) in the South African energy system in line with the move towards a net-zero economy

Additionally, South Africa, alongside with Egypt, Kenya, Morocco, Mauritania and Namibia, launched the Africa Green Hydrogen Alliance, with the intention to foster collaboration and ensure the continent is able to lead in the development of green hydrogen for energy transition.

NWU identified notably three areas of major interest for green hydrogen hub installation:

- **Boegoebaai Bay** which targeting both regional and export hydrogen opportunities, due to its proximity to agricultural and industrial sectors and to Namibia borders.
- **Coega** for the green ammonia production plant that HIVE Energy company planned to build to support a regional hydrogen economy development. The plant will combine green hydrogen with nitrogen to produce renewable ammonia which can be used as a fertilizer or as a fuel for hydrogen fuel cell vehicles.
- **Saldhana bay**: as a consequence of the high-RES potential that can count on ample solar irradiation and consistent wind supply, Saldanha Bay has the capacity

to power large-scale electrolysis plants for the production of green hydrogen and exports.

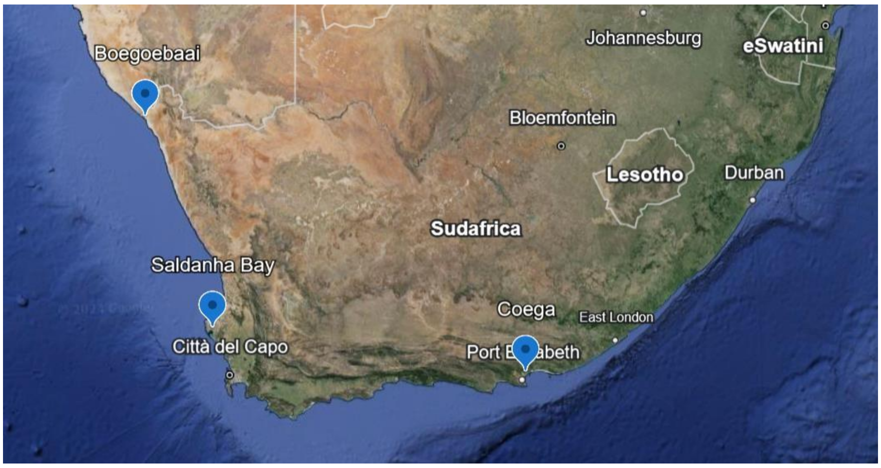

Figure 4: Selected South African "Hydrogen Hotspots"

3.1.3. Kenya Use Case

Among East African countries, Kenya accounts for about 88% from Renewable Energy Sources in its energy generation mix. Along with wind, solar and hydropower, geothermal is a fundamental energy source for electricity production in the country ensuring a steady and reliable power supply. The installed capacity is about 940 MW, corresponding to approximately 30% of the total generation. Due to its expertise in clean energy generation and the presence of established renewable energy projects, like the Lake Turkana Wind Power project, that provides a platform for integrating green hydrogen technologies, Kenya has the opportunity to enhance its energy storage capabilities leading the Green Hydrogen development and export in Eastern Africa. The Kenyan Green Hydrogen Strategy and Roadmap identified and categorized potential hydrogen use in various sectors from industry to agriculture. Use cases in terms on confidence in role on hydrogen are illustrated in the following figure. STRATH has investigated these aspects and identified the following potential hydrogen hub areas:

- **Mombasa port area**, especially for its port and energy infrastructures that could facilitate import and export and the coastal position that could exploit seawater electrolysis.
- **Nairobi Capital District** because of it is the central node of the country and represents an attractive location for green hydrogen production that could ensure industrial and manufacturing sector improvement to a fossil-free economic grow.
- **Olkaria geothermal plant area**, mostly for the presence of the Olkaria Geothermal Plant, one of the largest geothermal plants globally and the proximity to a large water availability of the Lake Naivasha and nearby rivers.

Figure 5: Selected Kenyan “Hydrogen Hotspots”

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3. GENERAL OVERVIEW AND METHODOLOGY

3.1 What is thermo-economics? Why is it relevant for Green Hydrogen Production assessment?

The increasing demand for natural resources by current energy conversion technologies and the concern for the impact on the environment due to emission, waste disposal and signs of global warming have brought about the creation of new disciplines that help to understand how to improve the design and operation of energy systems and prevent residues from damaging the environment.

Thermoeconomics is, in its widest possible sense, the science of natural resources saving that connects physics and economics by means of the Second Law of Thermodynamics.

Thermal power plants, smart grids and district heating systems or chemical plants are examples of energy systems formed from a set of subsystems or processes. These systems interact with their environment, consuming some external resources, which are then transformed into products. The final purpose of this transformation is to increase the economic utility.

The production process of a complex energy system can be analyzed in terms of its economic profitability and efficiency with respect to resource consumption. An economic analysis can calculate the cost of fuel, investment, operation and maintenance for the total plant or even individual components but provide no means on how to allocate costs among them and its products. On the other hand, thermodynamic analysis let us calculate the efficiency of the individual process of the plant and locates and quantifies the irreversibility but it cannot evaluate their significance in terms of the overall production process.

Thermoeconomic analysis combines economic and thermodynamic analysis by applying the concept of cost, originally an economic property, to exergy. Most analysts agree that exergy is an adequate thermodynamic property to which we allocate cost because it accounts for energy quality. The exergy of a thermodynamic flow is the minimum amount of work needed for its production, from the reference environment.

Once the reference environment is defined, exergy is a thermodynamic function of state which makes it possible to formulate the equivalence between different energy and/or matter flow streams of a plant. Two flows are thermodynamically equivalent, that is, it is theoretically possible to get one from the other without additional consumption of energy resources if, and only if, they have the same exergy. Exergetic efficiency compares a real process to an ideal process, i.e. reversible, of the same type. An exergy analysis locates and quantifies irreversibility in a process.

The physical entity connecting thermodynamics and economics is entropy generation or more specifically irreversibility. It represents the “useful” energy lost or destroyed, in all physical processes, and it has been used for pinpointing the true inefficiencies of industrial processes. Since all common processes in an actual plant are not reversible, exergy is destroyed and some natural resources are consumed and lost forever, which involves a cost

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in economic terms. The more irreversible a process is, the more natural resources are consumed.

The exergy balance accounts for the degradation of the exergy. The input exergy into a process will always be greater than the exergy output:

Exergy Input - Exergy Output = Irreversibility > 0

This expression only keeps in mind the irreversibility of the process. The purpose of this process is set by means of the definition of its efficiency. This is to say, that there is an implicit classification of the flows crossing the boundary of the system: the flows that are the production objective, the resources required to carry out the production and those that are residual. This information is not implicit in the second law and is the most important conceptual leap separating and at the same time uniting physics with economics. The following equation:

Resources (F) – Products (P) = Residues (R) + Irreversibility (I) > 0

is of utmost importance because it places "purpose" in the heart of thermodynamics.

The concept of efficiency defined as

Efficiency = Product / Resource

is older than thermodynamics and measures the quality of a process. The desire to produce a certain product is external to the system, and must be defined beforehand. Once this has been done, the design of the system and its functional structure will fit the aim of using available resources (capital, raw material, man power...). Every definition of efficiency demands a comparison of the product obtained with the resources needed to obtain it. Its inverse value is:

Unit Consumption = Resources / Product

This expression is also a definition of the unit average cost when resources refer to the overall plant instead of individual processes. This concept is the key of thermoeconomics. A logical chain of concepts can be established (Fig.1), which allows connecting physics with economics.

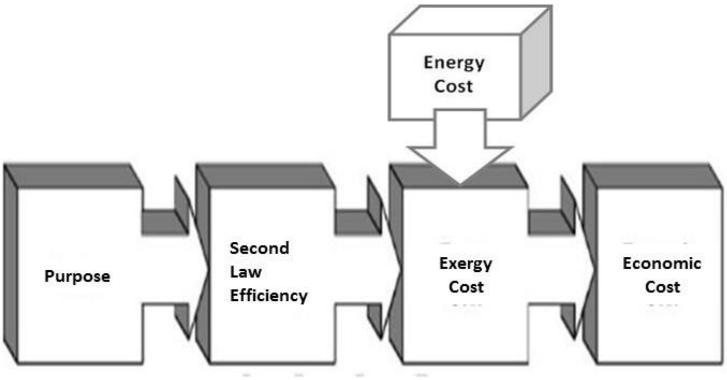

Figure 6: Logical chain of thermoeconomic concepts

Thermoeconomics deals with human engineered energy systems. Its efficiency is a purposive concept and so they are the thermoeconomics analyses. Thus, thermoeconomics assesses the cost of consumed resources, money and system irreversibility in terms of the overall production process.

They help to point out how resources may be used more effectively in order to save them. Money costs express the economic effect of inefficiencies and are used to improve the cost

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effectiveness of production processes. Assessing the cost of the flow streams and processes in a plant helps to understand the process of cost formation, from the input resources to the final products.

These analyses can solve problems related to complex energy systems that could not be solved by using conventional energy analyses. Among other applications thermoeconomics are used for:

- Rational prices assessment of plant products based on physical criteria.
- Optimization of specific process unit variables to minimize the final product cost, i.e. global and local optimization.
- Detection of inefficiencies and calculation of their economic effects in operating plants, i.e. plant operation thermoeconomic diagnosis.
- Evaluation of various design alternatives or operation decisions and profitability maximization.
- Energy audits.

Thermo-economic analysis is a well-known method to approach multi-vector energy systems, in order to develop efficient and profitable real time controllers and to identify the best size for the different installed devices.

This is of particular importance particularly in RES Based energy systems (as Green Hydrogen production hubs are) and in off-grid contexts (as in Hydrogen Hubs analysed in JUST GREEN AFRH2ICA) in order to properly exploit the available energy sources also thanks to the proper integration, sizing and management of energy storage (batteries – hydrogen storage)

3.2 Thermo-economic approach and methodology applied in this study

The purpose of the analysis presented in this deliverable is to analyze the optimal management and size of a 1 MW PEM electrolyser coupled with local RES plants (wind – PV – geothermal) in the different JUST GREEN AFRH2ICA identified use cases in Morocco, South Africa and Kenya demosites in order to calculate LCOH at local level, the overall CAPEX of the plant and the number of yearly equivalent operating hours (EOH) of the green hydrogen production hub. To do so, . A one-year analysis is carried out with one hour time intervals, taking into proper account the time-dependent nature of energy demands, RES generation and investigating the best operational strategy for the devices, with particular focus on storage technologies.

Such yearly analysis is performed considering a typical week per each month (particularly to evaluate the local Renewable energy production potential) in all the identified use cases

The optimization process is performed employing the UNIGE original software W-ECoMP (Web-based Economic Cogeneration Modular Program) which aims to investigate the best management strategy of the devices installed in polygenerative energy districts in

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order to satisfy the load energy demands and make eventual new equipment installations profitable and that has been already used by the UNIGE Staff in previous research whose goal was the assessment of optimal sizing of green hydrogen production sites[1],[2].

W-ECoMP (Web-based Economic Cogeneration Modular Program) is a FORTRAN based code with a Java based user interface that presents a modular approach and a standard component interface, which allows the user to build complex cycle configurations in a short time. This approach maintains the flexibility and the extendibility of library components (51 modules are available), allowing users to add new components without modifying the core of the program. Each component is described by three subroutines, which define mass and energy flows, off-design performance curves, variable and capital costs.

W-ECoMP software is provided with cost equations that evaluate the capital cost of the single components of the plant based on the installed power (for gas turbines, fuel cells, electrolytic cells, etc) or on the flows entering the modules (for chemical reactors, distribution networks, etc). The determination of cost functions for the different modules has been performed thanks to the contribution by UNIGE industrial partners over the last years or by referring to literature data. Cost functions are updated periodically in order to consider the development in performance improvement and market prices as well.

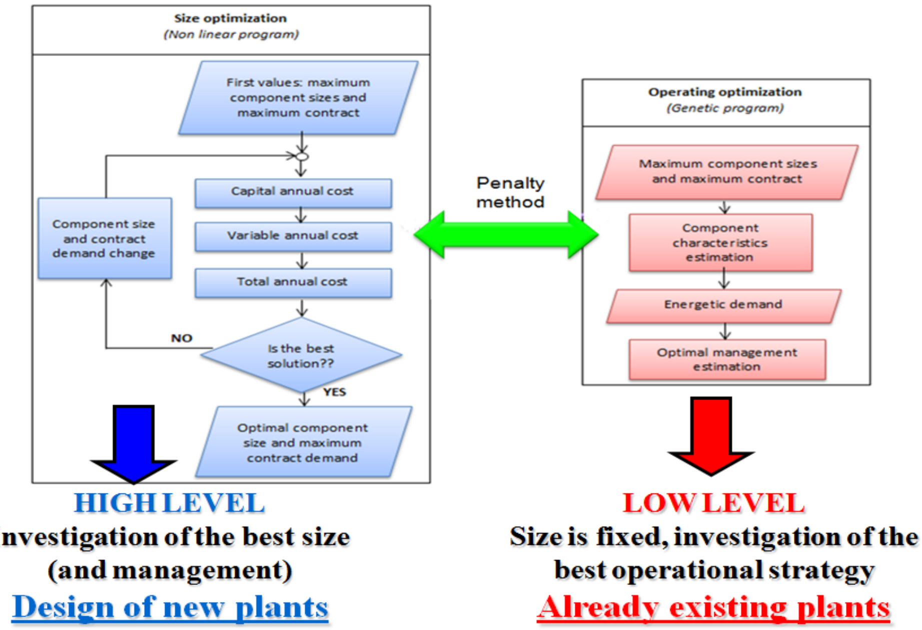

Figure 7: W-ECoMP hierarchical optimum research approach

The software receives as inputs: (i) electricity, heat, chemicals, etc., load curves versus time; (ii) economic scenario where the plant should operate, with corresponding trade prices

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[1] Rivarolo, M.; Riveros-Godoy, G.; Magistri, L.; Massardo, A.F. Clean Hydrogen and Ammonia Synthesis in Paraguay from the Itaipu 14 GW Hydroelectric Plant. *ChemEngineering* 2019, *3*, 87. https://doi.org/10.3390/chemengineering3040087

[2] Clean H_2 and NH_3 large production in Paraguay by the 14 GW Itaipu hydroelectric facility, G. Riveros-Godoy, M. Rivarolo, A.F. Massardo and G. Arevalos E3S Web Conf., 113 (2019) 01009, DOI: https://doi.org/10.1051/e3sconf/201911301009

(fuel cost, energy cost, etc.); (iii) component capital costs vs. size; (iv) operating and maintenance costs vs. time. Figure 2 shows the software structure. W-ECoMP is based on a hierarchical optimization structure.

There are two different optimization levels: low and high levels, respectively.

At low levels, layout and plant size are considered fixed (therefore capital costs are fixed) and the best operational strategy is used to minimize the function that represents the hourly (or less) variable cost.

$$C_{\text{var}} = F_i \cdot \sum_{i=1}^{N} c_{fuel,i} + c_{el} \cdot E_{acq} + c_{virt} \cdot \left(F_{virt} + E_{virt} + Q_{virt}^{*}\right) \quad (1)$$

Variable costs are made up of the following terms: (i) a term related to fuel consumption costs, (ii) a term related to electrical energy costs and (iii) a term that represents "virtual costs". It is important to underline that the "*virtual flows*" term, added to the cost function, is not a real cost. It represents exchanges between system and environment (electrical grid, fuel grid, storage system, etc.) necessary to meet the optimization procedure constraints. Since virtual costs have a very high value, in order to find optimum conditions without any virtual energy demand (constraint violation), the optimization process is forced to find a plant configuration which minimizes virtual flows (i.e. zero virtual costs).

The problem's constraints are the balance equation between supply and demand of components. For example, the energy balance includes the energy produced by the prime movers (ICE, gas turbines, etc.) in the system, the energy sold to the user and the energy consumed by system components (i.e. electrolytic cells, users…)

$$E_{req} = \sum_{i=1}^{N} E_{i,prod} + E_{acq} + E_{virt} - \sum_{i=1}^{N} E_{i,cons} \quad (2)$$

At high levels, it is possible to evaluate the optimal size of the plant components while minimizing total annual costs, which are the sum of variable costs C_{var} calculated at low level analysis and capital plant costs C_{cap}.

$$C_{tot} = C_{\text{var}} + C_{cap} \quad (3)$$

The total capital costs of the plant are the sum of the total capital costs of all plant components.

$$C_{cap} = \sum_{i=1}^{N} C_{cap,i} \quad (4)$$

Therefore, the optimization procedure is carried out to simultaneously obtain the plant and the component sizes, together with the plant operation. The optimal size value for the desired component is found between two limit values set by the user. At every iterative cycle, total annual costs are calculated by changing the value of the nominal size of the component and also by taking into account how virtual flows contribute to find the optimal component size, in order to determine the global minimum value of the objective function.

For both high level and low level optimizations, the program's goal is to minimize the objective function, which represents total annual plant cost. At low levels, W-ECoMP minimizes variable costs, reducing to zero penalty costs associated to virtual flows that would represent conditions with no constraint satisfaction. At high optimization levels, the software takes into account fixed costs too, finding the optimal size for plant components.

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Demands must be satisfied at every optimization level: if this condition is not verified, strong penalties are applied and the objective function gets higher because of virtual costs C_{virt} associated to virtual flows. Via this approach, fulfilling electric and H&C demand is the first mandatory objective of the optimizer, obviously trying to minimize the costs.

In W-ECoMP, to easily build complex plant configurations in a short time and to estimate the complete optimum time-dependent thermo-economic performance, a modular visual approach is available (51 different modules are available at the moment). Four subroutines were developed to calculate each component: (i) design and off design performance; (ii) capital costs; (iii) variable costs; and (iv) operating and maintenance costs. The calculation is then carried by out by dividing the operational time (usually a year) in a sufficient number of representative periods (one hour or less depending on the particular application).

3.2.1. Use Case Modelling Approach

In order to assess the green hydrogen potential in African countries and in particular in the selected uses cases the following methodology has been pursued, realizing a model in WECoMP as the one presented in the figure below.

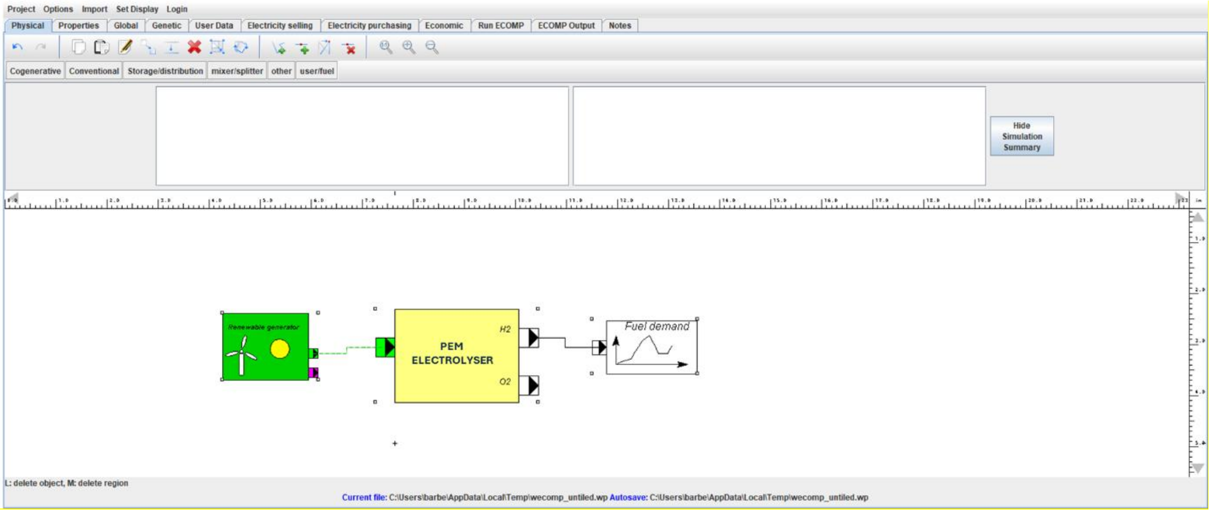

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Figure 8: Green Hydrogen Production Hub Modelled in WECoMP

First of all, data related to local RES potential have been collected from available RES atlases and databases.

The incident solar radiation and wind speed have been analyzed thorough the Photovoltaic Geographical Information System (PVGIS) web tool. PVGIS tool is developed by the JRC (Joint Research Center) of the European Commission in order to provide the necessary data required to know the potential for electricity production from PV systems.

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The data collected by PVGIS have been elaborated and integrated in the Renewable Energy Generation model present in WECoMP.

The simulation carried out acquired weekly weather data for each month from PVGIS tool to develop an annual estimation based on solar, wind and geothermal renewable energy potential curves and estimation of the renewable hydrogen potential production through the electrolytic process performed at weekly level per each month

The electrolyzer considered into the analysis, along with the solar, the wind and the geothermal plant size, are scaled on 1 MW and proportionally variated depending on the Use Case. A PEM Electrolyser (as the most flexible electrolysis technology) has been considered also looking at its off-design performances (as reported in Eq.5 and Fig.9 via an industrial reference curve, provided by BluEnergyRevolution, one of the partners of JUST GREEN AFRH2ICA consortium).

$$y = -2{,}5875x^4 + 7{,}2399x^3 - 7{,}3787x^2 + 3{,}2086x + 0{,}4973 \qquad (4.1)$$

where:
y = Eta Actual/Eta Nominal
x = % LOAD ELY

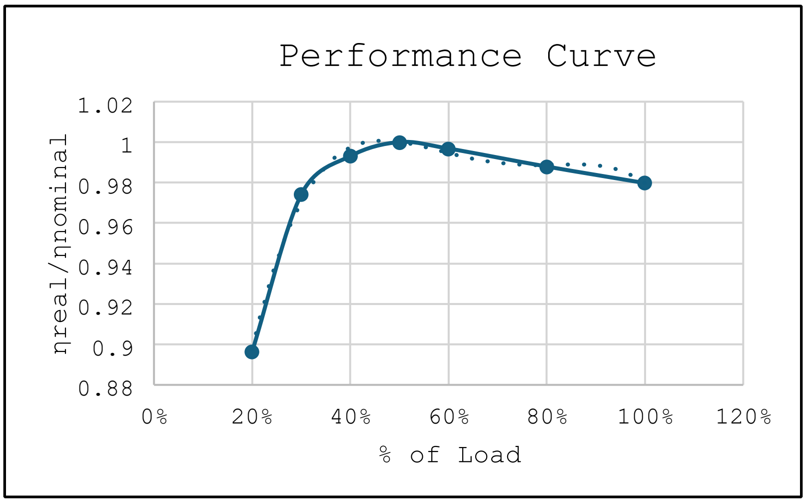

Figure 9: Off-Design curve of the PEM Electrolyser integrated in WECoMP PEM Electrolyser module

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Renewable energy production module has been then integrated with the PEM Electrolyser module (also integrating a specific cost function for water supply as reported in D2.1 and in an UNIGE Publication[3]) and a Li-On battery.

No specific demand (neither from electric nor from hydrogen point of view) was integrated, thus the green hydrogen production plant was required to produce at its "Maximum capabilities".
As no specific demand is present, the rationale behind the WECoMP Optimizer is mostly what is presented in the next lines and in Fig.10

1) The potential renewable production Photovoltaic (PV), Wind and geothermal (GEO) for the Use Case is estimated firstly starting from renewable atlases data.
2) If the RES production is under the minimum Load of the electrolyser (ELY), the energy production is stored into a battery. If the battery is charged, a potential power input can come from the battery to enable the ELY to operate.
3) If the RES production is over the minimum ELY Load but over the ELY Nominal Power, the energy production is stored into the battery.
4) If the RES production is over the minimum ELY Load and under the ELY Nominal Power, the RES production goes to the electrolyser in order to produce green hydrogen.
5) Looking at the overall RES production value going effectively to the electrolyser, based on the above mentioned electrolyser efficiency curve, the actual efficiency of the electrolyser is calculated and the green hydrogen production is calculated hour per hour.

This process is performed hour per hour looking at a typical weekly profile per each month of the year. Starting from weekly production results per each use case and per each month. Afterwards (and having multiplied by four each week) the monthly and annual production values are calculated.
From the Equivalent Operating Hours (EOH) of the electrolyser, annual ELY efficiency is calculated.
Based on the efficiency of the ELY, the H2 potential production (as well as other KPIs) for each Use Case are estimated.

---

[3] - Massimo Rivarolo, Stefano Barberis, Aurora Portesine and Aristide F. Massardo, "Evaluation of water/energy intensity of green hydrogen production plants in Africa scenario", Journal of Physics: Conference Series, Volume 2893, The 79th ATI Annual Congress 04/09/2024 - 06/09/2024 Genoa, Italy, https://doi.org/10.1088/1742-6596/2893/1/012074

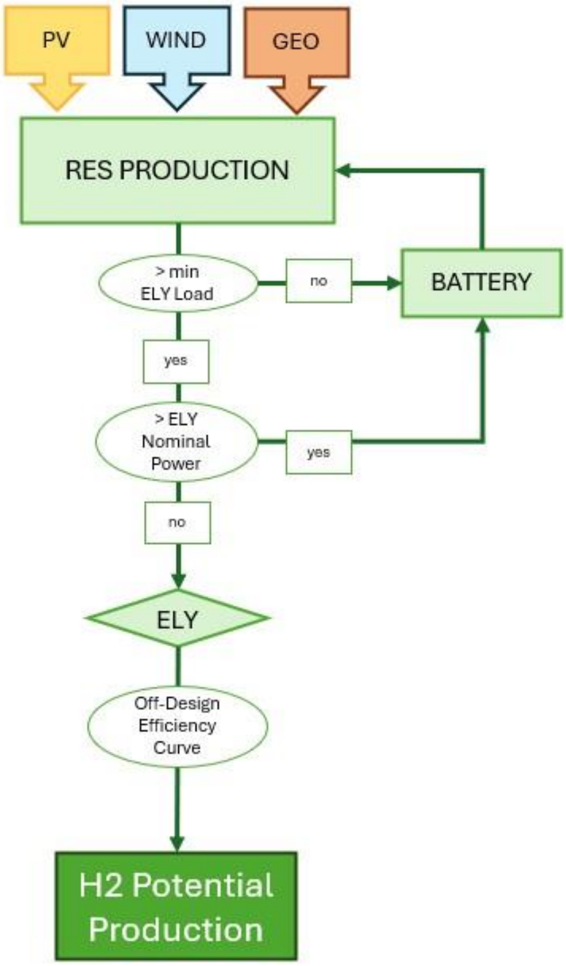

Figure 10: Simplified adopted Methodology for the mathematical modelling of the study of the potential green hydrogen production via WECoMP Tool in the JUST GREEN AFRH2ICA Use cases

While, as mentioned above, for what it concerns solar and wind, available atlases theoretical RES potential has been considered (and duly implemented in WECoMP RES Generation Module to calculate the effective production potential), differently from the other RES sources, the potential inputs from the Geothermal source has been evaluated (only in the Olkaria use case) based on real data.

As also discussed during the visit that the JUST GREEN AFRH2ICA consortium organized in February 2024, Olkaria power plant managed by KENGEN has indeed an issue along the overnight period that oblige KENGEN to vent geothermal steam to the ambient instead of producing electric power due to the reduced electric load of the country along the night.

Specific values related to such “geothermal steam waste” are not public due to confidentiality aspects, thus it has been supposed that the whole geothermal power production (equivalent to 45 MW) coming from “Olkaria 1 Power Station” is dedicated in the low demand timeframe from 10pm to 6am) to the green hydrogen production (coupled to a 50 MW ELY) supposing its cost of production equal to zero.

3.2.2. Techno-economic KPIs and scope of the simulation

All in all, the goal of the overall methodological approach is to determine the Annual Hydrogen Potential production, its LCOH as well as the annual potential renewable production properly exploited by the electrolyser.
The outcomes of that process are two scenarios of the green hydrogen potential production per each Use Case: a current scenario and a 20-years future scenario, targeting higher efficiency of the enabling technologies (Batteries/Electrolysers) and their reduced CAPEX.

To assess the techno-economic viability of green hydrogen production in the different use cases, the technoeconomic analysis calculated different KPIs that all compete to the evaluation of the LCOH (Levelized Cost of Hydrogen) at local level based on renewable hydrogen production data coming from the modelling of the use cases.

The main Key Performance Indicators (KPIs) considered in the analysis are:

- Equivalent Operation Hours (EOH) of the RES power plant or of the electrolyzer [h]:

$$\text{EOH}= \frac{\text{Annual ELY production [kg]}}{\text{Nominal ELY Production [kg]}}$$

- RES Levelized Cost of Electricity (LCOE) [€/MWh] :

$$\text{RES LCOE} = \frac{\text{RES CAPEX [€]} + 20\text{ yrs} * \text{RES annual OPEX [€]}}{\text{RES annual production} \times 20\text{ yrs [MWh]}}$$

(obtained assuming a 2% of CAPEX as yearly maintenance cost of the plant for a lifetime of 20 years for the plant)

- Overall cost of electricity of RES (based on LCOE) [€]:

$$\text{Cost of electricity of RES [€]} = \sum(\text{Annual LCOE} \times \text{RES annual production})$$

- Monthly and annaul H2 production [kg]:

$$Monthly\ H2\ production\ [kg] = Weekly\ overall\ H2\ production\ [kg] \times 4$$

$$Annual\ H2\ production = \sum Monthly\ H2\ production$$

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- Specific Energy Consumption of the electrolyser [MWh/kg]:

$$\text{Specific Energy Consumption} = \frac{Annual\ RES\ Production\ [MWh]}{\text{Annual H2 Production [kg]}}$$

- Annual efficiency of the ELY [%] (4.10):

$$Annual\ efficiency\ of\ the\ ELY = \frac{33.3\ kWh}{\text{Annual ELY Energy Consumption}}$$
$$(where\ 33{,}3\ kWh\ is\ the\ low\ heating\ value\ of\ 1\ kg\ of\ H2)$$

- Total OPEX [€/kg] (4.11):

$$OPEX = Cost\ of\ Power + Maintenance\ Cost$$

CAPEX estimation has been performed according to some specific cost functions (coming from current Renewables and Hydrogen projects and market studies) reported here below (Tab.1).

Tab.1 - CAPEX actual and future cost function values

TECHNOLOGY	**CURRENT**	**FUTURE**
PV	1000 €/kW	800 €/kW
WIND	2100 €/kW	1800 €/kW
BATTERY	200 €/kWh	130 €/kWh
ELECTROLYSER	1200 €/kW	1000 €/kg

Also considering for the electrolyser:
+ 15% of CAPEX for installation and commissioning
+ 40% for civil works and other installation aspects

- Levelized Cost of Power [€/kg] (4.12):

$$Cost\ of\ Power = \frac{Overall\ annual\ Cost\ of\ Electricity\ [€]}{Annual\ H2\ Production\ [kg]}$$

- Levelized Cost of Capital [€/kg] (4.13):

$$Cost\ of\ Capital\ [\frac{€}{kg}] = \frac{Total\ CAPEX \times \text{IRR}\ \ [€]}{\text{Annual H2 Production }][\text{kg}]}$$

- Levelized Cost of Hydrogen (LCOH) [€/kg]:

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$$LCOH = (\text{Overall } Cost\ of\ Capital + Total\ OPEX \text{ along 20 yrs })/\text{ H2 production in 20 yrs}$$

In the following the additional parameters considered to calculate the Techno-economic KPIs parameters are exposed.

- IRR (Cost of Capital) = 5%;
- Maintenance Cost = 2% of CAPEX;

It is significant to consider that H2 storage and compressor costs are assumed equal to 0 € since the “Hydrogen Hotspot” approach is based on the idea of localizing the plant where there is a single and continuous demand of hydrogen.

4. GREEN HYDROGEN PRODUCTION ASSESSMENT IN THE DIFFERENT USE CASES

Based on the methodology outlined in Section 3, This chapter aims to provide a techno-economic evaluation about Green Hydrogen potential production in Morocco, South Africa and Kenya and provide the LCOH economic analysis for each Use Case.

Per each Use Case the more convenient battery size has been selected based on the WECoMP optimization tool targeting different targets via four main KPIs all competing to minimize the LCOH:

- H2 Production;
- Annual electrolyser efficiency;
- RES not Exploited;
- Battery CAPEX;

The results and the main considerations per each Use Case are detailed in this chapter.

4.1 Morocco use cases

4.1.1. Tanger

Tanger is a city located in northern Morocco, it offers several compelling reasons why it could be a suitable location for green hydrogen projects:

- Strategic Geographic Location. Tangier is strategically located at the entrance to the Mediterranean Sea and the gateway to Europe. This position provides opportunities for exporting green hydrogen to European markets, which have a growing demand for clean energy sources, including hydrogen.
- Coastline Regions for Available Seawater Resources. Tangier is located along the northern coastline of Morocco, providing access to seawater resources. This geographical advantage can be important for technologies that utilize seawater, such as desalination.
- Availability of Land. Tangier offers available land for renewable energy infrastructure, such as solar arrays and wind turbines. The suitability of land, including factors like land ownership, topography, and soil quality, should be considered during the planning phase.
- Availability of Infrastructure for Export (Ports). Tangier boasts a well-developed infrastructure and a major port, the Tangier-Med port, which is one of the largest and busiest ports in the Mediterranean region. This infrastructure is advantageous for exporting energy or importing equipment. The city also offers the possibility of building new infrastructures if required to support renewable energy projects.

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Tangier, with its high renewable energy potential, diverse local industries, coastal location, available land, and robust infrastructure, presents itself as a promising location for green hydrogen projects.
The figure below shows the average daily solar irradiance for each month and is useful to have an overview of the daily potential renewable energy production.

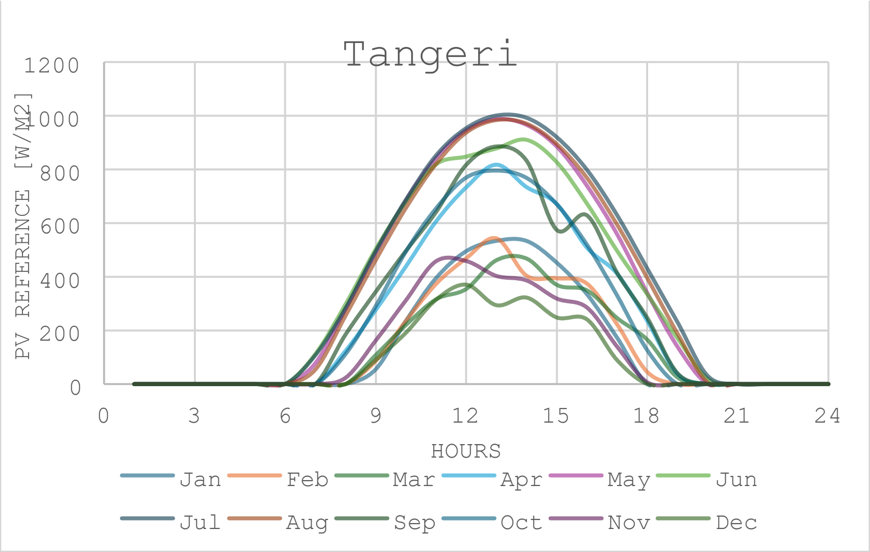

Figure 11: Tanger solar irradiance in a typical monthly day

Tanger present scenario (only PV - 1,5x electrolysis size):

In Tanger use case, considering a solar plant of 1,5 MW for 1 MW of electrolysis, the annual PV production estimated is 3208 MWh. However, due to seasonal and daily fluctuation of solar energy, it is convenient to exploit a battery not significantly large (around 2.27 MWh) which provides an annual H2 production of 51231 kg with a LCOH of 5,31 €/kg that underline the convenience of the location.

Tanger future scenario (only PV - 1,5x electrolysis size):

In 2040 time-horizon, the CAPEX reduction of hydrogen production, battery and PV plant will decrease the LCOH to 4,08 €/kg.

4.1.2. Jorf Lasfar

The new port of Jorf Lasfar is located between the White Cape (to the north) and the current port of Jorf Lasfar (to the south). The identified site can leverage the following advantages:

- availability of land in the backyard of the coastal areas to facilitate logistics operation as well as potential renewable power plant installations
- proximity to both the local industrial site, the former port and the existing motorway/civil infrastructure (thus facilitating import/export logistics)
- availability of a stable electric supply also thanks to local natural gas driven power plants
- Presence of relevant local H2 industrial end users: The presence of local relevant Hydrogen off-takers for fertilizers and ammonia production in the Jorf-Casablanca region is one of the key driver in the identification of this use case. Ammonia/fertilizer production is mostly related to the company named Office Chérifien des Phosphates (OCP). OCP is a major phosphate mining and processing company based in Morocco, and it plays a significant role in the global fertilizer and ammonia industry. The steel industry, including companies like MagrebSteel in Casablanca and SONASID in Jorf Lasfar in the Maghreb region, is another relevant potential future hydrogen off-takers for H2 driven DRI processes as well as for H2 combustion in the process. Companies like MagrebSteel and SONASID are prominent players in the steel industry within the Maghreb region, producing various steel products to meet domestic and international demand. Their operations are essential for supporting various industries and contributing to the economic development of the region and the broader global economy.
- Coastline Regions for Available Seawater Resources: The Jorf-Casablanca region in Morocco does have access to seawater resources as it is located along the country's coastline. Access to seawater is a fundamental requirement for green hydrogen production through a process known as seawater electrolysis. This process involves using electricity generated from renewable sources, such as wind or solar power, to split water into hydrogen and oxygen.
- Availability of Infrastructure for Export (Ports): Jorf-Casablanca features a welldeveloped infrastructure, including the presence of ports (Port of Jorf Lasfar) and transportation facilities. The region has well-developed transportation networks, including road, rail. These infrastructures facilitate the movement of hydrogen and hydrogen-related equipment. Efficient logistics are crucial for reducing distribution costs and ensuring reliable supply chains.

The figure below shows the average daily solar irradiance for each month and is useful to have an overview of the daily potential renewable energy production.

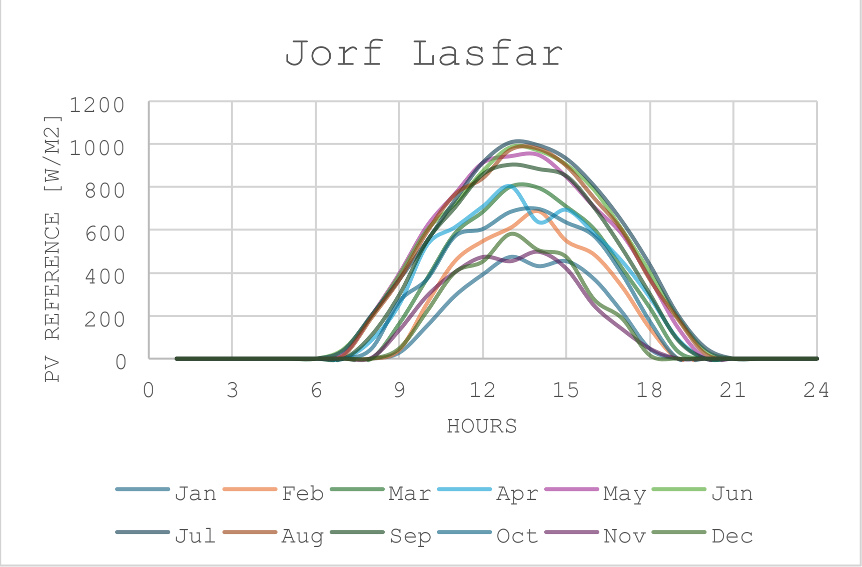

Figure 12: Jorf Lasfar solar irradiance in a typical monthly day

Jorf Lasfar present scenario (only PV - 1,5x electrolysis size):

Jorf Lasfar use case considered a solar plant of 1,5 MW for 1 MW of electrolysis obtaining an annual PV production of 3366 MWh/year. Similar to Tanger use case, the presence of seasonal and daily fluctuation of solar energy, makes convenient the use of a battery not significantly large, with a size around 2,53 MWh provides a H_2 production of 54784 kg/year, a LCOH of 5,03 €/kg and the electrolyzer load of 54,25%.

Jorf Lasfar future scenario (only PV - 1,5x electrolysis size):

In 2040 time-horizon, the CAPEX reduction of hydrogen production, battery and PV plant will decrease the LCOH to 3,86 €/kg.

4.1.3. Dakhla

Dakhla-Laayoune is a region located in the southwestern part of Morocco. The region encompasses two main cities: Dakhla and Laayoune, which serve as its administrative and economic centers.

Thanks to its enormous green hydrogen potential and land availability, this area attracted the interest of different investors and green hydrogen project developers, like Polish company Green Capital group.

➢ Availability of Land: The region offers vast open spaces, which are ideal for the deployment of renewable energy infrastructure, such as solar farms and wind turbines. The

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availability of land can make it easier to establish large-scale hydrogen production facilities.

- Renewable Energy Potential: Dakhla's location, near the Moroccan Sahara Desert, offers a strategic advantage for solar energy production due to its proximity to vast desert areas that are suitable for large-scale solar installations.
- The Dakhla-Laayoune region, offers significant potential for the availability of renewable resources:
- Solar Energy: The region offers abundant sunshine throughout the year, making it wellsuited for solar energy production. Solar panels and concentrated solar power (CSP) technologies can be deployed to harness this energy for electricity generation and other applications.
- Wind Energy*:* The coastal location of Dakhla and Laayoune makes the region favorable for wind energy development[7]. The area benefits from consistent winds, which can be harnessed by wind turbines to generate electricity. Wind farms can be established to capitalize on this resource.
- Infrastructure Development: The Dakhla-Laayoune region is marked by a well-established infrastructure and features a significant port, the Dakhla-Laayoune Port. This port, although currently in the planning stages, is a foreseen infrastructure project that holds great promise for the region's economic development and connectivity. Once constructed, the Dakhla-Laayoune Port is expected to play a pivotal role in supporting various industries, including fisheries, agriculture, and potentially renewable energy projects, making it a key driver of regional development and trade expansion. Morocco recently announced the launch of a newly built seawater desalination plant in Dakhla which will be beneficial for hydrogen production projects in the future too.

Figures 13 show the average daily solar irradiance and the wind speed per each month and are useful to have an overview of the daily potential renewable energy production.

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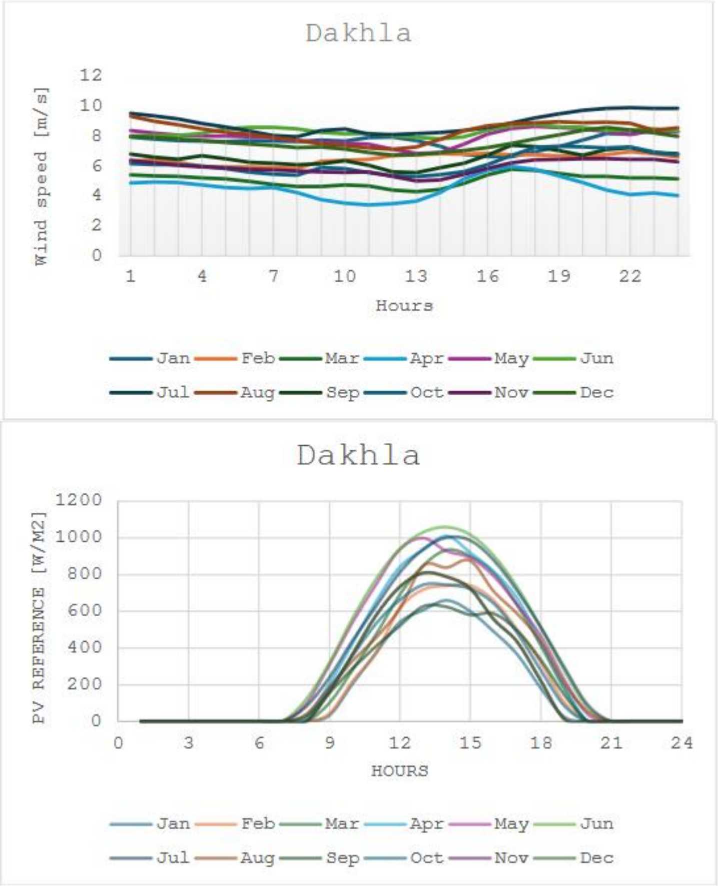

Figure 13: Dakhla-Laayoune wind speed and monthly solar irradiance in a typical monthly day

<u>Dakhla present scenario (WIND - 1,25x electrolysis size - PV 1x electrolysis size):</u>

Dakhla use case, considered a solar plant of 1 MW combine to a wind power plant of 1,25 MW for 1 MW of electrolysis, the annual PV and wind production estimated is 2443 MWh and 1223 MWh, respectively. Also in this case, seasonal and daily fluctuation of solar energy makes convenient to exploit an averaged sized battery (2,38 MWh) which provides an annual H2 production of 60822 kg with a LCOH of 7,04 €/kg.

<u>Dakhla future scenario (WIND - 1,25x electrolysis size - PV 1x electrolysis size):</u>

In 2040 time-horizon, the CAPEX reduction of hydrogen production, battery, wind and PV plant will decrease the LCOH to 5,65 €/kg.

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Dakhla-further present scenario (WIND - 1x electrolysis size - PV 1,25x electrolysis size): by variating wind and solar plant size, and consequently their production (979 MWh/year for wind and 3053 MWh/year for solar), LCOH decreases to 6,57 €/kg compared to the previous scenario (7,04 €/kg) thanks to Wind CAPEX reduction. However the battery sizing is more significant (and its related CAPEX) at around 4,75 MWh. Despite this storage capacity increase, ELY load, instead, will be reduced from 55,30% to 54,90% due to the fact that wind plant size reduction (which has a relevant impact on RES power plant CAPEX and then in overall Green Hydrogen Hub CAPEX) minimizes the EOH of the electrolyzer.

Dakhla-further future scenario (WIND - 1x electrolysis size - PV 1,25x electrolysis size):

In 2040 time-horizon, the CAPEX reduction of hydrogen production, battery and PV plant will decrease the LCOH to 5,18 €/kg.

4.2. South Africa use cases

4.2.1. Boegoebaai Bay

Boegoebaai Bay, situated in Northern Cape Province about 60 km north of Port Nolloth and 20 km south of Namibian border, has great potential in the context of green hydrogen production and export and is moving forward to develop the Green Hydrogen Strategy. This location benefits from:

- Availability of Land: this area expands on 9608 km² in Richtersveld Local municipality in Northern Cape Province.
- Potential local demand of hydrogen: sectors such as Agriculture, Mining (iron, Manganese), Manufacturing (Cement, Steel).
- RES presence: Best renewable energy resource in South Africa with a solar radiation of 2100 kWh/m^2 and wind speed average of 6,3 m/s.
- H2 Development plans: MoA Signed for Domestic and Export of 400 kt pa hydrogen by 2030.
- Infrastructures: Northern Power Transmision corridor, Port infrastructure

The figures below show the average daily solar irradiance and the wind speed for each month and are useful to have an overview of the daily potential renewable energy production.

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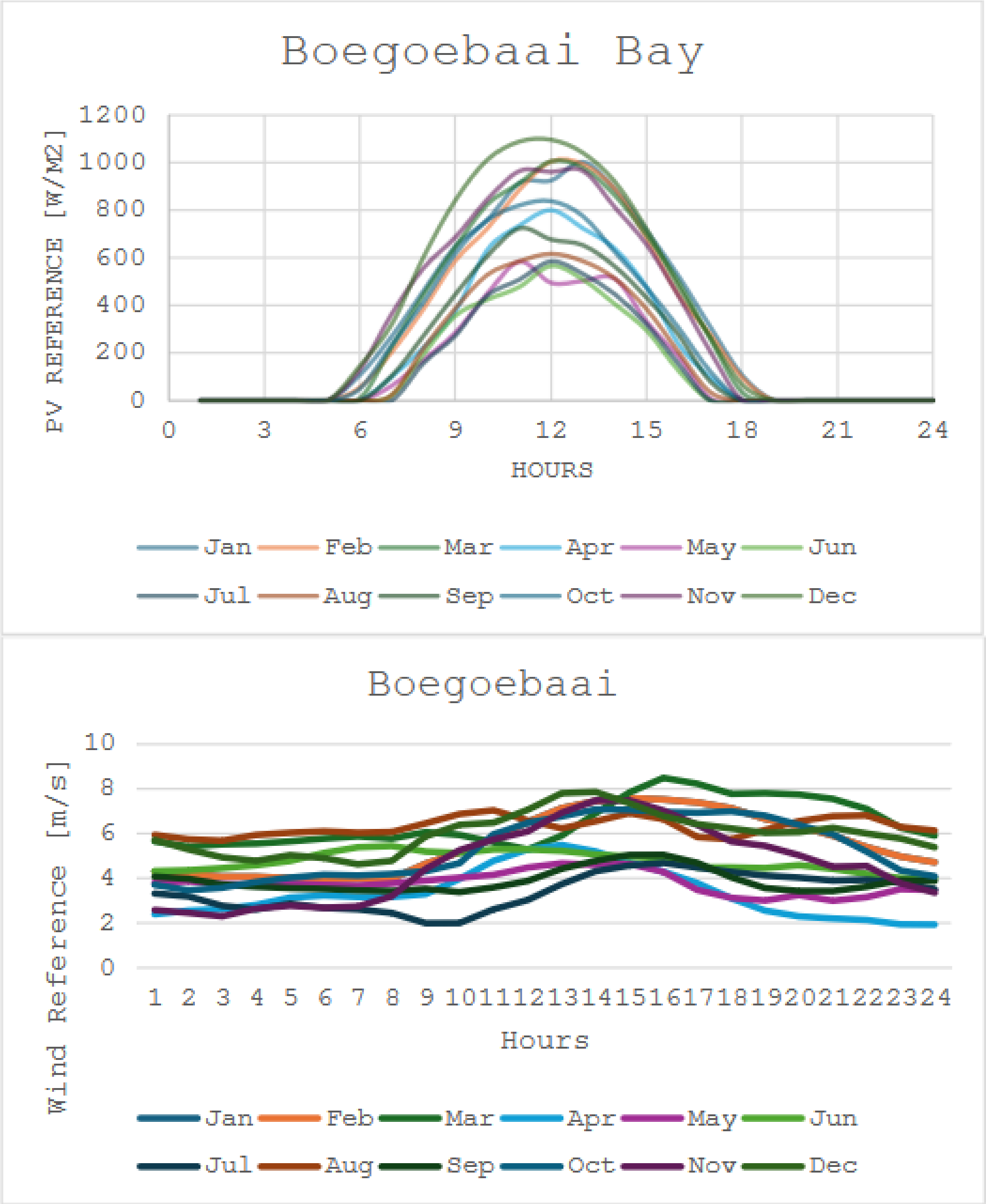

Figure 14: Boehoebaai wind speed and daily solar irradiance in a typical monthly day

Boegoebaai present scenario (WIND - 1,25x electrolysis size - PV 1x electrolysis size):

In Boegoebaai use case, considering a solar plant of 1 MW and a wind plant of 1,25 MW for 1 MW of electrolysis, the annual PV production estimated is 2313 MWh and the wind production is 636 MWh. From this data emerges that the best battery size choice is not so relevant (around 2.38 MWh), which provides a high H2 production of 49263 kg/year and an electrolyzer load of 55,68%, for the best value of LCOH of 8,57 €/kg.

Future scenario (WIND - 1,25x electrolysis size - PV 1x electrolysis size):

In 2040 time-horizon, the CAPEX reduction of hydrogen production, battery, wind and PV plant will decrease the LCOH to 6,90 €/kg.

Boegoebaai-further present scenario (only PV 1,5x electrolysis size):

Considering the high LCOE of wind power production around 247,66 €/MWh, a second scenario only driven by a 1,50 MW PV plant was assessed. By doing this variation, the annual PV production estimated is 3469,65 MWh with a battery size of 3,03 MWh. Hydrogen production increases to 59273 kg/year, LCOH reduces to 5,07 €/kg against 8,57 €/kg of previous scenario and annual load of the electrolyzer reduces a little to 53,57% due to the fact that PV plant does not produce at night.

Boegoebaai-further future scenario (only PV 1,5x electrolysis size):

In 2040 time-horizon, the CAPEX reduction of hydrogen production, battery and PV plant will decrease the LCOH to 3,88 €/kg.

4.2.2. Coega

The Coega Special Economic Zone (SEZ) is an industrial development initiative situated in the Eastern Cape Province near to Porth Elizabeth. Coega is an interesting hydrogen hotspot for its access to the Easter Cape and Western Cape markets, incentivised renewable energy production and local hydrogen uptake through the manufacturing industry, this area is, indeed, attracted interest from EU green hydrogen project promoters like HIVE Energy Furthermore, the location offers:

- Availability of land: around 90 km^2 of industrial park;
- Potential local demand of hydrogen for manufacturing sector such as Automotive, FMCG and Pharmaceuticals);
- RES potential: solar irradiance of 1800 kWh/m^2, wind speed around 6,7 m/s; ➢ Presence of infrastructure: Eastern transmission corridor, Port of Ngqura.

The figure below shows the average daily solar irradiance per each month and is useful to have an overview of the daily potential renewable energy production.

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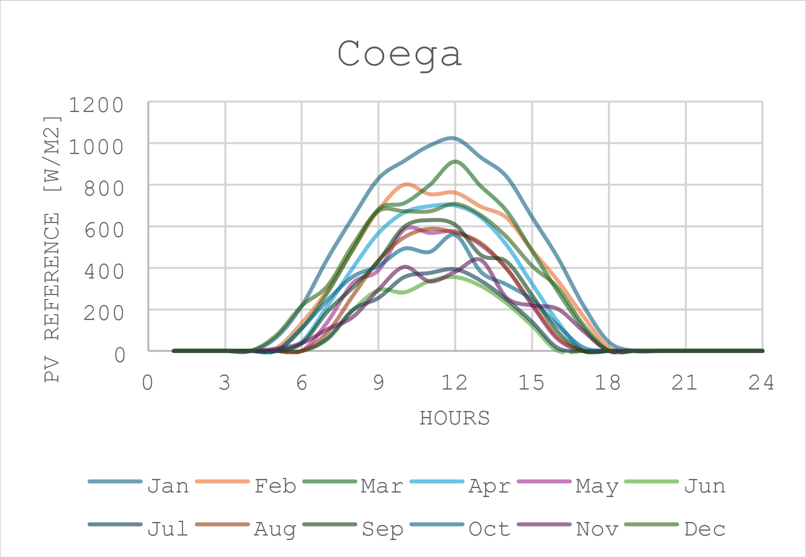

Figure 15: Coega daily solar irradiance in a typical monthly day

Coega present scenario (only PV 1,5x electrolysis size):

In Coega use case it has been considered a 1,5 MW of solar plant. However, PV EOH are less than 2000 hours/year (1827 hours) thus bringing to higher PV LCOE is high that drives LCOH over 6 €/kg (6,11€/kg). Therefore, in this case is preferred to not install the battery because of the savings in terms of battery CAPEX, even if that means renouncing to 540 MWh/year of RES, lowering ELY load to 45,78% (and its efficiency) and obtaining the LCOH at 6,38€/kg.

Future scenario (only PV 1,5x electrolysis size):

In 2040 time-horizon, the CAPEX reduction of hydrogen production, battery and PV plant will decrease the LCOH to 5,01 €/kg.

4.2.3. Saldanha Bay

Located in the Western Cape, this area already attracted the interest of different hydrogen project promoters like the Irish Phelan Green Energy and ArcelorMittal (for production of green steel at local level via green hydrogen driven DRI. Saldanha Bay dispose of:

- Land availability of 2015 km^2
- Potential local hydrogen demand by Steel (AMSA Green Steel project), Agriculture and Mining sectors
- RES potential: 2100 kWh/m^2 of solar, wind speed average of 7,7 m/s, renewables development zones of Overberg and Komsburg.

- Domestic and Export plans

The figure below shows the average daily solar irradiance and the wind speed per each month and are useful to have an overview of the daily potential renewable energy production.

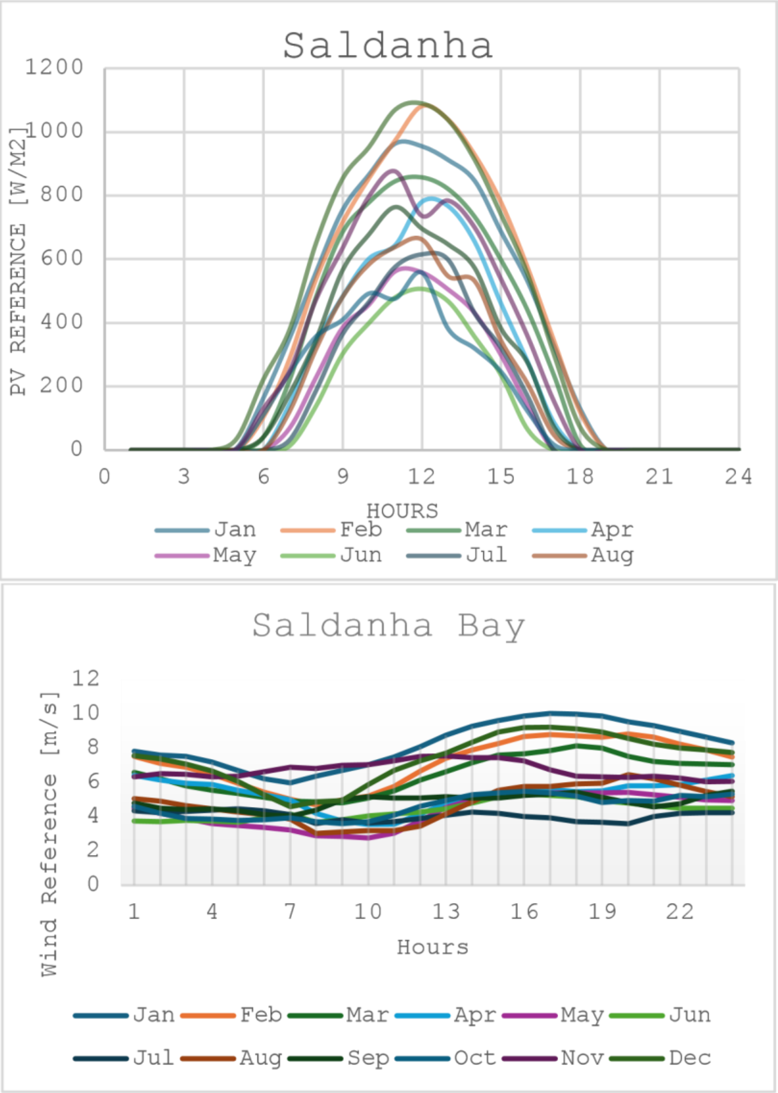

Figure 16: Saldanha Bay wind speed and daily solar irradiance in a typical monthly day

<u>Saldanha Bay present scenario (WIND - 1,25x electrolysis size - PV 1x electrolysis size):</u>

In Saldanha Bay use case, considering a wind plant of 1,25 MW and a solar plant of 1 MW for 1 MW of electrolysis, the annual wind production is 852 MWh and a PV production is 2243 MWh. The seasonal and daily fluctuation of solar energy is compensated by the wind plant which allows the installation of a not very large battery

(2,30 MWh), halving the battery CAPEX but still guaranteeing a fair number for H2 production (51363 kg/year) with a LCOH of 8,20 €/kg.

Future scenario (WIND - 1,25x electrolysis size - PV 1x electrolysis size):

In 2040 time-horizon, the CAPEX reduction of hydrogen production, battery and PV plant will decrease the LCOH to 6,60 €/kg.

4.3. Kenya use cases

4.3.1. Mombasa

Mombasa, situated in the coastal area in the southeastern part of the country, emerges as a potential hub for hydrogen production and export due to its proximity to essential transport networks and abundant water sources. As the premier port catering to the supply chain needs of Eastern Africa, Mombasa Port holds a pivotal position in facilitating trade among nations like Ethiopia, Uganda, South Sudan, Rwanda, Burundi, northern Tanzania, and the Democratic Republic of Congo. Its role extends beyond being the primary gateway; Mombasa is a linchpin for exports, handling various commodities like coffee, tea, and minerals. Simultaneously, it serves as a hub for imports, including vital substances like hydrogen, ammonia, methanol, and nitrogenous fertilizers. The existing infrastructure, including transport networks such as roads and railways, further bolsters Mombasa's significance as a key port for facilitating the import and export of goods, potentially including hydrogen-related products. As an added advantage the city's coastal position near seawater allows potential for electrolysis.

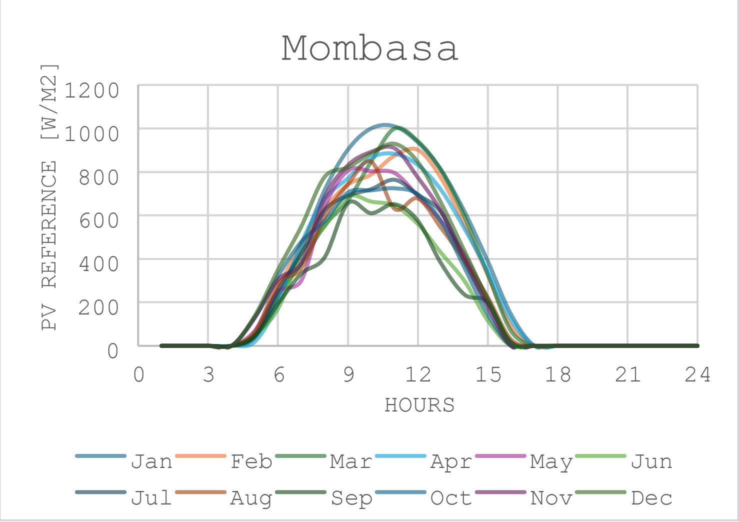

Figure 17: Mombasa daily solar irradiance in a typical monthly day

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Mombasa present scenario (only PV 1,5x electrolysis size):

Mombasa use case, considering a solar plant of 1,5 MW for 1 MW of electrolysis, presents high PV production (3529,43 MWh/year) and, thanks to its latitude, it can count on a low seasonal and daily fluctuation compared to Morocco and South Africa use cases. In this regard, an additional simulation is made reducing the battery to 1 MWh. However, results underline higher efficiency of the ELY and higher H2 production operating with a battery of 2,76 MWh achieving a LCOH of 4,80 €/ kg for an annual production of 58107 kg /year and an electrolyzer load of 54,88%.

Future scenario (only PV 1,5x electrolysis size):
In 2040 time-horizon, the CAPEX reduction of hydrogen production, battery and PV plant will decrease the LCOH to 3,68 €/kg.

4.3.2. Nairobi

Nairobi, Kenya's capital, serves as a central node with multiple power sources and well-developed infrastructure. Its strategic positioning in close proximity to power network nodes like Suswa and significant industrial parks makes it an attractive potential location for hydrogen production facilities. The city is also the primary aviation gateway in Kenya, Jomo Kenyatta International Airport (JKIA) plays a crucial role as a regional hub for air transport. While the direct transportation of hydrogen via aircraft might present challenges due to safety and logistics concerns, the airport's role extends beyond direct shipping. It serves as a vital logistical hub where hydrogen-related technologies, equipment, and expertise may be imported or exported, facilitating the development and expansion of the hydrogen sector in the region.

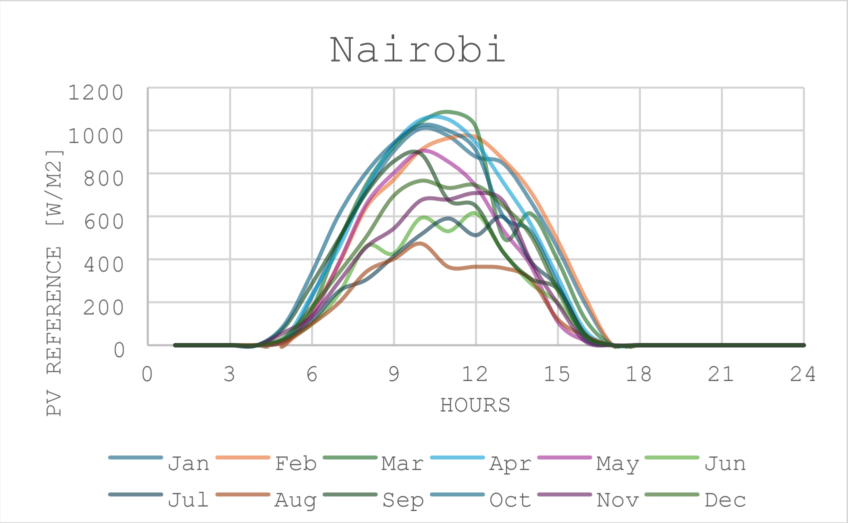

Figure 18: Nairobi daily solar irradiance in a typical monthly day

The figure above shows the average daily solar irradiance per each month and it is useful to have an overview of the daily potential renewable energy production in Nairobi.

Present scenario (only PV 1,5x electrolysis size):

Nairobi use case is similar to Mombasa case and considers a solar plant of 1,5 MW for 1 MW of electrolysis, the estimated PV production is of 3454 MWh/year accounting on a lower seasonal and daily fluctuation compared to Morocco and South Africa use cases with the possibility of installing then a limited battery (2,15 MWh). In this regard, an additional simulation is made reducing the battery to 1 MWh. Also in this case, results underline higher efficiency of the ELY and higher H2 production operating achieving a LCOH of 5,02 €/ kg for an annual production of 53842 kg /year and an electrolyzer load of 51,96%.

Future scenario (only PV 1,5x electrolysis size):
In 2040 time-horizon, the CAPEX reduction of hydrogen production, battery and PV plant will decrease the LCOH to 3,87 €/kg.

4.3.3. Olkaria

Situated within the Kenyan Rift Valley, Olkaria stands out as a region with immense geothermal energy potential. The area's high load factor of above 90% for geothermal energy production and accessibility to a large water body like Lake Naivasha and river streams position it as a lucrative site for establishing hydrogen production facilities. This hotspot benefits of the excess of geothermal power production usually not exploited during the night period. The study assumed 50 MW of the electrolyzer plant combining 50 MW of solar plant with 45 MW of wasted geothermal power from Olkaria 1 plant that is now renovating considering zero the LCOE of the geothermal, reason why LCOH are very low. Nevertheless, in Olkaria case is interesting to notice that the presence of geothermal energy (provided from 10pm to 6am) increases system reliability at night even without the presence of a battery.

The figure below shows the average daily solar irradiance per each month and the geothermal wasted daily potential per each month: these values are useful to have an overview of the daily potential renewable energy production.

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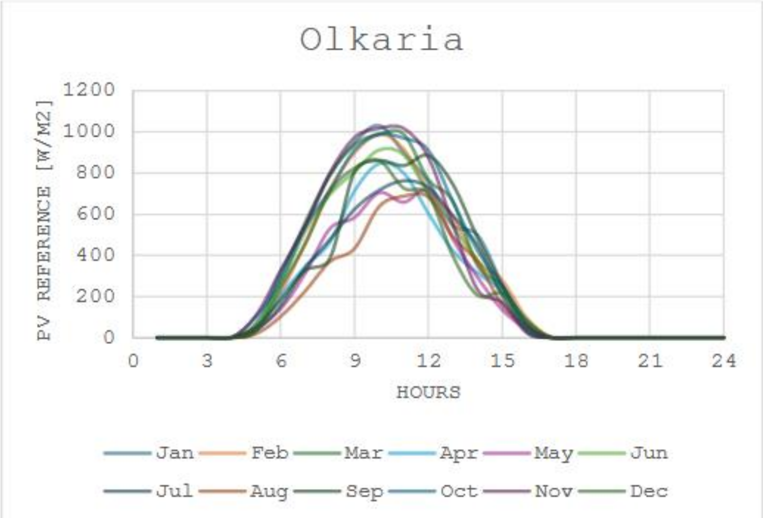

Figure 19: Olkaria daily solar irradiance in a typical monthly day

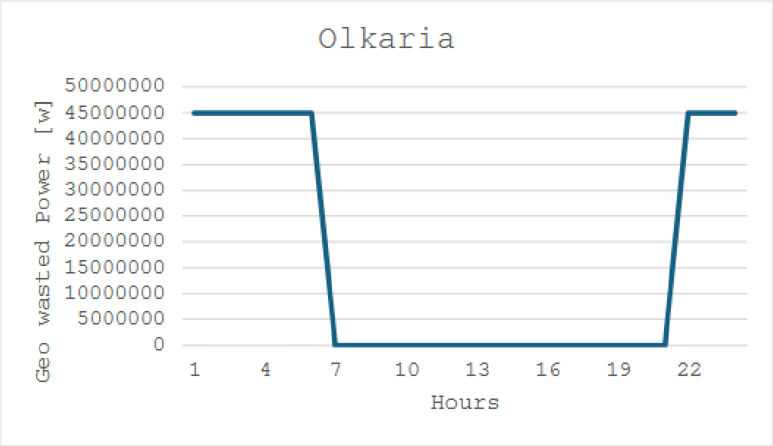

Figure 20: Olkaria daily wasted geothermal energy

Present scenario (PV 50x electrolysis size – GEO 45MW):

Differently than all the other scenarios, considering the relevant amount of “wasted power” present in Olkaria, Olkaria use case has been modelled considering a 50 PV Plant combined to 45 MW of geothermal plant providing Renewable power (more or less along whole day and night, thus not needing for a battery) to a 50 MW of electrolysis, at 54,34% of the load and with no battery, the total hydrogen production is 4123945 kg/year. PV production estimated is 116881 MWh/year while geothermal energy produces 136080 MWh/year. LCOH is 2,49 €/kg. It is relevant to consider that renewable energy sources not exploited are not low, but it should be considered that, currently, the geothermal energy utilized for this study would be lost.

Future scenario (PV 50x electrolysis size – GEO 45MW):
In 2040 time-horizon, the CAPEX reduction of hydrogen production, battery and PV plant will decrease the LCOH to 1,95 €/kg.

4.4. Results assessment and comparison

The aim of the presented analysis was to conduct a techno-economic assessment of Green Hydrogen potential in nine "Hydrogen Hotspots" selected by the JUST GREEN AFRH2ICA Consortium evaluating them mostly looking at LCOH as the main KPI for their comparison,in order to extrapolate guidelines for the the battery sizing to be coupled to local PEM electrolysers looking for the best-balanced-system in the current scenario and in 2040 time horizon.

The results of the analysis highlight that:

- **for Morocco**: the seasonality influences the solar power production making essential the battery support per each Use Case. In particular, in all the three analysed use cases, the battery has been sized on the average energy capacity value identified along the months.
  Tangier and Jorf Lasfar have similar situation characterized by a 1,5 MW of PV plant and a LCOH about 5 €/kg for present scenarios and dropping to around 4 €/kg in the future. In Dakhla wind potential (with EOH values lower than 2000 hours), appeared not relevant for H2 production but assured an improvement of EOH of the electrolyzer and, consequently, an enhancing of its efficiency. The LCOH is 7,04 €/kg for the current scenario (mostly due to higher values of wind LCOE driven by the aforementioned low operating timing of the wind turbines) and 5,65÷5 €/kg in the future.

- **South Africa**: it has a similar situation compared to Morocco in terms of seasonality underlining the needs of an "average size battery" presence per each Use Case. Even in South African context, the inputs of wind assessed in Boegoebaai in combination with PV does not look effective as hydrogen production values are similar to those ones evaluated for a PV paired with battery production plant. From the LCOH economic analysis this second option resulted more convenient.
  In Coega the current LCOH analysis shows values of over 6 €/kg caused by the low EOH of PV plant (less than 2000 hours) and around 5 €/kg in 2040 scenario. In that case is preferrable to not install a battery in order to save its CAPEX costs for a similar LCOH value.
  In Saldanha Bay wind plant energy generation allows the installation of a battery of average size instead of the maximum battery size, halving the battery CAPEX

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but still guaranteeing a fair number for H2 production. However, wind turbines installation costs lead LCOH to 8,20 €/kg nowadays and to 6,60 €/kg in the future.

- **Kenya:** its local latitude stabilizes solar power to seasonal's differences and day-night's fluctuation permitting to minimize the battery size only for daily management. Olkaria Case is peculiar due to the exploitation of geothermal energy that eliminates the needs of a battery. Geothermal energy recovered from Olkaria 1 power plant, provides a resilient power supply during the night from 10pm to 6am, when solar energy cannot be exploited. The study ideally assumed LCOE equal to zero achieving low values of LCOH (2,49 €/kg).

Tab. 2 – LCOH Comparison for present and future scenarios

								Present H2 cost	Future H2 cost
		Plant	MW	Plant	MW	Batt size	MWh	€/kg	€/kg
Morocco									
	Tangier	PV	1,50			avg	2,27	5,31	4,08
	Jorf Lasfar	PV	1,50			avg	2,53	5,03	3,68
	Dakhla	PV	1,00	Wind	1,25	avg	2,78	7,04	5,65
	Dakhla-bis	PV	1,25	Wind	1,00	avg	4,74	6,57	5,18
South Africa									
	Boegoebaai Bay	PV	1,00	Wind	1,25	avg	2,38	8,57	6,90
	Boegoebaai Bay-bis	PV	1,50			avg	3,03	5,07	3,88
	Coega	PV	1,50			none	0,00	6,38	5,01
	Saldanha Bay	PV	1,00	Wind	1,25	avg	2,30	8,20	6,60
Kenya									
	Mombasa	PV	1,50			avg - dev std	2,30	5,20	3,68
	Nairobi	PV	1,50			avg - dev std	2,15	5,02	3,87
	Olkaria	PV	50,00	Geo	45,00	none	0,00	2,49	1,95

To sum up, areas that are not in proximity to Equator suffer of solar energy fluctuation that can be solved by installing a battery of a relevant size, thus increasing from one side LCOE (and OPEX/RES fraction of the LCOH) but also increasing the electrolyser annual efficiency and production. Another approach to increase the annual efficiency of the electrolyser and its equivalent operating hours is the combination of PV plant with wind farms. However, wind power plants are more CAPEX Intensive than the PV plants thus, they should operate for over 2000 hours/year in order to not affect the LCOH results heavily.

In the Tab. 2 the comparison of the costs of hydrogen production between the different location under evaluation is shown.

Considering the present scenario the level of costs is between 5 €/kg to 8 €/kg with a decrease from 4 €/kg to 7€/kg in a time horizon of 2040. The last scenario evaluated (Olkaria – Kenya) seems to be the best case (from 2,5 €/kg to 2 €/kg) but the PV power plant installed is thirty time bigger than the other simulations due to the fact that in this area the aim is also to recover the geothermal energy of the existing plant.

In conclusion, Africa has a huge renewable potential for all the selected Uses Cases. In particular, for the nine selected areas, the elevated solar irradiance guarantees low LCOE for photovoltaic technology assuring advantageous values of LCOH (about 4-6 €/kg) even considering auxiliary costs of the plant and assuming an unfavorable efficiency related to the load of the electrolyser (about 58%). On the other hand, for the selected areas the solution to use wind power only is less convenient than the PV plants.

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5. TECHNO-ECONOMIC ASSESSMENT OF GREEN PRODUCTS PRODUCED EXPLOITING LOCALLY PRODUCED GREEN HYDROGEN

Starting from green hydrogen production costs assessed in Chapter 4, the goal of the analysis presented in this chapter is to benchmark the potential export from Africa to Europe of: i) green hydrogen produced, ii) enhanced environmental value goods and products (such as steel, cement, urea, ammonia, formaldehyde, methanol and refined gasoline) to be manufactured via the locally produced green hydrogen and subsequently transporting these finished products in Europe exploiting the already existing value chain in order to understand which of the products is most advantageous to be transported from AU to EU in terms of costs and carbon dioxide emissions. It is known, in fact, that some products are strongly influenced by the cost of hydrogen, making transport potentially unaffordable. Secondly, it is necessary to assess whether, for all countries, if it is actually convenient to export green hydrogen or whether, on the contrary, it is preferable to use them locally, given that transport costs of such molecula could be prohibitive

The aim of this study therefore is to carry out an economic analysis on the transport of green hydrogen and final products from the African to the European scenario.

Per each of the analysed products, it was first analyzed how much hydrogen is needed to make the production of these goods and how much CO2 is emitted during the production of one ton of each of them using “state of the art/fossil” methods. Subsequently, thanks to a proper market assessment, an economic analysis was carried out in order to evaluate the cost of production and transport of H2 and products from the African continent to the European continent, identifying Rotterdam and Genoa as the two “final hubs” destinations. The ultimate goal is therefore to understand, through a cost analysis, what should be done:

- Producing green hydrogen in African hubs and transporting it to Europe;
- Producing green hydrogen in African hubs, using it to produce, in African territory, the products mentioned above and subsequently transporting them to European territory.

Such analysis has been performed per each JUST GREEN AFRH2ICA Use Cases, starting from an assessment of locally available industries and from the LCOH evaluated in Chapter

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4. In this way it has been possible to define, per each UC, which product can be manufactured and then transfer it to Genova and Rotterdam via trucks (firsts) and ships or Natural gas pipelines subsequently.

In Fig.21, the overall picture of the products analysed in each use case is presented

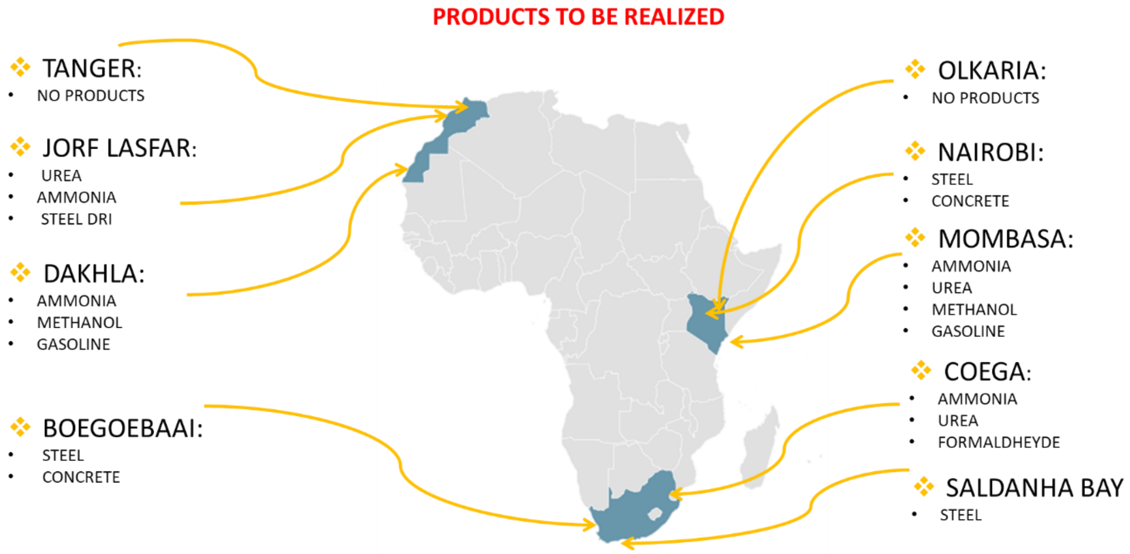

Figure 21: Overview of products analysed in each use case

5.1 Evaluation of need of hydrogen to produce the identified products

In order to assess the impact of the production of green hydrogen in the production chain of the products under analysis, the first objective is to understand how much hydrogen is needed to produce one ton of the products under analysis

5.1.1 STEEL

Steel is a metal alloy that is mainly composed of iron and carbon. In this alloy, carbon usually represents a variable percentage between 0.02% and 2.1% of the total weight.

Its production is a complex process that takes place inside a blast furnace at high temperatures, in which the reduction of iron ore, usually hematite ($Fe2O3$) or magnetite ($Fe3O4$), takes place, through the use of carbon monoxide (CO) with the production of metallic iron (Fe) and carbon dioxide ($CO2$).

Since steel is not directly produced from H2, to calculate the amount of H2 needed for the production of green steel, thus avoiding CO2 emissions, literature values were used that report the consumption of primary energy (natural gas or coal) used in combustion processes for steel production.

First, the energy consumption required to produce 1 ton of steel by the blast furnace process was determined, which is 24 GJ, equivalent to 24 MJ to produce 1 kg of steel.
The next step is to determine the amount of natural gas required, expressed in kg, to produce 1 kg of steel; taking into consideration, for all 3 nations the calorific value of natural gas in the Sahara area equal to 46.58 MJ/kg and assuming the same efficiency for the hydrogen and natural gas combustion system

$$\text{Natural gas required [kg]} = \frac{Energy\ Consumption[MJ]}{LHV\ Natural\ Gas[\frac{MJ}{Kg}]} = = \frac{24MJ}{46{,}58MJ/kg} = = 0.52 \text{ kg o}$$

After establishing the amount of natural gas needed to produce 1 kg of steel, it is necessary to consider hydrogen LHV, equal to 120 MJ/kg, and calculate the ratio between the two calorific values. The LHV ratio is given by:

$$\text{LHV ratio} = \frac{LHV\ H2}{LHV\ NG} = = \frac{120MJ/kg}{46{,}58MJ/kg} = 2.58$$

Using this ratio, the amount of hydrogen equivalent to produce 1 kg of final product can be determined:

$$\text{Mass of } H_2 \text{ required} = \frac{NG\ needed\ [kg]}{LHV\ Ratio} = \frac{0{,}52kg}{2{,}58} = 0.2\text{kg}$$

Therefore, 200 kg of hydrogen are needed to produce 1 ton of steel.

5.1.2 DRI STEEL

DRI steel, or Direct Reduced Iron, is a type of steel that is produced using the direct iron ore reduction process. This process is an alternative to the traditional blast furnace method.
Iron ore is reduced to metallic iron by the use of reducing gases, such as hydrogen and carbon monoxide, which are mainly produced from natural gas. This process takes place in a reactor called a direct reduction reactor or direct reduction furnace. Hydrogen can be used as a reducing agent to reduce iron oxides, producing metallic iron and water (H_2O):

a) **Calculation for Hematite (Fe2O3):**

$Fe2O3 + 3H2 \rightarrow 2Fe + 3H2O$

Molar Mass:

Molar mass of Fe_2O_3 = 2 × 55.85 (Fe) + 3 × 16 (O) = 159.7 g/mol
Molar mass of H_2 = 2 g/mol

Reaction and Stoichiometry:

1 mole of Fe_2O_3 requires 3 moles of H_2 to produce 2 moles of Fe.
Weight of 1 mole of Fe_2O_3 = 159.7 g
Weight of 3 moles of H_2 = 6 g

To obtain 2 moles of Fe (111.7 g), 6 g of H_2 is required.

Calculation for 1 ton of Fe:

1 ton (1,000 kg) of Fe requires the same amount in moles as molar mass. To obtain 1,000 kg of Fe, considering the efficiency of the process, we approximate the amount of hydrogen needed.

Fe moles=$\frac{1000g}{55,85g/mol}$= 17900mol Fe

According to the reaction, for 2 moles of Fe, 3 moles of H_2 are needed. So for 17,900 moles of Fe:

H_2 moles =17900 $* \frac{3}{2}$=26850mol ki H2

Mass of H_2 needed:

Mass in H_2=26850$mol * 2g/mol$=53700g

b) **Calculation for Magnetite (Fe_3O_4):**

Fe3O4 + 4H2 → 3Fe + 4H2O

Molar Mass:

1) Molar mass of Fe_3O_4 = 3 × 55.85 (Fe) + 4 × 16 (O) = 231.55 g/mol

Reaction and Stoichiometry:

1 mole of Fe_3O_4 requires 4 moles of H_2 to produce 3 moles of Fe.

Weight of 1 mole of Fe_3O_4 = 231.55 g

Weight of 4 moles of H_2 = 8 g

To obtain 3 moles of Fe (167.55 g), 8 g of H_2 is required.

Calculation for 1 ton of Fe:

To obtain 1,000 kg of Fe, considering the reduction process and efficiency, the amount of hydrogen needed is approximately similar to the estimate based on Fe_2O_3.

So about 50kg of H2 is needed to produce one ton of DRI steel.

5.1.3 AMMONIA

The production of ammonia (NH_3) through the synthesis process at Haber-Bosch requires hydrogen (H_2) and nitrogen (N_2) as feedstocks.

The synthesis of ammonia is described by the following balanced chemical reaction:

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$$N_2+3H_2 \rightarrow 2NH_3$$

Determination of the Stoichiometric Ratio

The reaction requires 3 moles of hydrogen (H_2) for every mole of nitrogen (N_2) to produce 2 moles of ammonia (NH_3).

Molar mass and stoichiometry:

Molar mass of H_2 = 2 g/mol

Molar mass of N_2 = 28 g/mol

For every mole of N_2, 3 moles of H_2 are needed.

Calculating the Amount of Hydrogen for a Specific Amount of Ammonia

Suppose we want to produce one ton of ammonia, then let's calculate the necessary amount of H2:

Molar mass of NH_3 = 14 (N) + 3 × 1 (H) = 17 g/mol

NH_3 Piers in 1 Ton:

$$\text{NH3 moles} =\frac{1000000g}{17g/mol}=58824 \text{ moles of NH3}$$

According to the reaction, 2 moles of NH_3 require 3 moles of H_2:

$$\text{H2 Moles}=58824mol * \frac{3}{2}= 88236\text{mol's H2}$$

Mass of H_2 required:

$$\text{Mass of H2}=88236mol * 2g/mol=176472\text{g H2}$$

So 176 kg of H2 is needed to produce one ton of ammonia.

5.1.4 UREA

Urea is a fundamental organic molecule in the nitrogen cycle and has many industrial and biological applications, especially being the basic component of most nitrate fertilizers on the market today, it is defined by the formula CH_4N_2O

Urea is produced industrially through two main processes:

Synthesis in Haber-Bosch:

Ammonia production: Nitrogen and hydrogen are combined to produce ammonia by Haber-Bosch's synthesis process.

$$N_2+3H_2 \rightarrow 2NH_3$$

Urea Synthesis:

Reaction of Ammonia with Carbon Dioxide: Ammonia is combined with carbon dioxide to produce urea and water.

$$2NH_3 + CO_2 \rightarrow CH_4N_2O + H_2O$$

Most industrially produced urea is used as fertilizer. It provides nitrogen to plants, an essential nutrient for growth.

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Determination of the Amount of Hydrogen

Calculation for Urea

Molar Mass:

Urea molar mass = 14 (N) + 2 × 1 (H) + 12 (C) + 16 (O) = 60 g/mol

Urea moles:

To produce 1 ton (1,000 kg) of urea:

Moles of urea=$\frac{1000000g}{60g/mol}$=16.667mol of Urea

Ammonia Needed:

Urea synthesis requires 2 moles of ammonia per 1 mole of urea:

NH3 moles =$16667mol * 2$= 33.334 NH3 mol

Hydrogen Needed for Ammonia Production:

Ammonia production requires 3 moles of H_2 for every mole of N2:

Moles of H2=$33.334mol * \frac{3}{2}$=50 mols of H2

Mass of H_2 required:

Mass in H2=$50mol * 2g/mol$= 100 g of H2

In summary, to produce 1 ton of urea, the calculated amount of hydrogen needed is 100 kg.

5.1.5 METHANOL

Methanol, also known as methyl alcohol, is a chemical compound with the molecular formula CH3OH. It is the simplest of alcohols and has numerous industrial and chemical applications, for example the production of formaldehyde.

The synthesis of methanol takes place according to the following reaction:

$$CO + 2H2 \rightarrow CH3OH$$

Determination of Molar Mass

Methanol molar mass of CH3OH:

C: 12 g/mol

H: 3 × 1 g/mol (per CH_3) + 1 g/mol (per OH) = 4 g/mol

O: 16 g/mol

Total = 12 + 4 + 16 = 32 g/mol

Calculation of Methanol Moles

To produce 1 ton (1,000 kg) of methanol:

MeOH Moles =$1.000.000g * 32g/mol$=31.250mol of CH3OH

Calculating the Amount of Hydrogen Needed

The reaction requires two moles of hydrogen for every mole of methanol:

H2 moles =$31.250mol * 2$= 62.500 mol H2

Molar mass of hydrogen (H_2) = 2 g/mol

H2 mass =$62.500 mol * 2 g/mol$=125000 g of H2

Therefore, about 125 kg of H2 are needed to produce 1 ton of Methanol.

5.1.6 FORMALDEHYDE

Formaldehyde is an organic chemical compound with the molecular formula CH_2O. It is a simple, highly reactive compound that comes in different chemical forms and has many industrial and commercial applications. Used for the production of resins such as urea-formaldehyde resin or used in building materials.

Production of Formaldehyde by Methanol Oxidation

Methanol is oxidized to produce formaldehyde and water:

$$2\ CH_3OH + O_2 \rightarrow 2\ CH_2O + 2\ H_2O$$

Determination of the Molar Mass of Formaldehyde.

Molar mass of formaldehyde (CH_2O): 30 g/mol

Calculation of Formaldehyde Moles

To produce 1 ton (1,000 kg) of formaldehyde:

Moles of formaldehyde =$\frac{1.000.000g}{30g/mol}$= 33.333mol

Determination of Methanol Moles Needed

From the chemical reaction, 2 moles of methanol produce 2 moles of formaldehyde. So, the moles of methanol needed are equal to the moles of formaldehyde:

Moles of methanol=33.333 moles of formaldehyde

Calculating the Hydrogen Moles Needed

From the process of synthesis of methanol, 2 moles of methanol are produced from 4 moles of hydrogen. Therefore

H2 moles = $33.333 mol * 2$=66.666mol

Calculating the Mass of Hydrogen Needed

Molar mass of hydrogen is 2 g/mol so

H2 mass =$66.666\text{mol} * 2\text{g/mol}$=133.333g

To produce 1 ton (1,000 kg) of formaldehyde, 133.3 kg of hydrogen is needed.

4.1.7 CEMENT

Cement is a building material, defined as a chemical compound based on calcium silicate, produced through a process of firing and grinding selected raw materials. Cement is mainly

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composed of a mixture of minerals and chemical materials that give the product its binding and hardening properties.

As done once analysing steel's hydrogen need, cement is not produced directly from hydrogen, which is why the same method used previously was used.

Cement production is a process that is less energy intensive than steel. The average energy consumption is about 4GJ of primary energy to obtain one ton of product, energy mainly used in combustion processes

By converting to obtain 1 kilogram of product, there will be an energy consumption of 4MJ.

The next step is the same as that used in section 4.1.1 to determine the amount of natural gas required, using the PCI of Sahara natural gas of 46.58 MJ/kg, using the formula:

$$\text{Natural gas required [Kg]}=\frac{Energy\ need\ [MJ]}{NG\ LHV\ [\frac{MJ}{kg}]}=\frac{4MJ/gg}{46{,}58MJ/gg}=0.09\text{ kg}$$

Using the previously calculated LHV ratio between NG and H2, it is possible to calculate, the amount of hydrogen equivalent to produce 1 kg of final product can be determined:

1) Mass of H_2 required $=\frac{NG\ Needed\ [kg]}{LHV\ ratio}=\frac{0{,}09\ kg}{2{,}58}=0.033\text{Kg}$

Therefore, 33.3 kg of hydrogen is needed to produce 1 ton of cement.

4.1.8 GASOLINE

To determine the amount of H2 needed to produce one ton of Gasoline (therefore about 1333 litres); it is possible to refer to the Methanol to-Gasoline(MTG) process, a technology that converts methanol into gasoline, mainly used for the production of liquid fuels from resources such as natural gas, coal or biomass. The MTG process takes place in two main phases:

1. **Hydrocarbon synthesis**: Methanol is first dehydrated to diethyl ether (DME), through the use of an aluminum-based catalyst, which subsequently undergoes further chemical reactions to form a mixture of light hydrocarbons.

$$2CH3OH \rightarrow CH3OCH3 + H2O$$

2. **Olefin Formation Read from DME:**

$$CH3OCH3 \rightarrow C2H4 + H20$$

Diethyl ether can decompose into light olefins such as ethylene (C_2H_4) under the action of a catalyst, such as ZSM-5.

3. **Oligomerization and Cyclo-Oligomerization of Olefins:**
   - Oligomerization of light olefins to form larger olefins:

$$3C2H4 \rightarrow C6H12$$

   - Cyclo-oligomerization and formation of cyclohexane:

$$C6H12 \rightarrow C6H10+H2$$

Light olefins such as ethylene can oligomerize to form hexen (e.g. 1-hexene). Hexene can then cyclize (cyclo-oligomerization) to form unsaturated cyclic compounds such as cyclohexene (C_6H_{10}), which can be further hydrogenated to produce cyclohexane (C_6H_{12}).

Determine the amount of H2 needed

Therefore, 6 molecules of CH_3OH are needed to produce 1 molecule of C_6H_{12}, thus knowing the mass of CH_3OH and C_6H_{12} under stoichiometric conditions:

1) $6CH_3OH = 192g$
2) $C_6H_{12} = 84g$

Considering that 18 molecules of H_2 are needed to produce 192g of Methanol, therefore 36g of H_2, from the methanol production reaction, through a ratio, it is possible to define the amount of H_2 necessary for the production of 1 ton of refined gasoline, which is a value equal to 428.57 kg of H_2

So to produce 1 ton of refined gasoline which is equivalent to about 1333 liters, it is necessary to use around 430 kg of H_2.

5.2 Evaluation of the amount of CO2 emitted by each process

In order to be able to assess the enhanced sustainability of the products analyzed in the various case studies thanks to the use of green hydrogen, it is important to be able to evaluate the amount of CO_2 emitted during the reference production process of the previously mentioned products.

In the production processes of products that involve combustion processes (steel and cement), CO_2 is essentially generated in the latter, while for synthetic products it is important to highlight that carbon dioxide emissions are closely related to the method used for the production of hydrogen.

When hydrogen is produced through steam reforming or by gasification of fossil fuels, CO_2 emissions tend to be relatively high. These methods, in fact, involve the conversion of natural gas or coal into hydrogen, with the consequent production of CO_2 as a by-product of the process.

On the contrary, if hydrogen is produced by water electrolysis, there are no CO_2 emissions into the air. This is especially true if the electricity used comes from renewable sources, such as wind or solar energy, making the entire hydrogen production process virtually free of environmental impact in terms of greenhouse gas emissions.

5.2.1 STEEL AND DRI STEEL

Steel production by blast furnace is extremely energy-intensive and involves the use of coke, a coal derivative, as the main reducing agent. This leads to significant carbon dioxide (CO_2) emissions. For every ton of steel produced using natural gas, the amount of CO_2 emitted

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amounts to 1400 kg. This value is calculated by multiplying the amount of natural gas needed to produce one ton of steel and then multiplying CO2/kgNG by 2.75kg, i.e. the amount of CO_2 emitted for each kilogram of natural gas used.

In the case of grey hydrogen, as a fuel, the amount of CO_2 emitted is calculated by multiplying the amount of hydrogen needed by 9kgCO2/kgH2, since this is the amount of CO_2 generated for each kilogram of hydrogen produced via steam reforming.

The amount of CO_2 emitted in the production of one ton of steel through the Direct Iron Reduction (DRI) process depends to a large extent on the type of reducing agent used and the overall efficiency of the process. The use of reductants such as natural gas makes DRI a less carbon-intensive solution than traditional methods, as it produces fewer carbon dioxide emissions.

The integration of the DRI process into the steel production cycle allows a significant reduction in CO_2 emissions, estimated at around 25%, compared to the traditional blast furnace (EAF) method. As a result, the amount of CO_2 emitted into the atmosphere during the production of one ton of steel via DRI is around 1.13 tons, depending on the technologies and feedstocks specifically used. This makes DRI not only a technologically advanced choice, but also a strategic solution for steel industries that intend to reduce their environmental impact, thus contributing to global decarbonization goals.

5.2.2 AMMONIA AND UREA

To accurately determine the amount of CO_2 emitted during the production of one ton of ammonia and one ton of urea, two main sources of emissions must be considered. The first concerns the production of hydrogen (H_2), an essential component in ammonia synthesis. The second is related to the process of separating nitrogen (N_2) from the air.

Hydrogen Production

The production of hydrogen, typically obtained through the **steam reforming** process of natural gas, is the most significant source of CO_2 emissions.

Chemical Reactions of the Steam Reforming Process

1. **Steam Reforming Reaction:**

$$CH_4+H_2O \rightarrow CO+3H_2$$

In this reaction, one mole of methane produces one mole of carbon monoxide and three moles of hydrogen.

2. **Water-Gas Shift Reaction:**

$$CO + H_2O \rightarrow CO_2 + H_2$$

Here, one mole of carbon monoxide reacts with one mole of steam to produce one mole of CO_2 and one mole of hydrogen.

Calculation of CO_2 Emissions:

Calculation of CO_2 Produced per Mole of Methane:

- **Steam Reforming:**

For every mole of methane (CH_4) consumed, 1 mole of carbon monoxide (CO) is produced.

- **Water-Gas Shift:**

Each mole of CO produced in the steam reforming phase is converted into one mole of CO_2.

Therefore, for every mole of methane used, 1 mole of CO_2 is produced.

1) The molar mass of methane (CH_4) is 16 g/mol.
2) The molar mass of CO_2 is 44 g/mol.

So, the amount of CO_2 produced by 1 mole of methane is 44 g of CO_2.

Calculation of CO_2 Emissions per Ton of Hydrogen Produced:

Calculating the Amount of Methane Needed:

The steam reforming reaction produces 3 moles of H_2 for every mole of methane.
The water gas shift reaction produces 1 mole of H2 for every mole of CO that is produced from one mole of methane.

So, to produce 1 mole of H_2, you need 0,25 mole of methane. Considering the molar mass of hydrogen (2 g/mol) and the molar mass of Methane (16 g/mol) it's easy to calculate that per each ton of Hydrogen, 2 tons of methane are needed.
Thus considering the emission factor of methane, the production of 1 ton of hydrogen (H_2) results in the emission of 9 tons of CO_2, and considering that 176 kg of hydrogen is required to produce 1 ton of ammonia (NH_3), it can be determined that the production of 176 kg of H_2 generates about 1584 kg of CO_2. In addition, about 100 kg of hydrogen are needed to produce 1 ton of Urea which generates about 900 kg of CO2.

Nitrogen Production

Nitrogen (N_2) separation does not directly generate CO_2, as the process does not involve chemical reactions that produce this gas. However, CO_2 emissions are related to the energy source used to power the separation process, especially if the energy comes from fossil fuels or coal.
Three main nitrogen separation processes were identified: fractional distillation, pressure swing adsorption (PSA) and separation membranes. However, only fractional distillation has actually been considered, as it is the most commonly used method.

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For the calculation of CO_2 emissions, the kg of CO_2 emitted per kWh of electricity produced in the following three countries were considered, using the emission factors of these countries:

- Morocco: 0.705 kg CO_2/kWh
- Kenya: 0.533 kg in CO_2/kWh
- South Africa: 1,013 kg CO_2/kWh.

Fractional distillation is a traditional technique that takes advantage of differences in the boiling points of various components of the air. In this process, the air is cooled to liquid, after which it is gradually heated in a distillation column. Nitrogen, having a lower boiling point than oxygen and other gases in the air, is separated into gaseous form in the early stages of heating. This method is very efficient and produces nitrogen with a high degree of purity, but requires considerable energy consumption.
Literature shows that a fractional distillation plant has an electricity consumption that varies between about 0.4 and 0.5 kWh per cubic meter (m^3) of nitrogen produced.
Given the nitrogen density of 1.25 kg/m^3, it is possible to calculate the energy consumption per kilogram of nitrogen (N_2) produced, equal to 0,36 kWh/lg of N2

By knowing the CO_2 emission factor for electricity produced in each country, it is possible to define the amount of CO_2 emitted for each kilogram of N_2 produced

MOROCCO: emission factor 0,705 kgCO2/kWh → 0,254 kg CO2/kgN2

KENYA: emission factor 0 533 kgCO2/kWh → 0,192 kg CO2/kgN2

SOUTH AFRICA: emission factor 1,013 kgCO2/kWh → 0,365 kg CO2/kgN2

Considering that approximately 823 kg of N_2 is required to produce one ton of ammonia, it is possible to determine the amount of CO_2 emitted to produce one ton of ammonia (NH_3) and urea, taking into account the CO_2 emission factor for each country's electricity and the amount of nitrogen required.

AMMONIA

- MOROCCO: 208.87 kg of CO2/tNH3
- KENYA: 157.92 kg of CO2/tNH3
- SOUTH AFRICA: 300.13 kg of CO2/tNH3

UREA:

- MOROCCO: 118 kg of CO2/tUREA
- KENYA: 89,3 of CO2/tUREA
- SOUTH AFRICA:169,58 kg of CO2/tUREA

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5.2.3 METHANOL AND FORMALDEHYDE

The reactions that lead to the formation of formaldehyde include two main steps: the first is the synthesis of methanol, while the second is the catalytic oxidation of methanol, which produces formaldehyde.

For every ton of methanol produced, CO_2 emissions come from the combustion of methane to produce the synthesis gas. The amount of CO_2 emitted can be calculated using typical emission coefficients and the chemical reactions involved.

To produce one ton of methanol, about 875 grams of carbon monoxide (CO) and about 500 grams of methane (CH_4) are needed.
From the water-gas shift reaction, it is possible to determine the amount of carbon dioxide (CO_2) emitted: it can be found that 1,400 grams of CO_2 are emitted for every 875 grams of CO used in the production of one ton of methanol.

To calculate the amount of CO_2 emitted in the production of one ton of formaldehyde, the production processes and the associated CO_2 emissions must be considered.

To produce 1 ton of formaldehyde, approximately 1.07 tons of methanol are required, based on the reaction ratio and process efficiency.

Using the average CO_2 emissions value (i.e. 1.4 tons of CO_2 per ton of methanol produced as referred above), it is possible to calculate the emissions for formaldehyde production.

$$\text{CO2 emissions}=1.49 \text{ tons of CO2 per ton of formaldehyde produced}$$

5.2.4 CEMENT

As regards the CO_2 emissions deriving from the production of one ton of cement, the same method was adopted as in the case of steel. First, the CO_2 emissions from the use of natural gas were calculated by multiplying the amount of natural gas used by 2.75 kgCO2/kgNG (Emission factor) thus obtaining a value of 235 kg. In the case of using grey hydrogen as fuel, the amount of hydrogen needed to produce one ton of cement was multiplied by 9kgCO2/kgH2, which represents the number of kilograms of CO_2 emitted for each kilogram of hydrogen produced, to obtain a value of 300kg.

5.2.5 GASOLINE

Burning one litre of petrol produces around 2.3 kg of CO_2. This value represents a general average, which may vary slightly depending on the specific combustion conditions and the type of gasoline.
To calculate the total CO_2 emissions associated with the production of gasoline in a more significant amount, such as one ton, we obviously need to use the gasoline density value of 0.72 ton/m^3. This conversion is crucial to make the correct calculations.

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Using the data mentioned above, we can determine the total amount of CO_2 emitted from the production of one ton assessing that the production of one ton of gasoline is responsible for the emission of 3067 kg of CO_2.

5.3 Evaluation of the product production costs

Following the preliminary calculation of the amount of hydrogen required for the production of products and carriers, as described in paragraph 5.1, it is possible to proceed with an in-depth economic analysis in order to determine the production cost of each of the products under analysis. This analysis will be based on the production costs of green hydrogen, previously calculated in chapter 4 in JUST GREEN AFRH2ICA Use cases.

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The analysis start with the determination of the production cost of a single ton of "grey" product, i.e. produced with conventional technologies, and the possible cost of a kilogram of hydrogen produced through steam reforming, assumed at $2/kg (market value).

Starting from this data and the amount of H2 needed to produce each product as per paragraph 5.1, it is possible proceed with the calculation of the cost of hydrogen needed to produce one ton of material.

The next step is to remove this cost from the overall cost of producing the ton of "grey material.". Once this is done, the cost of green hydrogen is added, which is calculated by multiplying the specific cost of one kilogram of green hydrogen for each production site and the amount of hydrogen needed to produce each ton of material.

The production costs for grey products, which will serve as a reference point and obtained via a specific literature and market assessment, are as follows:

- Steel: $550/t;
- DRI steel: $300/t;
- Ammonia: 441 $/t;
- Urea: $400/t;
- Metanolo: 336 $/t;
- Formaldehyde: 500 $/t;
- Cement: $130/t;
- Refined gasoline: $1580/t;

As regards the cost of steel and cement production, the figure obtained from the reference is based on processing from Natural Gas. To define the cost of production through the use of H2, the costs of natural gas must be removed and the costs of hydrogen must be added.

- Steel = 841$/ton = $\left(\frac{550\$}{ton} - \frac{108{,}2\$}{ton}\right) + \left(\frac{200kg}{ton} * \frac{2\$}{Kg}\right)$
- Cement = 176$/ton = $\left(\frac{130\$}{ton} - \frac{20\$}{ton}\right) + \left(\frac{33Kg}{ton} * \frac{2\$}{Kg}\right)$

By following these steps, it is possible to represent the final formula for each of the green materials analyzed.

Green product cost=$\left(Grey\ product\left[\frac{\$}{ton}\right] - H2\ needed\ [kg] * 2\$/kg\right) + (H2\ needed[kg] * Green\ H2\ LCOH\left[\frac{\$}{kg}\right])$

Finally, for each production site, using the relative LCOH, it was possible to define the production cost of green materials in that specific context and production area

- **Jorf Lasfar**

a) DRI Steel: 506.82 $/ton
b) Urea: 783 $/ton
c) Ammoniaca: 1115,8 $/ton

- **DAkhla-Layoune:**

a) Ammoniaca: 1468,84 $/ton
b) Metanolo: 930 $/ton

- **Mombasa:**

a) Ammonia: 933,8 $/ton
b) Urea: 680 $/ton
c) Metanhol: 686 $/ton

- **Nairobi:**

a) Steel: 1445 $/ton
b) Cement: 275.66 $/ton

- **Goega:**

a) Ammonia: 1164,36 $/ton
b) Urea: 811 $/ton
c) Formaldehyde: 1047,86 $/ton

- **Saldanha Bay:**

a) Steel:2081 $/ton

- **Boegoebaai Bay:**

a) Steel: 1455 $/ton
b) Cement: 277.31 $/ton

After determining the cost of the green product at each green hydrogen production site, the second analysis carried out focuses on two fundamental aspects. The first concerns the economic impact linked to the use of grey hydrogen/natural gas, in particular in the form of a Carbon Tax. This tax is applied for each tonne of grey material produced, considering a tariff of €70 for each tonne of CO_2 emitted.

To assess the impact of this tax, it was necessary to calculate the amount of CO_2 emitted per tonne of product, as explained in section 5.2. By multiplying the emission value by 70 €/t ($/t) of CO_2, it was possible to determine the additional amount that must be paid for the production of one tonne of grey product. This additional cost does not apply in the case of the green product, as CO_2 emissions are practically zero.

Now let's see the additional amount to be paid due to the Carbon Tax for the production of one ton of product; taking into account that CO2 emissions for ammonia and urea vary according to the country in which they are produced (due to the variation of the emission related to the production of Nitrogen via air separation unit).

- STEEL: 125 $/ton of product
- CEMENT: 20.79 $/ton of product
- DRI STEEL: 98 $/ton of product
- AMMONIA:

a) Morocco: 125.51 $/ton of product
b) Kenya: 121.87 $/Ton of product
c) South Africa: 131.88 $/Ton of product

- UREA:

a) Morocco: 71.26 $/Ton of product
b) Kenya: 69.23 $/Ton of product
c) South Africa: 74.83 $/Ton of product

- REFINED GASOLINE: 222,95 $/Ton of product
- METHANOL: 98 $/Ton of product
- FORMALDEHYDE: 104.3 $/Ton of product

This comparison highlights not only the environmental impact, but also the economic implications of choosing between green and grey hydrogen. While the production of grey hydrogen incurs significant additional costs due to CO_2 emissions, green hydrogen, due to its almost non-existent emissions, is not subject to such costs, making it a more economically and environmentally sustainable choice in the long term.

The second crucial aspect to consider concerns the percentage that the costs of grey and green hydrogen represent on the production cost of grey and green materials. This comparison makes it possible to accurately determine the incidence of the cost of hydrogen on the overall cost of production.

It is clear that, since the production cost of grey H2 is significantly lower than that of green H2, the incidence of the latter on the final cost of green products is much greater. In particular,

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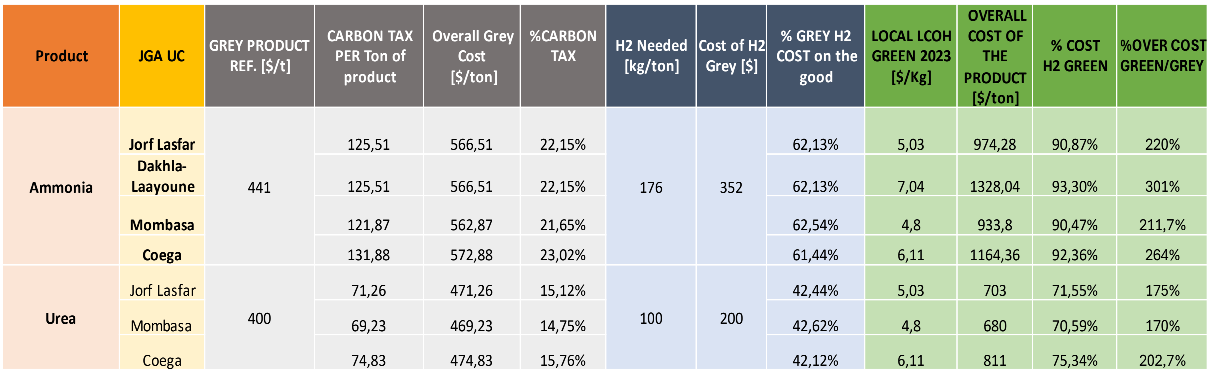
the weight of the cost of green H2 on the production cost of green products varies between 70% and 90%. On the contrary, the cost of grey H2 affects the cost of grey materials to a lesser extent, with a percentage that varies between 30% and 60%.

Take, for example, the case of Jorf Lasfar-Casablanca in Morocco, where the percentage of the cost of grey H2 for the production of one tonne of DRI steel is 36%. In comparison, the cost percentage of green H2 to produce one ton of green DRI steel rises to 59%. This figure underlines the importance of continuous technological development, which aims to reduce the cost of producing green H2. Only through these advances will it be possible to ensure that the incidence of the cost of green H2 on the final price of products approaches or equals that of grey hydrogen, produced through Steam Reforming.

In the next tables some comparisons for the different products are presented

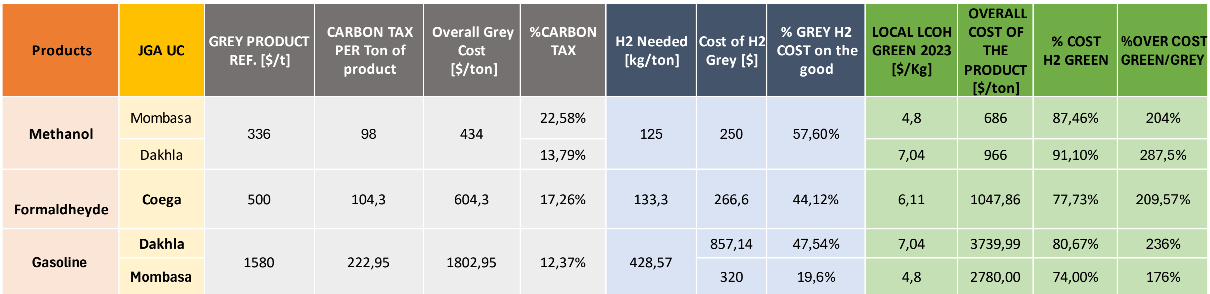
Product	JGA UC	GREY PRODUCT REF. [$/t]	CARBON TAX PER Ton of product	Overall Grey Cost [$/ton]	%CARBON TAX	H2 Needed [kg/ton]	Cost of H2 Grey [$]	% GREY H2 COST on the good	LOCAL LCOH GREEN 2023 [$/Kg]	OVERALL COST OF THE PRODUCT [$/ton]	% COST H2 GREEN	%OVER COST GREEN/GREY
Concrete	Nairobi	130	20,79	150,79	13,79%	33	66	15,38%	5,02	275,66	60%	156,6%
	Boegoebaai Bay								5,07	277,31	60,3%	157,56%
Steel	Nairobi	550	125,09	675,09	18,53%	200	320	19,6%	5,02	1445	69,4%	172%
	Saldanha Bay								8,2	2081	78,8%	247,44%
	Boegoebaai Bay								5,07	1455	69,6%	173%
Steel DRI	Jorf Lasfar	300	31,5	331,5	9,50%	54	108	32,58%	5,03	463,62	58,6%	154%

Figure 22: Overview of cost and emission of production of "Green products" → COMBUSTION PRODUCTS



Product	JGA UC	GREY PRODUCT REF. [$/t]	CARBON TAX PER Ton of product	Overall Grey Cost [$/ton]	%CARBON TAX	H2 Needed [kg/ton]	Cost of H2 Grey [$]	% GREY H2 COST on the good	LOCAL LCOH GREEN 2023 [$/Kg]	OVERALL COST OF THE PRODUCT [$/ton]	% COST H2 GREEN	%OVER COST GREEN/GREY
Ammonia	Jorf Lasfar	441	125,51	566,51	22,15%	176	352	62,13%	5,03	974,28	90,87%	220%
	Dakhla-Laayoune		125,51	566,51	22,15%			62,13%	7,04	1328,04	93,30%	301%
	Mombasa		121,87	562,87	21,65%			62,54%	4,8	933,8	90,47%	211,7%
	Coega		131,88	572,88	23,02%			61,44%	6,11	1164,36	92,36%	264%
Urea	Jorf Lasfar	400	71,26	471,26	15,12%	100	200	42,44%	5,03	703	71,55%	175%
	Mombasa		69,23	469,23	14,75%			42,62%	4,8	680	70,59%	170%
	Coega		74,83	474,83	15,76%			42,12%	6,11	811	75,34%	202,7%

Figure 23: Overview of cost and emission of production of "Green products" → N2+H2 SYNTHESIS PRODUCTS



Products	JGA UC	GREY PRODUCT REF. [$/t]	CARBON TAX PER Ton of product	Overall Grey Cost [$/ton]	%CARBON TAX	H2 Needed [kg/ton]	Cost of H2 Grey [$]	% GREY H2 COST on the good	LOCAL LCOH GREEN 2023 [$/Kg]	OVERALL COST OF THE PRODUCT [$/ton]	% COST H2 GREEN	%OVER COST GREEN/GREY
Methanol	Mombasa	336	98	434	22,58%	125	250	57,60%	4,8	686	87,46%	204%
	Dakhla				13,79%				7,04	966	91,10%	287,5%
Formaldheyde	Coega	500	104,3	604,3	17,26%	133,3	266,6	44,12%	6,11	1047,86	77,73%	209,57%
Gasoline	Dakhla	1580	222,95	1802,95	12,37%	428,57	857,14	47,54%	7,04	3739,99	80,67%	236%
	Mombasa						320	19,6%	4,8	2780,00	74,00%	176%

Figure 24: Overview of cost and emission of production of "Green products" → CO2+H2 SYNTHESIS PRODUCTS

5.4 Evaluation of transport costs

As previously mentioned, the overall economic assessment starts from the LCOH values presented in Chapter 4. In order to properly estimate the export scenarios, it has been then necessary to investigate the transport costs. This has been done via a market assessment as reported in the next paragraphs. Three possible methods of transporting hydrogen were investigated: by truck, by ship and by natural gas pipeline. Each of these methods has its own benefits and challenges, which have been analyzed in detail to identify the most efficient and sustainable solution based on the needs of the different products and use case.

Transport of H2 in existing Natural gas pipelines (also in accordance to D2.4) has been estimated around 0,1 – 0,3 €/kg H_2 /100 km.

For the other two transport options, the next paragraphs are introducing the assessment.

Two possible transport destinations have been identified: Rotterdam, Europe's main port and a strategic entry point for goods into Northern Europe, thanks to its privileged location and highly developed port infrastructure.

The second destination is Genoa, a significant port hub for maritime transport to southern Europe and the surrounding regions and equipped with modern port infrastructures capable of handling high volumes of traffic.

The transport cost analysis must consider various factors, including sea distances, modes of transport, loading and unloading costs, and port fees specific to each destination.

This analysis process (mainly based on the analysis of market costs and literature references) will provide a clear overview of the overall costs associated with the transport of hydrogen and the other products analyzed in this thesis from African production sites to European markets.

5.4.1 Transport by ships

First of all, per each JGA use case, the nearest port to the production sites was identified

Morocco

a) Tanger: the port of Tanger Med
b) Jorf Lasfar-Casablanca: il porto di El Jadida 30Km away
c) Dakhla-Layoune: Il Porto de Dakhla

Kenya

a) Olkaria: the port of Mombasa at 350Km
b) Mombasa: the port of Mombasa
c) Nairobi: the port of Mombasa at 480Km

South Africa

a) Goega: Porto di East London at 100Km

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b) Saldanha Bay: the Port of Saldanha
c) Boegoebaai Bay: the Port of Saldanha at 80Km

Subsequently, per each type of product, a different type of ship was identified, as each product comes in different forms.

For the transport of cement, steel, DRI steel and urea, two types of dry bulk carriers have been selected:

1. **MV Berge Sthal**: This vessel is classified as Capesize, one of the largest categories of cargo vessels, designed specifically for transporting large-volume cargo. Capesize ships typically have a length of more than 250 meters and a width that can exceed 40 meters, with high cargo capacities. In particular, the MV Berge Sthal has a capacity of 365,000 gross tonnage (DWT). However, to calculate net tonnage, i.e. the amount that can actually be transported, it is necessary to consider non-usable spaces, such as:

    - The engine room;
    - Ballast tanks;
    - Spaces and services for the crew;
    - Spaces for security equipment.

Through this analysis, 52% of unusable spaces were estimated, thus determining the amount of load that can actually be transported:

Net Tonnage = $365.000 * (1 - 0{,}52) = \ 176.000\ tonnes$

This type of ship is suitable for both long and shorter voyages; therefore, suitable for all three case studies.

Figure 25: Berge Sthal vessel

2. **MV Pacific Basin**: This is a Handysize vessel, a category of relatively small merchant vessels, valued for their versatility and ability to access smaller ports. The Handysize vessels are approximately 150 meters long and approximately 25 meters wide, with a gross cargo capacity of 33,000 DWT tons. To determine the net tonnage, 30% of unusable spaces are also considered:

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$$\text{Net Tonnage}=33.000 * (1 - 0{,}3) = 23.100\ tonnes$$

This type of ship is used exclusively for short voyages; therefore, it is only suitable for the Morocco case study.

Figure 26: MNV Pacific Basin

3. For the transport of refined gasoline, which has a density similar to that of oil, we considered the use of an Oil Tanker, precisely the **TI Africa**. These vessels specialize in transporting large quantities of crude oil or refined petroleum products. The TI Africa is known for its enormous size and transport capacity, with a length of around 380 meters, a width of 70 meters and a gross cargo capacity of 440,000 DWT tons. The net tonnage, considering 47% of unusable spaces is:

    1) $\text{Net Tonnage}=440.000 * (1 - 0{,}47) = 234.000 tonnes$

Figure 27: TI Africa Oil tanker

4. For the transport of ammonia, formaldehyde and methanol, which are also transported in liquid form, Chemical Tankers was selected. These tankers are designed to handle a wide range of chemicals, many of which can be corrosive, toxic, or flammable. An example of such a ship is the **Stolt Pride**, with a length of 180 meters, a width of 32 meters and a net cargo capacity of 45 thousand m^3

Knowing the density of these chemical materials, it is easy to determine the actual tons to be transported.

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a) Ammonia =30717 ton/$45000m^3 * 0{,}6826 ton/m^3$
b) Formaldheyde =48600 ton/$45000m^3 * 1{,}08\ t/m^3$
c) $45000m^3 * 0{,}792 ton/m$^3 MeOH = 35640 t

Figure 28: Stolt Comes vessel

5. Finally, a vessel specialising in the transport of liquefied hydrogen, the Suiso Frontier, was considered for the transport of hydrogen in liquid form, designed to handle the temperature and safety challenges associated with this type of fuel. The ship is equipped with insulated tanks to keep the hydrogen at a temperature of around -253°C. It has a length of about 116 meters, a width of 19 meters and a net load capacity of about 1250m^3 and considering the density of liquid hydrogen equal to 0.07085 then it is possible to transport about 88.56 tons of liquid H2.

Figure 29: SUSO Frontier vessel

After identifying the types of ships suitable for each product, carriers and hydrogen, a nautical simulator was used to calculate the distance between the various ports closest to the hydrogen hubs and the final destinations (Rotterdam and Genoa). To obtain the most accurate value possible, ten different measurements were taken for each route, then averaged and approximated the resulting value. In addition, two different types of routes have been defined for Kenya: the first consists of circumnavigating Africa, while the second involves passing through the Suez Canal until it reaches the Mediterranean Sea.

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MOROCCO

- Tanger:

i. From the Port of Tanger Med to the Port of Rotterdam = 2.500 km
ii. From the Port of Tanger Med to the Port of Rotterdam = 1.700 km

- Jorf Lasfaar-Casablanca:

i. From the Port of El-Jadida to the Port of Rotterdam = 2.500 km
ii. From the Port of El Jadida to the Port of Rotterdam = 1.700 km

- Example-Layoune:

i. From the Port of Dakhla to the Port of Rotterdam = 4.200 km
ii. From the Port of Dakhla to the Port of Genoa = 3.400 km

KENYA

1st ROUTE: Circumnavigation of Africa

- Olkaria/Mombasa/Nairobi:

a) From the Port of Mombasa to the Port of Rotterdam = 17.500 km
b) From the Port of Mombasa to the Port of Genoa = 16.700 km

2nd ROUTE: Passage through the Suez Canal

- Olkaria/Mombasa/Nairobi:

a) From the Port of Mombasa to the Port of Rotterdam = 12.000 km
b) From the Port of Mombasa to the Port of Genoa = 8.700 km

SOUTH AFRICA

- Goega

a) From the Port of East London to the Port of Rotterdam = 12800 km
b) From the Port of East London to the Port of Rotterdam = 12000 kmm

- Saldanha Bay/ Boegoebaai Bay

a) From the Port of Saldanha Bay to the Port of Rotterdam= 11200 km
b) From the Port of Saldanha Bay to the Port of Genoa = 10400 km

In the next step, for each ship identified above, the operating speed in knots was estimated, based on data from reliable sources. These speeds were then converted to kilometers per hour (km/h), to ensure a uniform understanding of the operational capabilities of the ships transporting the different products. This conversion and approximation allowed us to more accurately determine the time required for transports, improving the reliability of our logistics estimates.

- **MV Berge Sthal**: 13.5 nodi = 25 km/h
- **MV Pacific Basin**: 13 nodi = 24 km/h
- **TI Africa**: 16,5 nodi = 30,5 km/h

- **Stolt Pride:** 14 nodi =26 km/h
- **Suiso Frontier:** 13 nodi =24 km/h

After determining the operational speed of the ships and the distance they must travel to reach their final destination, it was crucial to calculate a crucial figure: the hours needed to complete the voyage, which were subsequently converted into days of navigation, to provide a clear estimate that can be used in logistical and operational planning.

MOROCCO

1) Tanger

HYDROGEN

a) To Rotterdam: **Suiso Frontier:** time[hours]=$\frac{2500\ km}{24\ km/h} = 104h$
b) To Genoa: **Suiso Frontier:** time[hours]=$\frac{1700\ km}{24\ km/h} = 70{,}8h$

2) Jorf Lasfaar:

HYDROGEN: same as Tanger

DRI STEEL AND UREA

a) To Rotterdam: **MV Berge Sthal**: time[hours]=$\frac{2500\ km}{25\ km/h} = 100h$
b) To Genoa: **MV Berge Sthal**: time[hours]=$\frac{1700\ km}{25\ km/h} = 68h$
c) To Rotterdam: **MV Pacific Basin**: time[hours]=$\frac{2500\ km}{24\ km/h} = 104{,}2h$
d) To Genova: **MV Pacific Basin**: time[hours]=$\frac{1700\ km}{24\ km/h} = 70{,}83h$

AMMONIA

a) To Rotterdam: **Stolt Pride:** time[hours]=$\frac{2500\ km}{26\ km/h} = 96h$
b) To Genoa: **Stolt Pride:** time[hours]=$\frac{1700\ km}{26km/h} = 65{,}4h$

3) Dakhla Layoune:

HYDROGEN

a) To Rotterdam: **Suiso Frontier:** time[hours]=$\frac{4200\ km}{24\ km/h} = 175h$
b) To Genoa: **Suiso Frontier:** time[hours]=$\frac{3400\ km}{24\ km/h} = 141{,}6h$

AMMONIA

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a) To Rotterdam: **Stolt Pride:** time[hours]=$\frac{4200\ km}{26\ km/h} = 161{,}5h$

b) To Genoa: **Stolt Pride:** time[hours]=$\frac{3400\ km}{26\ km/h} = 130{,}7h$

METHANOL

a) To Rotterdam: **Stolt Pride:** time[hours]=$\frac{4200\ km}{26\ km/h}$=161,5h

b) To Genoa: **Stolt Pride:** time[hours]=$\frac{3400\ km}{26\ km/h}$=130,7h

REFINED GASOLINE

a) To Rotterdam: **TI Africa:** time[hours]=$\frac{4200\ km}{30{,}5\ km/h} = 137{,}7h$

b) To Genoa: **TI Africa:** time[hours]=$\frac{3400\ km}{30{,}5\ km/h} = 111{,}5h$

KENYA

1) Olkaria

HYDROGEN

1ST ROUTE

a) To Rotterdam: **Suiso Frontier:** time[hours]=$\frac{17500km}{24\ km/h} = 730h$

b) To Genoa: **Suiso Frontier:** time[hours]=$\frac{16700\ km}{24\ km/h} = 695{,}8h$

2ND ROUTE

c) To Rotterdam: **Suiso Frontier:** time[hours]=$\frac{12000\ km}{24\ km/h} = 500h$

d) To Genoa: **Suiso Frontier:** time[hours]=$\frac{8700\ km}{24km/h} = 362{,}5h$

2) Mombasa:

HYDROGEN: as per Olkaria

AMMONIA

1ST ROUTE

a) To Rotterdam: **Stolt Pride:** time[hours]=$\frac{17500\ km}{26\ km/h} = 673h$

b) To Genoa: **Stolt Pride:** time[hours]=$\frac{16700\ km}{26\ km/h} = 643h$

2ND ROUTE

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c) To Rotterdam: **Stolt Pride:** time[hours]=$\frac{12000\ km}{26\ km/h} = 462h$

d) To Genoa: **Stolt Pride:** time[hours]=$\frac{8700\ km}{26\ km/h} = 334{,}6h$

UREA

1ST ROUTE

a) To Rotterdam: **MV Berge Sthal**: time[hours]=$\frac{17500\ km}{25\ km/h} = 700h$

b) To Genoa: **MV Berge Sthal**: time[hours]=$\frac{16700\ km}{25\ km/h} = 668h$

2ND ROUTE

c) Verso Rotterdam: **MV Berge Sthal**: time[hours]=$\frac{12000\ km}{25\ km/h} = 480h$

d) To Genoa: **MV Berge Sthal**: time[hours]=$\frac{8700\ km}{25\ km/h} = 348h$

METHANOL

1ST ROUTE

a) To Rotterdam: **Stolt Pride:** time[hours]=$\frac{17500\ km}{26\ km/h} = 673h$

b) To Genoa: **Stolt Pride:** time[hours]=$\frac{16700\ km}{26\ km/h} = 642h$

2ND ROUTE

c) To Rotterdam: **Stolt Pride:** time[hours]=$\frac{12000\ km}{26\ km/h} = 462h$

d) To Genoa: **Stolt Pride:** time[hours]=$\frac{8700\ km}{26\ km/h} = 334{,}6h$

REFINED GASOLINE

1ST ROUTE

a) To Rotterdam: **TI Africa:** time[hours]= $\frac{17500\ km}{30{,}5\ km/h} = 573{,}7h$

b) To Genoa: **TI Africa:** time[hours]=$\frac{16700\ lm}{30{,}5\ km/h} = 547{,}5h$

2ND ROUTE

c) To Rotterdam: **TI Africa:** time[hours]=$\frac{12000\ km}{30{,}5\ lm/h} = 393h$

d) To Genoa: **TI Africa:** time[hours]=$\frac{8700\ km}{30{,}5\ km/h} = 285h$

Nairobi

HYDROGEN: as per OLKARIA

STEEL AND CEMENT:

1ST ROUTE

a) To Rotterdam: **MV Berge Sthal**: time[hours]=$\frac{17500\ km}{25\ km/h} = 700h$

b) To Genoa: **MV Berge Sthal**: time[hours]=$\frac{16700\ km}{25\ km/h} = 668h$

2ND ROUTE

c) To Rotterdam: **MV Berge Sthal**: time[hours]=$\frac{12000\ lm}{25\ km/h} = 480h$

d) To Genoa: **MV Berge Sthal**: time[hours]=$\frac{8700\ km}{25\ km/h} = 348h$

SOUTH AFRICA

Goega:

HYDROGEN

a) To Rotterdam: **Suiso Frontier:** time[hours]=$\frac{12800\ km}{24\ km/h} = 533{,}3h$

b) To Genoa: **Suiso Frontier:** time[hours]=$\frac{12000\ km}{24\ km/h} = 500h$

UREA:

a) To Rotterdam: **MV Berge Sthal**: time[hours]=$\frac{12800\ km}{25\ km/h} = 512h$

b) To Genoa: **MV Berge Sthal**: time[hours]=$\frac{12000\ km}{25\ km/h} = 480h$

AMMONIA:

a) To Rotterdam: **MV Navigator Neptune:** time[hours]=$\frac{12800\ km}{26\ km/h} = 492h$

b) To Genova: **MV Navigator Neptune:** time[hours]=$\frac{12000\ km}{26\ km/h} = 461h$

FORMALDEHYDE:

a) To Rotterdam: **Stolt Pride:** time[hours]=$\frac{12800\ km}{26\ km/h} = 492h$

b) To Genoa: **Stolt Pride:** time[hours]=$\frac{12000\ km}{26\ km/h} = 461h$

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Saldanha Bay

HYDROGEN

a) To Rotterdam: **Suiso Frontier:** time[hours]=$\frac{11200\ km}{24\ km/h} = 466,6h$

b) To Genoa: **Suiso Frontier:** time[hours]=$\frac{10400\ km}{24\ km/h} = 433,33h$

STEEL

a) To Rotterdam: **MV Berge Sthal**: time[hours]=$\frac{11200\ km}{25\ km/h} = 448h$

b) To Genoa: **MV Berge Sthal**: time[hours]=$\frac{10400\ km}{25\ km/h} = 416h$

Boegoebaai Bay

HYDROGEN: as per Saldanha Bay

STEEL AND CEMENT: as per Saldanha Bay

This step is particularly useful because it allows you to accurately determine the days required for the ship to travel. By establishing the duration of the voyage and knowing the daily cost of chartering a vessel with the specific capabilities required, an accurate estimate of the total charter cost for the entire duration of the transport can be obtained. This calculation provides an overall and detailed view of the associated logistics costs, contributing to more efficient and informed economic planning. The data relating to the total rental cost for each route will be shown in the table at the end of the document. Below, the charter costs for a single day of the ships described in the previous paragraphs will be indicated.

- **MV Berge Sthal**: 35000 $/Day
- **MV Pacific Basin**: 20000 $/Day
- **TI Africa**: 85000 $/Day
- **Stolt Pride:** 25000 $/Day
- **Suiso Frontier:** 25000$/Day

After determining the charter cost of each vessel based on the planned route, calculated as the product of the daily charter cost and the number of days needed to reach the port of destination, and having already defined the Net Capacity in the previous pages, it is possible to calculate the transport cost for a single ton of product.

However, in addition to the cost of chartering a cargo ship, there are several additional costs that must be taken into account for a comprehensive assessment of operating expenses. Below is a list of the main additional costs:

- Fuel costs
- Port costs
- Labor costs

- Maintenance and repair costs
- Insurance

Additional costs to be considered included include those related to on-board personnel, port fees and the costs of loading and unloading goods. As for the staff, it was agreed to establish a uniform number of crew members for all ships, set at 25 people, with an average monthly salary of 6000 dollars. Subsequently, the total cost of the crew for the entire route was calculated using the following formula:

$$\text{Crew Cost [\$]} = \frac{N.personell\,[single\ person] * average\ salary\left[\frac{\$}{person}\right] * Sailing\ days[Day]}{Selling\ to\ trips[Day]}$$

In addition, a port fee and a fixed cost for loading and unloading goods of $10,000 were taken into account. Both of these costs were allocated according to the capacity of the vessel, expressed in tonnes, to determine the cost per tonne of product transported.
The cost of fuel consumption per tonne has been calculated separately from the additional costs. This calculation is based on the price per litre, which varies according to the type of fuel used: Bunker Fuel, Marine Diesel Oil and Low Sulphur Fuel Oil, with an average cost of about one dollar per litre. Next, the fuel consumption for each ship was determined, based on the cruising speed. For larger ships, such as the MV Berge Stahl and the TI Africa, consumption is about 400 liters per 100 km (i.e. 4 liters/km); while for smaller ships, such as the MV Pacific Basin, the Stolt Pride and the Suiso Frontier, consumption is about 200 liters per 100 km (2 liters/km).

Finally, the total fuel cost per ton of product was calculated using the appropriate formula.

$$\text{Fuel cost[\$/t]} = \frac{cost\ of\ fuel\left[\frac{\$}{l}\right] * fuel\ consumption\left[\frac{l}{Km}\right] * journey[Km]}{Capacity[tonn]}$$

Adding this figure to the additional costs and the cost of transporting a single ton of product, carriers and hydrogen, it was possible to determine the total cost of transporting one ton of each of them from African to European ports.

In this section, not only an economic analysis was carried out to determine the cost of transporting one tonne of material from the three African countries to the two European ports, but an environmental impact analysis was also carried out concerning the amount of CO2 emitted into the atmosphere. Starting from literature references, it was possible to estimate the amount of CO2 emitted per ton of product per kilometer traveled, obtaining a range between 10 and 40gCO2/Km per ton of tonnage, depending on the tonnage of the ship. An average value of 25 grams of CO2 emitted per tonne-kilometre was then chosen. Subsequently, this value was multiplied by the distance traveled and the tonnage of the individual ships, thus making it possible to determine the amount of CO2 emitted in kilograms per ton of product.

5.4.2 Transport by trucks

As highlighted at the beginning of the previous paragraph, some production sites of the various products are located in locations far from the ports from which ships depart for Rotterdam and Genoa. For this reason, a detailed economic analysis was conducted on the cost of transport by truck to the final destination.
Locations that are located far from the ports of departure include:

- **Morocco**: The town of Jorf Lasfar-Casablanca is located about 30 km from the port of El-Jadida, which is the nearest port.
- **Kenya**: For the city of Nairobi, the nearest port is Mombasa, 480 km away. Similarly, the town of Olkharia is located 350 km from the port of Mombasa itself.
- **South Africa**: The town of Goega is located 100 km from the port of East London, while BoegoeBaai Bay is 80 km from the port of Saldanha.

To optimize transport, the most suitable type of truck was identified based on the physical shape of the substances to be transported, distinguishing between solid and liquid materials.

- **Solid materials**: For the transport of cement, steel and urea, the Volvo FH was chosen, a five-axle flatbed truck with an authorised total weight of 26 GVW with a transportable load of 9 tonnes.

This truck operates at an average speed of 65 km/h, reaching a top speed of 80 km/h when fully loaded.

- **Liquid materials**: For the transport of liquid compounds such as ammonia, formaldehyde and methanol, a four-axle tanker truck, such as the Scania R-500, was selected, specifically designed for the transport of hazardous liquids. This vehicle travels at an average speed of 75 km/h and can reach a top speed of 90 km/h. In the case of substances that require special conditions, such as ammonia, which must be kept at -33°C to remain in liquid form, the empty weight of the truck is higher, as it includes cryogenic tanks and other necessary thermal devices.

When calculating the load capacity of the truck, an authorised net weight of 20 m^3 was taken into account. Knowing the density of liquid ammonia and formaldehyde we were easily able to determine the net load capacity in tons.

a) $20\ \mathrm{m3} * 0{,}682\ ton/\mathrm{m3}$: = 13,64 ton for Ammonia
b) 20 m^{3}* 1.08ton/ m^{3} = 21.6 ton for Formaldehyde

By considering the distance to be covered and the average speed of a fully loaded truck, it is possible to calculate the time required (in hours) to cover that distance. Next, using the daily rate for a 20-ton truck, we estimated the total cost per ton of product transported.
The comparison was made with the rental of a 20-ton truck in South Africa, where the estimated costs were as follows:

- **Daily rate**: 1600 South African rands, equivalent to about 80 euros per day.
- **Fare per kilometre**: 18 South African rands, equivalent to approximately 90 cents for each kilometre travelled.
- **Driver cost**: 650 South African rand per day, equivalent to about 35 euros for the route taken.

All these values were divided by the tons of material to be transported.
To calculate the cost of fuel per tonne of product, an average fuel price of $1.8 per litre was established, in line with current prices. The fuel consumption of a fully loaded truck has been estimated at 40 liters per 100 km, equivalent to about 0.4 liters per kilometer traveled.

Based on these two data:

$$\text{Fuel cost[\$/t]}=\frac{fuel\ specific\ cost\left[\frac{\$}{l}\right]*fuel\ consumption\left[\frac{l}{km}\right]*journey\ distance[\ km]}{load\ [tonne]}$$

When it comes to additional costs, it's crucial to consider the variation in tolls and the cost of truck maintenance that vary in relation to the distance traveled. Road toll rates can vary significantly depending on the length of the journey: longer distances result in higher toll costs, while shorter journeys generally result in lower expenses.

a) For long distances: 100/120$
b) For medium distances: around $55
c) For short distances: around $35

From the combination of the five calculated data: daily rate, rate per kilometer, driver rate, fuel cost and additional costs, it is possible to determine the cost of road transport per ton of material.

Hydrogen can be transported by trucks both compressed in trailers as well as liquified.

Some of the production sites are located at a significant distance from the ports of Rotterdam and Genoa, which are the main starting points for the shipment of our products, carriers and hydrogen to international destinations. As is already the case with products and carriers, hydrogen also needs to be transported safely to these ports, and for this reason we have adopted cutting-edge logistics solutions.

For the transport of hydrogen, we use a specialized tanker truck, the Scania R-500, which is particularly suitable for transporting liquid materials. This truck is equipped with a tanker with a higher capacity than those used for other materials, capable of holding up to 60,000 liters. This increased capacity is necessary due to the low volumetric density of hydrogen when it is kept at very low temperatures, about -253°C, to remain in a liquid state.

At these extreme temperatures, hydrogen has a density of around 0.0708 tonnes per cubic metre, which means that, despite the tanker's high litre capacity, the total weight of the transportable load is limited to around 1.42 tonnes.

As indicated above, the distances to be covered for each truck have been identified, respectively:

- From Jorf Lasfar-Casablanca to Porto di El-Jadida: 30Km
- From Olkaria to Mombasa Port: 350Km
- From Nairobi to Mombasa Port: 480Km
- From Goega to East London Port: 100Km
- The Boegoebai Bay of El Porto's Saldanha: 80km

One of the key aspects is the travel time, which can be calculated by knowing the distance to be traveled and the average speed of the truck. Once we have the journey time, we can continue with the determination of the costs associated with the transport itself.

To illustrate the process, let's take as an example the offer found on the "Gas Tankers Rentals" website, which specializes in renting tankers made from high-quality materials. In particular, we found an offer for the rental of a tank used for transporting gas with a capacity of 60,000 liters at a cost of about 3650 euros per month. To get the daily rental cost, just divide the monthly amount by 30, the average number of days in a month. Thus, the daily rental cost stands at about 125 dollars and is subsequently multiplied by 1.5 to be able to transport liquid hydrogen. However, it is not enough to just consider the cost of renting the tank. It is crucial to add other expense factors, such as the cost of fuel, which must be calculated separately as stated in the paragraph. Added to this is the driver's daily salary with the same rate previously assumed. Finally, we must consider additional costs, such as motorway tolls, which can vary depending on the route and the motorway sections used.

To determine the additional costs, an estimate was made based on the distance to be travelled. As a result, the costs for a truck that travels 480 km are higher than the costs for a truck that has to travel 30 km. Especially:

- For a distance of 480 km, additional costs of $120 were considered.
- For a distance of 30 km, additional costs of $35 were considered.
- For a distance of 100 km, additional costs of 55 dollars were considered.

By integrating all these factors: truck rental, rate per kilometer, fuel, driver's salary, additional costs, we get a clear and complete view of the total cost of transporting the single ton of liquid hydrogen.

Similarly to what was done for maritime transport, an environmental analysis was also conducted for the transport of products, carriers and hydrogen by truck. This analysis made it possible to determine the amount of CO_2 emitted per tonne of product transported per kilometre travelled, equal to 62 g of CO_2. Next, this value was multiplied by the total distance of the route and converted from grams to kilograms, dividing the result by 1,000. In this way, it was possible to calculate the total amount of CO_2 emitted for each tonne of material transported along the entire route.

5.5 Overall Economic and Environmental Assessment for the Project Use Cases

In this chapter are reported for each product under analysis, the estimates of costs and CO2 emissions relating to the production and transport of the various products from the African case study sites to Genoa and Rotterdam.

For each product, there are two tables: in the first table, both an economic and environmental analysis is presented regarding the transport of products, carriers and hydrogen. In particular, the total cost of transport will be assessed, which results from the sum of the costs of transport by ship and by truck to the production sites that require these services. This will make it possible to identify which method of transport is actually more advantageous. At the same time, the environmental impact will be examined, calculating CO2 emissions.

Subsequently, in the second table, the results obtained will be integrated with those concerning the production costs for each ton of product or carriers. The main objective of this part of the analysis is to understand the specific weight of hydrogen on production and transport costs, determining how much these factors affect the total export price of materials produced in these countries.

In addition, an environmental analysis will be conducted to define the total amount of CO2 emitted. For products made using green hydrogen, emissions related to production are practically zero; therefore, it will be crucial to consider only those related to transport. In this regard, we aim to answer an essential question: what is the environmental impact of transporting a green product compared to the production and transport of a grey product, considering that the amount of CO2 emitted during transport is identical for both types of product?

These analyses will allow us to obtain a clear and detailed view of the economic costs and environmental impacts associated with each method of transport and production. In addition, they will provide the basis for informed decisions, oriented not only towards economic efficiency, but also towards environmental sustainability, with the aim of promoting more advantageous and environmentally responsible solutions.

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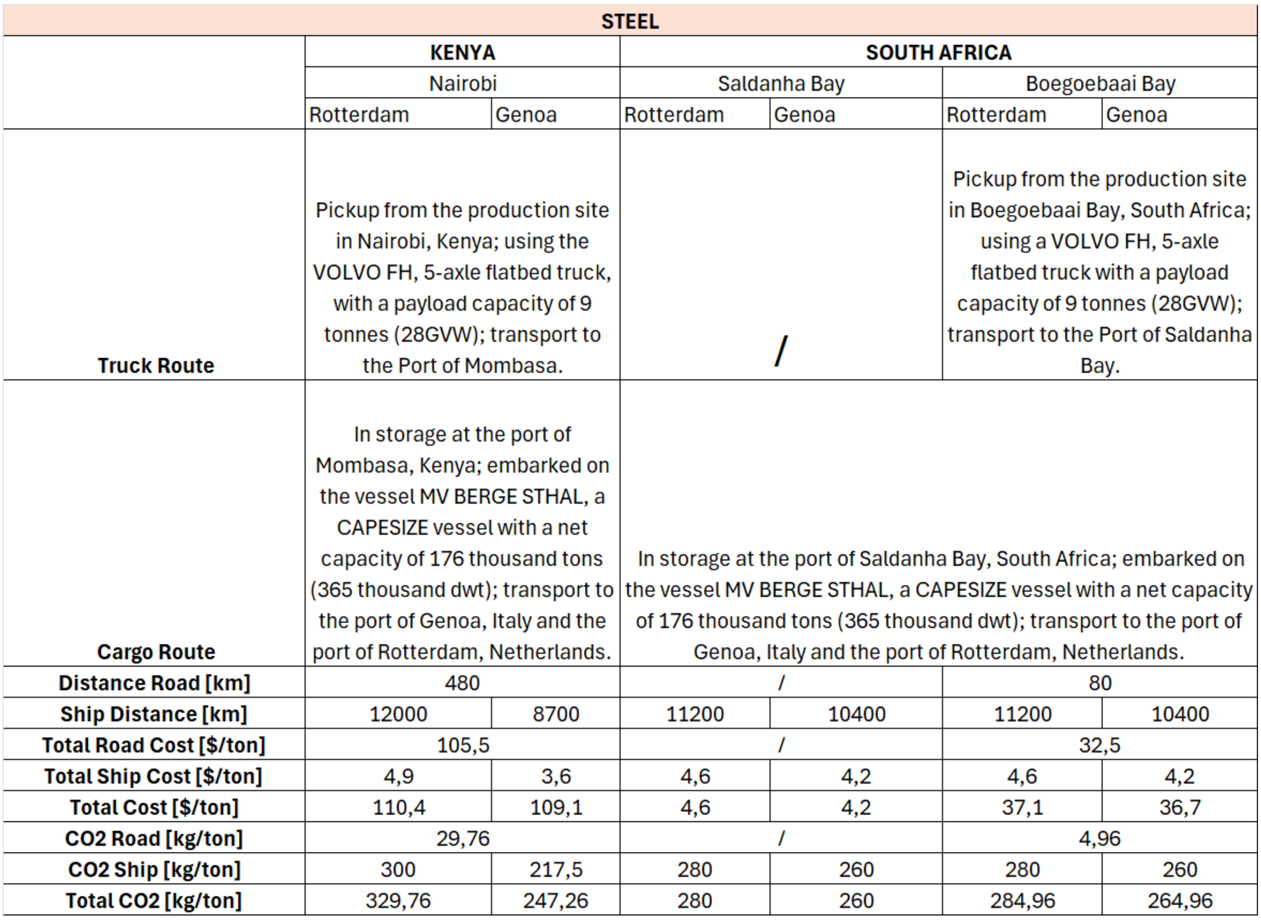
5.5.1 STEEL



STEEL						
	KENYA		SOUTH AFRICA			
	Nairobi		Saldanha Bay		Boegoebaai Bay	
	Rotterdam	Genoa	Rotterdam	Genoa	Rotterdam	Genoa
Truck Route	Pickup from the production site in Nairobi, Kenya; using the VOLVO FH, 5-axle flatbed truck, with a payload capacity of 9 tonnes (28GVW); transport to the Port of Mombasa.		/		Pickup from the production site in Boegoebaai Bay, South Africa; using a VOLVO FH, 5-axle flatbed truck with a payload capacity of 9 tonnes (28GVW); transport to the Port of Saldanha Bay.	
Cargo Route	In storage at the port of Mombasa, Kenya; embarked on the vessel MV BERGE STHAL, a CAPESIZE vessel with a net capacity of 176 thousand tons (365 thousand dwt); transport to the port of Genoa, Italy and the port of Rotterdam, Netherlands.		In storage at the port of Saldanha Bay, South Africa; embarked on the vessel MV BERGE STHAL, a CAPESIZE vessel with a net capacity of 176 thousand tons (365 thousand dwt); transport to the port of Genoa, Italy and the port of Rotterdam, Netherlands.			
Distance Road [km]	480		/		80	
Ship Distance [km]	12000	8700	11200	10400	11200	10400
Total Road Cost [$/ton]	105,5		/		32,5	
Total Ship Cost [$/ton]	4,9	3,6	4,6	4,2	4,6	4,2
Total Cost [$/ton]	110,4	109,1	4,6	4,2	37,1	36,7
CO2 Road [kg/ton]	29,76		/		4,96	
CO2 Ship [kg/ton]	300	217,5	280	260	280	260
Total CO2 [kg/ton]	329,76	247,26	280	260	284,96	264,96

Tab,3 Steel transport assessment

As you can see from the table, the total cost of transporting steel varies significantly depending on the location of departure

The main difference between these costs lies in the geographical location of the production sites. The green steel production site in Saldanha Bay is located in close proximity to the port, which significantly reduces transportation costs. In contrast, the sites of Nairobi and Boegoebaai Bay are located inland, with Nairobi particularly far from the main ports, which greatly affects transport costs, making the total cost of transport from Nairobi significantly higher. It is important to note that, for the Nairobi site, the transport of the final product represents approximately 95.5% of the total transport cost, given by the ratio between the transport cost by truck and the total cost.

However, unlike costs, the environmental impact of transport does not show such a marked difference. This is due to the fact that the CO2 emissions generated by truck transport, although existing, are relatively low. Consequently, even if the distances covered are high, the impact on the overall environmental impact is not particularly significant.

In summary, while transport costs vary substantially depending on the distance and geographical location of the production sites, the environmental impact remains smaller,

demonstrating that the location of the sites affects economic costs more than environmental costs.
For this reason, the use of green steel for Nairobi could be very useful on site, avoiding export.

STEEL				
		KENYA	SOUTH AFRICA	
		Nairobi	Saldanha Bay	Boegoebaai Bay
LCOH Green [$/kg H2]		5,02	8,2	5,07
Production cost [$/ton]		1033,2	1542	1041,2
% Cost H2 Green		77,00%	85,00%	78,00%
CO2 produced [kg of CO2/ton of product]		1787,04		
% CO2 saving		126,00%		
TOTAL COST EXPORT GREEN PRODUCT	Rotterdam	1143,6	1546,6	1078,3
	Genoa	1142,3	1546,2	1077,9
CO2 TOTAL EXPORT GREEN PRODUCT	Rotterdam	329,76	280	284,96
	Genoa	247,26	260	264,96
% COST H2 GREEN	Rotterdam	90,35%	99,70%	96,56%
	Genoa	90,45%	99,73%	96,60%
% TRANSPORT COST	Rotterdam	9,65%	0,30%	3,44%
	Genoa	9,55%	0,27%	3,40%
% CO2 Emitted transport and CO2 Emitted non green	Rotterdam	15,58%	13,55%	13,75%
	Genoa	12,15%	12,70%	12,91%

Tab,4 Steel Assessment (Benchmark between green and grey products)

A relevant figure to consider in the analysis is the percentage of CO2 saved, which in this case is extremely high, equal to 126%. This figure indicates that the production of one ton of grey steel involves a very high emission of CO2, making the hypothesis of producing green steel particularly advantageous from an environmental point of view, since the production of green steel does not involve CO2 emissions.
The second significant figure concerns the percentage relating to the production cost of green steel compared to the total cost. In all three cases analyzed, the cost of production represents more than 96% of the total cost. As a result, a reduction in the production cost of green hydrogen would lead to a decrease in the incidence of production cost on the overall cost. On an environmental level, the percentage of CO2 deriving from transport does not significantly affect the total emissions of production. In light of these data, it is clear that green steel production is essential to reduce CO2 emissions.
As for the production site in Kenya, the ideal option would be to use locally produced green steel, avoiding transport by truck, which would involve too high costs. With regard to the two South African production sites, the transport of green steel is advantageous for both countries; however, in the case of the Saldanha Bay site, the cost of production is currently too high due to the high cost of producing green hydrogen. In the future, however, this site could become a strategic port for global exports, if the cost of producing green hydrogen can be reduced.

As for Boegoebaai Bay, the goal should be to reduce the cost of land transportation, given that the cost of production is advantageous. Therefore, this site could represent the best solution for transporting green steel from Africa to European countries, guaranteeing both the lowest CO2 emissions and the lowest total costs.

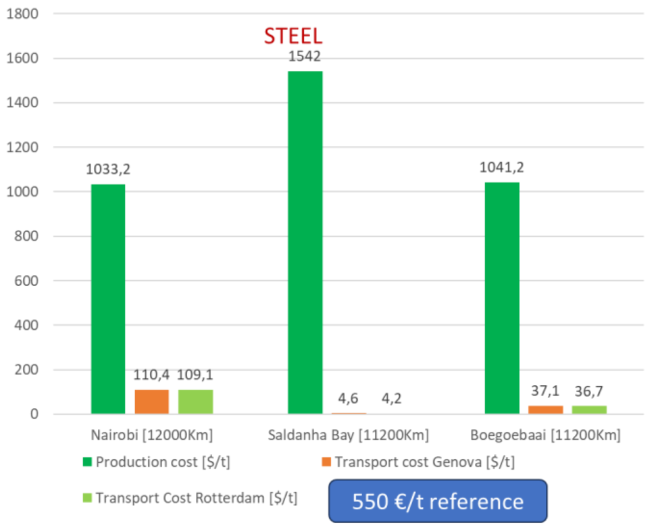
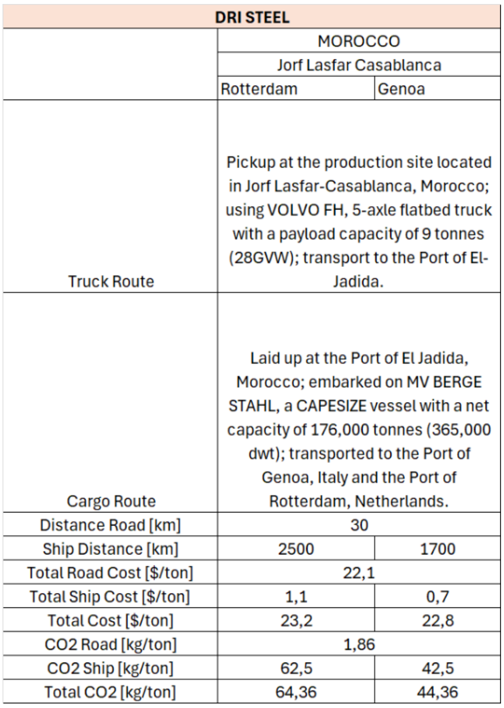


Figure 30: Overall cost assessment for Steel

5.5.2 DRI STEEL



DRI STEEL		
	MOROCCO	
	Jorf Lasfar Casablanca	
	Rotterdam	Genoa
Truck Route	Pickup at the production site located in Jorf Lasfar-Casablanca, Morocco; using VOLVO FH, 5-axle flatbed truck with a payload capacity of 9 tonnes (28GVW); transport to the Port of El-Jadida.	
Cargo Route	Laid up at the Port of El Jadida, Morocco; embarked on MV BERGE STAHL, a CAPESIZE vessel with a net capacity of 176,000 tonnes (365,000 dwt); transported to the Port of Genoa, Italy and the Port of Rotterdam, Netherlands.	
Distance Road [km]	30	
Ship Distance [km]	2500	1700
Total Road Cost [$/ton]	22,1	
Total Ship Cost [$/ton]	1,1	0,7
Total Cost [$/ton]	23,2	22,8
CO2 Road [kg/ton]	1,86	
CO2 Ship [kg/ton]	62,5	42,5
Total CO2 [kg/ton]	64,36	44,36

Table 5 DRI Steel Transport Assessment

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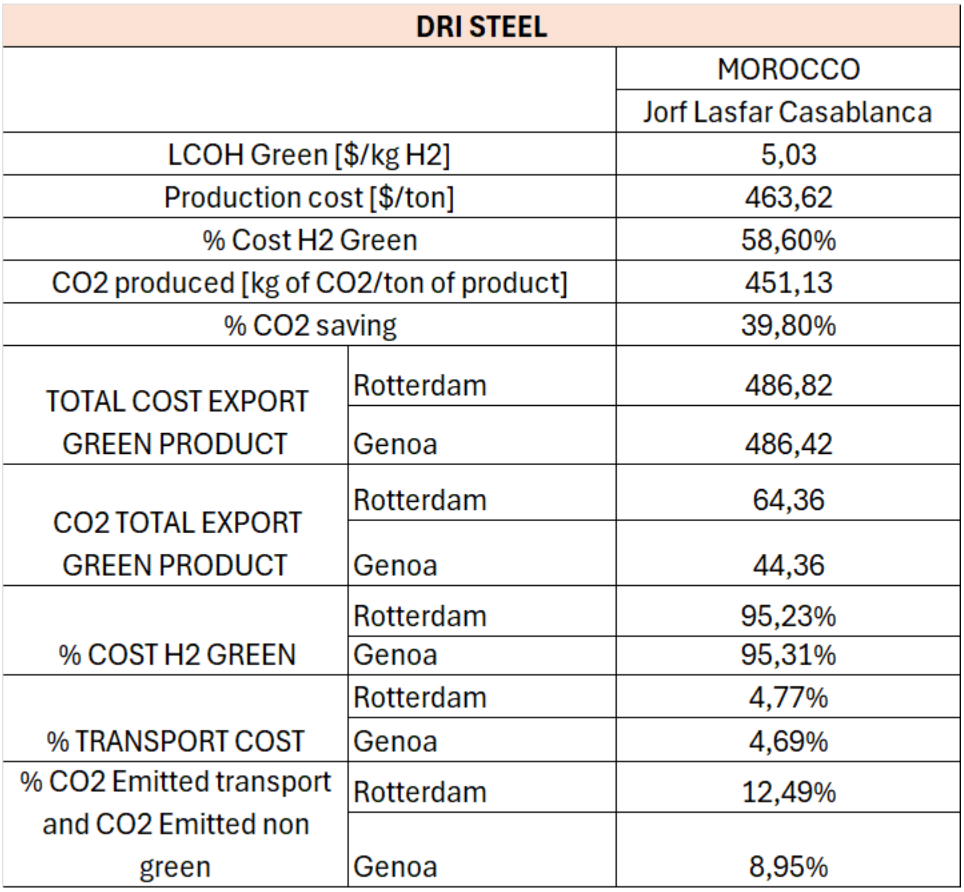
As for DRI steel, production in Africa is concentrated in a single site located in Jorf Lasfar, near Casablanca. The cost of transport is relatively low, especially by ship, since the distances from the final ports are very small. Also from an environmental point of view, the CO2 emissions associated with the transport of DRI steel are significantly lower, accounting for about 1/6 of those previously observed for traditional steel.



DRI STEEL		
		MOROCCO
		Jorf Lasfar Casablanca
LCOH Green [$/kg H2]		5,03
Production cost [$/ton]		463,62
% Cost H2 Green		58,60%
CO2 produced [kg of CO2/ton of product]		451,13
% CO2 saving		39,80%
TOTAL COST EXPORT GREEN PRODUCT	Rotterdam	486,82
	Genoa	486,42
CO2 TOTAL EXPORT GREEN PRODUCT	Rotterdam	64,36
	Genoa	44,36
% COST H2 GREEN	Rotterdam	95,23%
	Genoa	95,31%
% TRANSPORT COST	Rotterdam	4,77%
	Genoa	4,69%
% CO2 Emitted transport and CO2 Emitted non green	Rotterdam	12,49%
	Genoa	8,95%

Table 6 DRI Steel Assessment (Benchmark between green and grey products)

As we can see, the CO2 emissions related to the production of DRI green steel are significantly lower than those of traditional production. As a result, the percentage of CO2 saved in the production of DRI green steel stands at 40%. On an environmental level, CO2 emissions from the transport of DRI steel are slightly lower than those of cement, thanks to the lower emissions associated with transport.

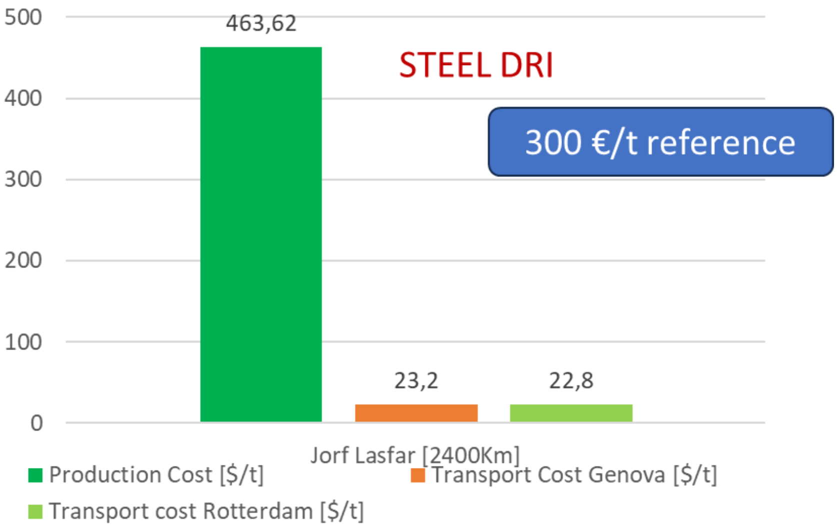


Figure 31: Overall cost assessment for Steel DRI

As it can be seen in Figure 31, in this context, the cost of transport accounts for about 5% of the total cost, thus offering a margin of reduction in production costs of 95%, lower than in previous cases, where the margin could reach up to 99%. This is due to the fact that the cost of producing green hydrogen at Jorf Lasfar is already relatively low.

In conclusion, both the on-site use of DRI green steel and its transport to European markets are valid options, thanks to the low production costs and reduced CO2 emissions.

5.5.3 CEMENT

In this case, cement is produced at two sites, both located at a considerable distance from ports: the first in Nairobi and the second in Boegoebaai Bay. The cost of transport by ship is similar for both sites, as the distances between the two European ports are comparable, with cost estimates of around $4/tonne. However, road transport costs are significantly higher for Nairobi, due to the distance that is about four times greater than that from the Boegoebaai Bay production site to the port of Saldanha.

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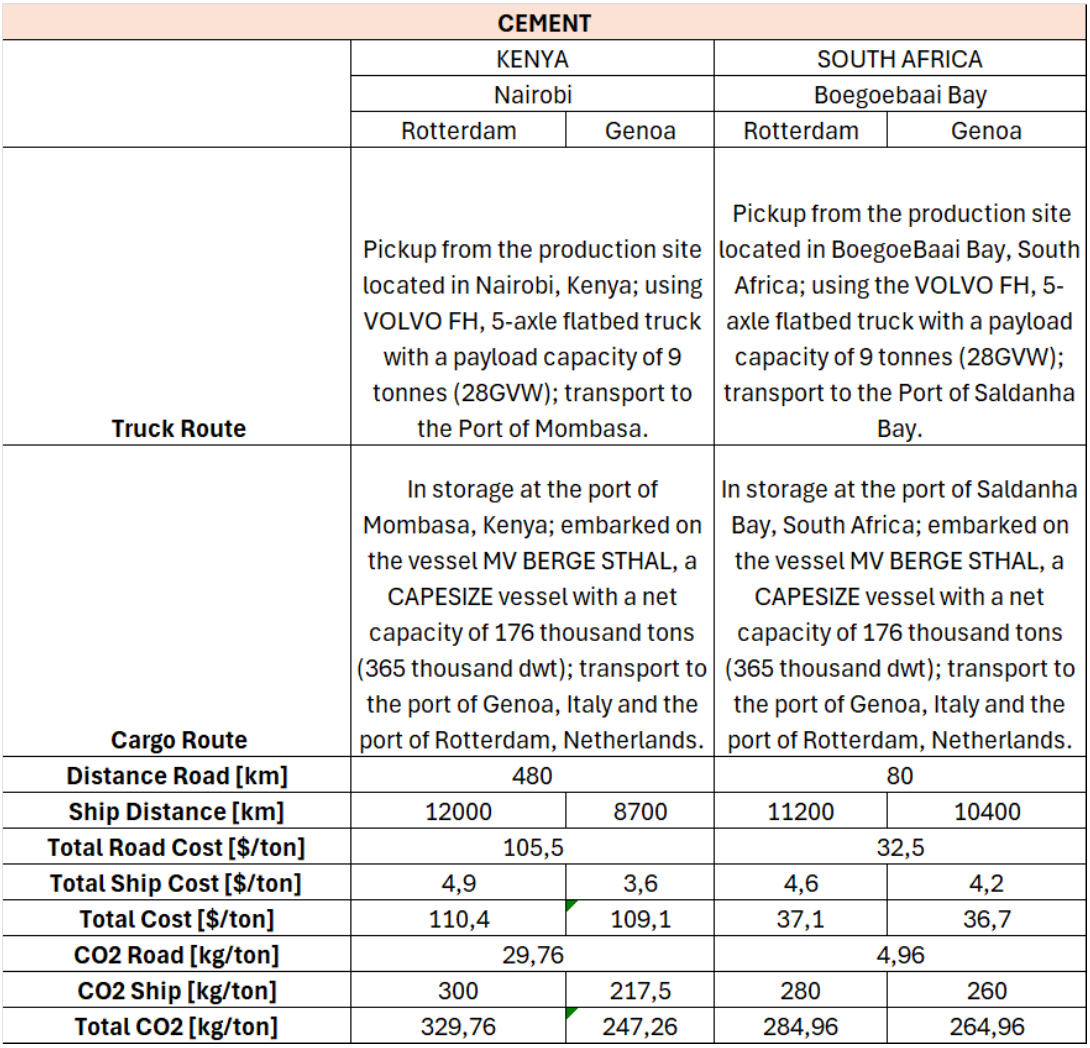

CEMENT				
	KENYA		SOUTH AFRICA	
	Nairobi		Boegoebaai Bay	
	Rotterdam	Genoa	Rotterdam	Genoa
Truck Route	Pickup from the production site located in Nairobi, Kenya; using VOLVO FH, 5-axle flatbed truck with a payload capacity of 9 tonnes (28GVW); transport to the Port of Mombasa.		Pickup from the production site located in BoegoeBaai Bay, South Africa; using the VOLVO FH, 5-axle flatbed truck with a payload capacity of 9 tonnes (28GVW); transport to the Port of Saldanha Bay.	
Cargo Route	In storage at the port of Mombasa, Kenya; embarked on the vessel MV BERGE STHAL, a CAPESIZE vessel with a net capacity of 176 thousand tons (365 thousand dwt); transport to the port of Genoa, Italy and the port of Rotterdam, Netherlands.		In storage at the port of Saldanha Bay, South Africa; embarked on the vessel MV BERGE STHAL, a CAPESIZE vessel with a net capacity of 176 thousand tons (365 thousand dwt); transport to the port of Genoa, Italy and the port of Rotterdam, Netherlands.	
Distance Road [km]	480		80	
Ship Distance [km]	12000	8700	11200	10400
Total Road Cost [$/ton]	105,5		32,5	
Total Ship Cost [$/ton]	4,9	3,6	4,6	4,2
Total Cost [$/ton]	110,4	109,1	37,1	36,7
CO2 Road [kg/ton]	29,76		4,96	
CO2 Ship [kg/ton]	300	217,5	280	260
Total CO2 [kg/ton]	329,76	247,26	284,96	264,96

Table 7 Cement transport assessment

From an environmental point of view, CO2 emissions are relatively high. As far as road transport is concerned, emissions are lower in the South African case, thanks to the shorter distances to be travelled. On the contrary, emissions by ship are lower for the Mombasa-Genoa route, since the distance is about 2000-3000 km shorter than in the other three cases analyzed. As a result, from an environmental point of view, transporting one tonne of product is not particularly advantageous.

CEMENT			
		KENYA	SOUTH AFRICA
		Nairobi	Boegoebaai Bay
LCOH Green [$/kg H2]		5,02	5,07
Production cost [$/ton]		220,6	222,1
% Cost H2 Green		68,20%	68,50%
CO2 produced [kg of CO2/ton of product]		297,84	
% CO2 saving		126%	
EXPORT GREEN PRODUCT	Rotterdam	331	259,2
	Genoa	329,7	258,8
EXPORT GREEN PRODUCT	Rotterdam	329,76	284,96
	Genoa	247,26	264,96
% COST H2 GREEN	Rotterdam	66,65%	85,69%
	Genoa	66,91%	85,82%
% TRANSPORT COST	Rotterdam	33,35%	14,31%
	Genoa	33,09%	14,18%
% CO2 Emitted transport and CO2 Emitted non green	Rotterdam	52,54%	48,89%
	Genoa	45,36%	47,08%

Table 8 Cement Assessment (Benchmark between green and grey products)

Unlike the previous two cases, where the cost of production was relatively high and had a significant impact on the total cost, in the case of green cement the situation is different as it can be seen in figure below. Since cement requires only small amounts of hydrogen, the cost of production is significantly lower, and as a result, the percentage of incidence of the cost of production on the total cost is much lower at about 65%. Therefore, from an economic point of view, producing and transporting green cement is particularly convenient.

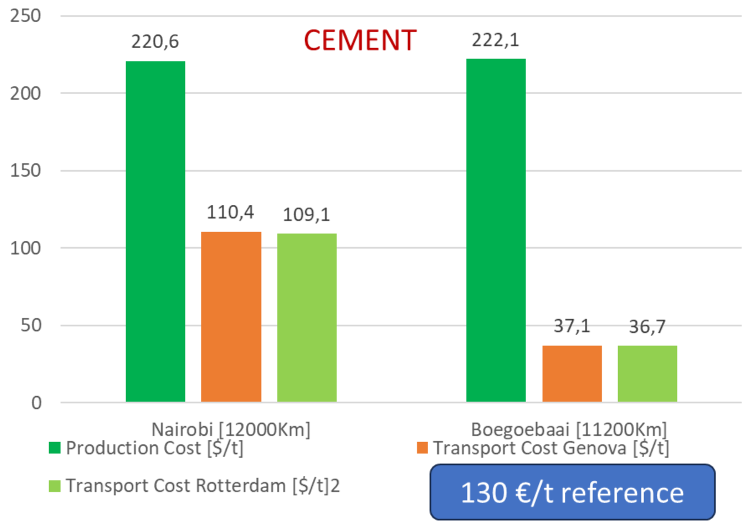

Figure 32: Overall cost assessment for Cement

Considering that the production of green cement requires a reduced amount of hydrogen, the associated CO2 emissions are also contained. In particular, the CO2 produced by the production of one ton of cement is equal to about 300 kg. However, CO2 emissions from

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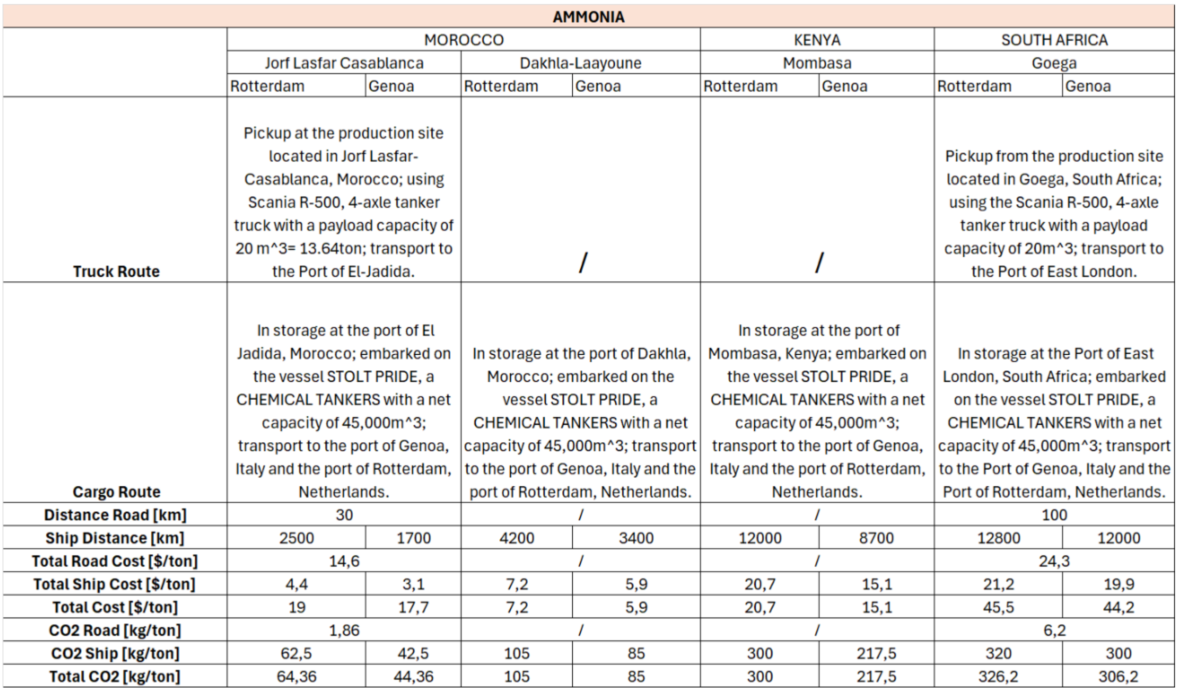
shipping account for a significant proportion, accounting for between 45% and 47% of total emissions.

For these reasons, on-site production of green cement is the best solution for two main reasons: it avoids CO2 emissions from transport by ship, which make up almost 50% of total emissions, and it benefits from the low cost of producing green cement. However, it is important to consider that the CO2 emissions from transport are the same for each product you intend to transfer. For this reason, transporting green cement could be one of the most advantageous options.

5.5.4 AMMONIA



AMMONIA								
	MOROCCO				KENYA		SOUTH AFRICA	
	Jorf Lasfar Casablanca		Dakhla-Laayoune		Mombasa		Goega	
	Rotterdam	Genoa	Rotterdam	Genoa	Rotterdam	Genoa	Rotterdam	Genoa
Truck Route	Pickup at the production site located in Jorf Lasfar-Casablanca, Morocco; using Scania R-500, 4-axle tanker truck with a payload capacity of 20 m^3= 13.64ton; transport to the Port of El-Jadida.		/		/		Pickup from the production site located in Goega, South Africa; using the Scania R-500, 4-axle tanker truck with a payload capacity of 20m^3; transport to the Port of East London.	
Cargo Route	In storage at the port of El Jadida, Morocco; embarked on the vessel STOLT PRIDE, a CHEMICAL TANKERS with a net capacity of 45,000m^3; transport to the port of Genoa, Italy and the port of Rotterdam, Netherlands.		In storage at the port of Dakhla, Morocco; embarked on the vessel STOLT PRIDE, a CHEMICAL TANKERS with a net capacity of 45,000m^3; transport to the port of Genoa, Italy and the port of Rotterdam, Netherlands.		In storage at the port of Mombasa, Kenya; embarked on the vessel STOLT PRIDE, a CHEMICAL TANKERS with a net capacity of 45,000m^3; transport to the port of Genoa, Italy and the port of Rotterdam, Netherlands.		In storage at the Port of East London, South Africa; embarked on the vessel STOLT PRIDE, a CHEMICAL TANKERS with a net capacity of 45,000m^3; transport to the Port of Genoa, Italy and the Port of Rotterdam, Netherlands.	
Distance Road [km]	30		/		/		100	
Ship Distance [km]	2500	1700	4200	3400	12000	8700	12800	12000
Total Road Cost [$/ton]	14,6		/		/		24,3	
Total Ship Cost [$/ton]	4,4	3,1	7,2	5,9	20,7	15,1	21,2	19,9
Total Cost [$/ton]	19	17,7	7,2	5,9	20,7	15,1	45,5	44,2
CO2 Road [kg/ton]	1,86		/		/		6,2	
CO2 Ship [kg/ton]	62,5	42,5	105	85	300	217,5	320	300
Total CO2 [kg/ton]	64,36	44,36	105	85	300	217,5	326,2	306,2

Table 9 Ammonia transport assessment

As can also be seen in this case, the transport of *gas carriers* such as ammonia is very advantageous, despite the transport volumes being significantly higher than those of solid materials. For example, considering the case of Jorf Lasfar, the cost of transporting ammonia to Rotterdam is four times higher than that of transporting DRI steel. However, for the same route, truck transport is more economical, since the use of a truck with a higher net transport capacity has been taken into account.

In general, from an economic point of view (as it can be seen in Fig.33), the transport of ammonia can be an advantageous choice for cost reduction, despite the associated environmental risks, since ammonia is a known pollutant. In addition, the amount of CO2 emitted during transport increases in proportion to the distance travelled; for this reason, the transport of ammonia involves high CO2 emissions, especially for countries such as South Africa and Kenya.

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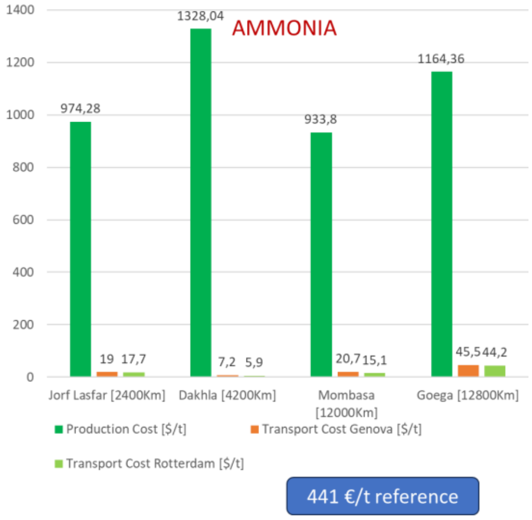

Figure 33: Overall cost assessment for Ammonia

AMMONIA					
		MOROCCO		KENYA	SOUTH AFRICA
		Jorf Lasfar Casablanca	Dakhla-Laayoune	Mombasa	Goega
LCOH Green [$/kg H2]		5,03	7,04	4,8	6,11
Production cost [$/ton]		974,28	1328,04	933,8	1164,36
% Cost H2 Green		90,00%	93,00%	90,00%	92,00%
CO2 produced [kg of CO2/ton of product]		1792,87		1741,9	1884,13
% CO2 saving		50,20%		51,67%	47,77%
TOTAL COST EXPORT GREEN PRODUCT	**Rotterdam**	993,28	1335,24	954,5	1209,86
	Genoa	991,98	1333,94	945,9	1208,56
CO2 TOTAL EXPORT GREEN PRODUCT	**Rotterdam**	64,36	105	300	326,2
	Genoa	44,36	85	217,5	306,2
% COST H2 GREEN	**Rotterdam**	98,09%	99,46%	97,83%	96,24%
	Genoa	98,22%	99,56%	98,72%	96,34%
% TRANSPORT COST	**Rotterdam**	1,91%	0,54%	2,17%	3,76%
	Genoa	1,78%	0,44%	1,28%	3,66%
% CO2 Emitted transport and CO2 Emitted non green	**Rotterdam**	3,47%	5,53%	14,69%	14,76%
	Genoa	2,41%	4,53%	11,10%	13,98%

Table 10 Ammonia Assessment (Benchmark between green and grey products)

The first observation that emerges from this table is that the incidence of transport cost compared to the final cost for the four production sites considered is extremely low; This is due to the high cost of producing green ammonia in these countries. From an economic point of view, Jorf Lasfar and Mombasa can represent two advantageous options for transporting this product to Europe, with total costs around 950-1000 $/ton. However, transport from Mombasa is unfavourable due to high CO2 emissions.

Transport from Goega, on the other hand, must be excluded due to the high production costs and significant CO2 emissions associated with transport. For this reason, there are two

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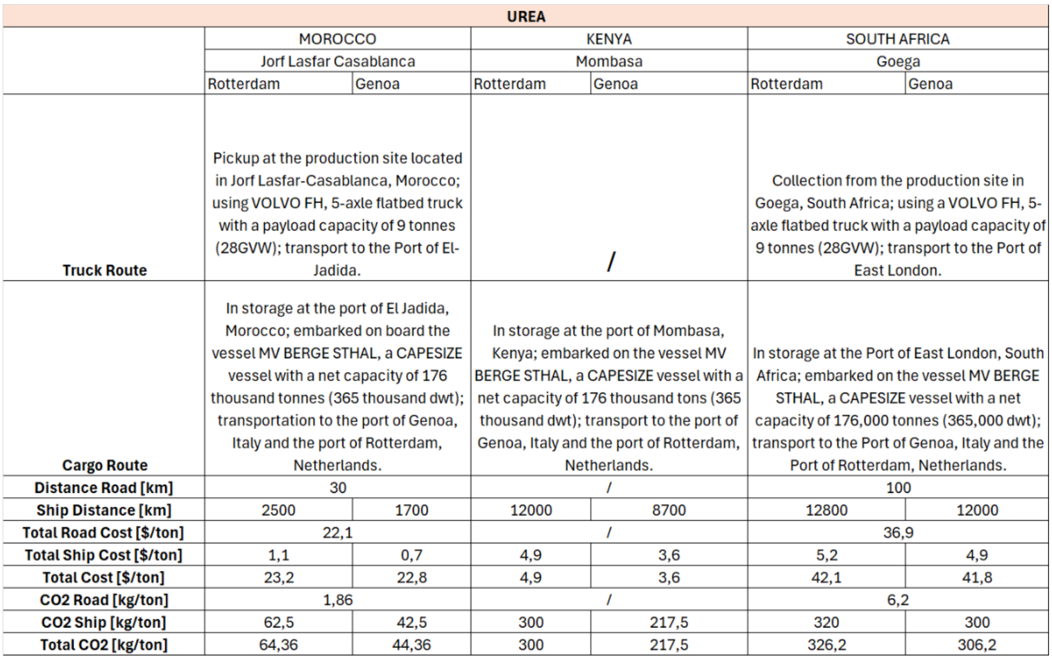
options to consider: use green ammonia locally, taking advantage of the low cost of transport by truck to distribute it within the country, or avoid the production of green ammonia altogether, given the high incidence of green hydrogen production costs, and focus on other materials. Finally, Dakhla must be excluded due to the high production costs

5.5.5 UREA

The transport of urea by ship is undoubtedly very cheap. For example, the cost for transportation from Goega to Rotterdam, over a distance of about 13,000 km, amounts to only $5.2/ton. On the other hand, transport by truck is significantly more expensive, due to the high rental costs of vehicles intended for the transport of solid materials. It should also be noted that compared to the previous table relating to ammonia, the cost of transporting urea by truck is about 1.5 times higher than that of ammonia, for the route from Goega to the port of East London. From an environmental point of view, transport-related CO2 emissions remain high, both for Goega and Mombasa.



UREA						
	MOROCCO		KENYA		SOUTH AFRICA	
	Jorf Lasfar Casablanca		Mombasa		Goega	
	Rotterdam	Genoa	Rotterdam	Genoa	Rotterdam	Genoa
Truck Route	Pickup at the production site located in Jorf Lasfar-Casablanca, Morocco; using VOLVO FH, 5-axle flatbed truck with a payload capacity of 9 tonnes (28GVW); transport to the Port of El-Jadida.		/		Collection from the production site in Goega, South Africa; using a VOLVO FH, 5-axle flatbed truck with a payload capacity of 9 tonnes (28GVW); transport to the Port of East London.	
Cargo Route	In storage at the port of El Jadida, Morocco; embarked on board the vessel MV BERGE STHAL, a CAPESIZE vessel with a net capacity of 176 thousand tonnes (365 thousand dwt); transportation to the port of Genoa, Italy and the port of Rotterdam, Netherlands.		In storage at the port of Mombasa, Kenya; embarked on the vessel MV BERGE STHAL, a CAPESIZE vessel with a net capacity of 176 thousand tons (365 thousand dwt); transport to the port of Genoa, Italy and the port of Rotterdam, Netherlands.		In storage at the Port of East London, South Africa; embarked on the vessel MV BERGE STHAL, a CAPESIZE vessel with a net capacity of 176,000 tonnes (365,000 dwt); transport to the Port of Genoa, Italy and the Port of Rotterdam, Netherlands.	
Distance Road [km]	30		/		100	
Ship Distance [km]	2500	1700	12000	8700	12800	12000
Total Road Cost [$/ton]	22,1		/		36,9	
Total Ship Cost [$/ton]	1,1	0,7	4,9	3,6	5,2	4,9
Total Cost [$/ton]	23,2	22,8	4,9	3,6	42,1	41,8
CO2 Road [kg/ton]	1,86		/		6,2	
CO2 Ship [kg/ton]	62,5	42,5	300	217,5	320	300
Total CO2 [kg/ton]	64,36	44,36	300	217,5	326,2	306,2

Table 11 Urea transport assessment

The first observation concerns the production cost of urea, which is significantly lower than that of ammonia, thanks to the lower amount of hydrogen needed for its production. As a result, the impact of transport costs on the total cost is of little significance for all three production sites considered, in particular for Mombasa, where it is practically negligible. In the future, a reduction in the production costs of green urea and green hydrogen could be a game-changer for European trade. However, urea production is already very cost-effective for all three sites.

UREA				
		MOROCCO	KENYA	SOUTH AFRICA
		Jorf Lasfar Casablanca	Mombasa	Goega
LCOH Green [$/kg H2]		5,03	4,8	6,11
Production cost [$/ton]		703	680	811
% Cost H2 Green		71,20%	71,00%	75,00%
CO2 produced [kg of CO2/ton of product]		1018,02	989,22	1069,57
% CO2 saving		88,41%	90,98%	84,15%
TOTAL COST EXPORT GREEN PRODUCT	**Rotterdam**	726,2	684,9	853,1
	Genoa	725,8	683,6	852,8
CO2 TOTAL EXPORT GREEN PRODUCT	**Rotterdam**	64,36	300	326,2
	Genoa	44,36	217,5	306,2
% COST H2 GREEN	**Rotterdam**	96,81%	99,28%	95,07%
	Genoa	96,86%	99,47%	95,10%
% TRANSPORT COST	**Rotterdam**	3,19%	0,72%	4,93%
	Genoa	3,14%	0,53%	4,90%
% CO2 Emitted transport and CO2 Emitted non green	**Rotterdam**	5,95%	23,27%	23,37%
	Genoa	4,18%	18,02%	22,26%

Table 10 Urea Assessment (Benchmark between green and grey products)

The main problem concerns the environmental aspect, especially for Mombasa and Goega, where transport-related CO2 emissions account for a quarter of total emissions. Despite this, the percentage of CO2 that could be saved with a possible transition to green urea production is significant and would make this transformation particularly beneficial. In summary, the conversion to green urea production is cost-effective for all three production sites. In Kenya and South Africa, it would be preferable to use urea locally, avoiding transport and thus reducing CO2 emissions by about 25%. As for Jorf Lasfar, it could become a viable competitor in the transport of green urea to European markets (as it can be seen in figure below).

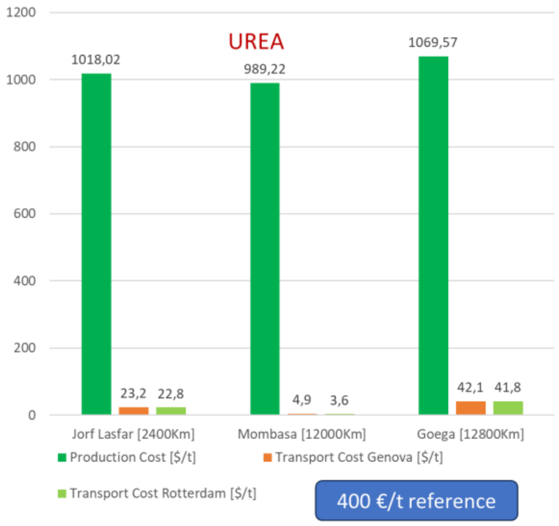
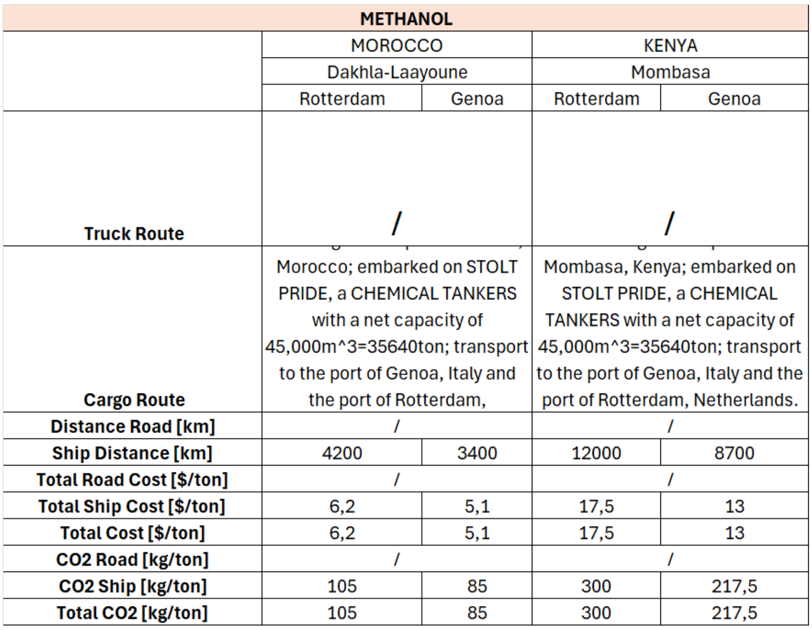


Figure 34: Overall cost assessment for Urea

5.5.6 METHANOL

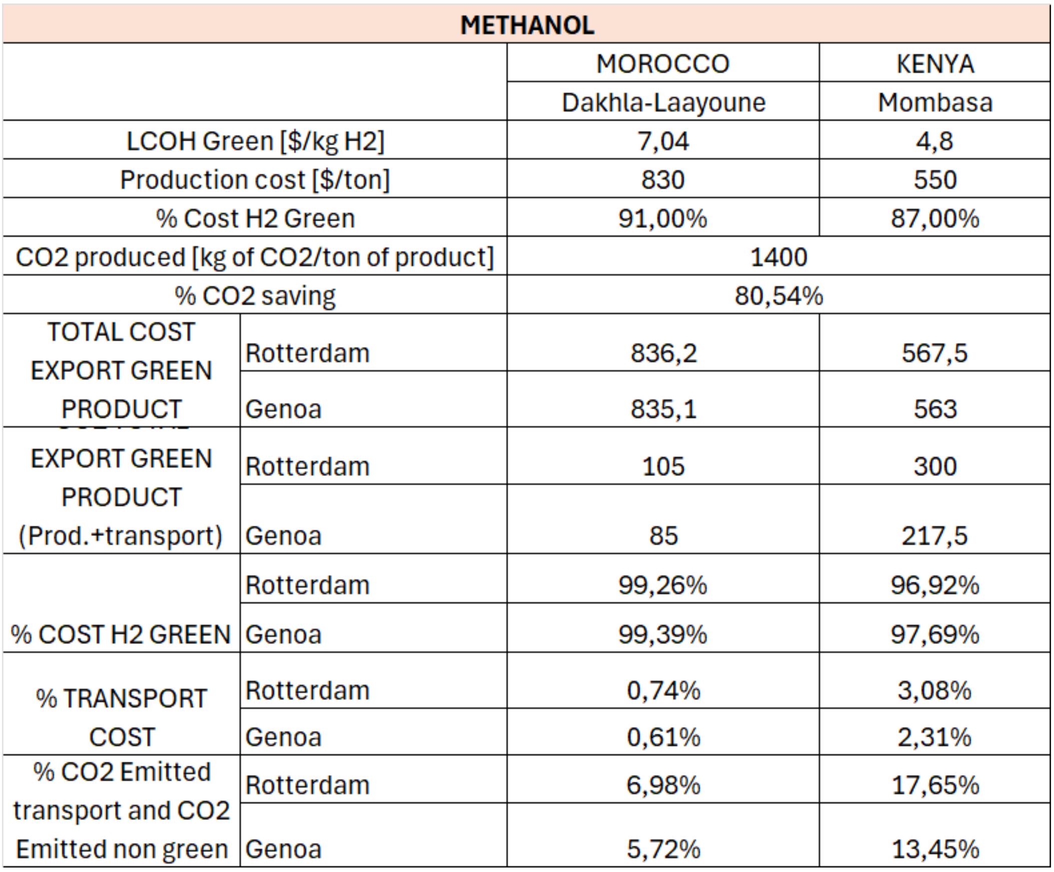


METHANOL				
	MOROCCO		KENYA	
	Dakhla-Laayoune		Mombasa	
	Rotterdam	Genoa	Rotterdam	Genoa
Truck Route	/		/	
Cargo Route	Morocco; embarked on STOLT PRIDE, a CHEMICAL TANKERS with a net capacity of 45,000m^3=35640ton; transport to the port of Genoa, Italy and the port of Rotterdam,		Mombasa, Kenya; embarked on STOLT PRIDE, a CHEMICAL TANKERS with a net capacity of 45,000m^3=35640ton; transport to the port of Genoa, Italy and the port of Rotterdam, Netherlands.	
Distance Road [km]	/		/	
Ship Distance [km]	4200	3400	12000	8700
Total Road Cost [$/ton]	/		/	
Total Ship Cost [$/ton]	6,2	5,1	17,5	13
Total Cost [$/ton]	6,2	5,1	17,5	13
CO2 Road [kg/ton]	/		/	
CO2 Ship [kg/ton]	105	85	300	217,5
Total CO2 [kg/ton]	105	85	300	217,5

Table 13 Methanol transport assessment

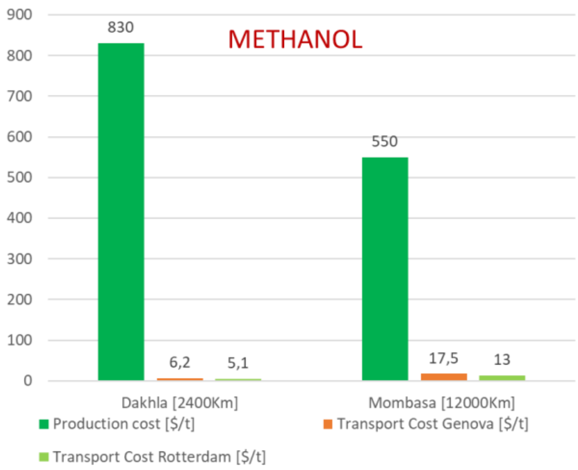
The first observation concerns the fact that, for Mombasa, making the same journey by ship for both ammonia and methanol is more convenient for the latter, since a greater quantity of methanol can be transported for the same carrying capacity. Transport costs are relatively low, as there is no need to consider truck transport, as the production sites are located close to ports. However, as already highlighted above, the amount of CO2 emitted by transport remains relatively high for countries such as Kenya.

The first observation concerns the reduction in the cost of production for one ton of methanol compared to one ton of ammonia, due to the lower amount of hydrogen needed. In both cases, the incidence of transport cost on the total cost is minimal, in particular for the Dakhla production site, where it represents less than 1% of the total cost. For this reason, and also considering the environmental aspect, the transport of green methanol from Dakhla to European markets can be a sustainable choice both from an economic and environmental point of view.
As for Mombasa, although CO2 emissions are relatively high, mainly due to the long distance, transport to European markets can still be an advantageous choice due to the relatively low total cost, despite this, on-site use is the most suitable solution.



METHANOL			
		MOROCCO	KENYA
		Dakhla-Laayoune	Mombasa
LCOH Green [$/kg H2]		7,04	4,8
Production cost [$/ton]		830	550
% Cost H2 Green		91,00%	87,00%
CO2 produced [kg of CO2/ton of product]		1400	
% CO2 saving		80,54%	
TOTAL COST EXPORT GREEN PRODUCT	Rotterdam	836,2	567,5
	Genoa	835,1	563
EXPORT GREEN PRODUCT (Prod.+transport)	Rotterdam	105	300
	Genoa	85	217,5
% COST H2 GREEN	Rotterdam	99,26%	96,92%
	Genoa	99,39%	97,69%
% TRANSPORT COST	Rotterdam	0,74%	3,08%
	Genoa	0,61%	2,31%
% CO2 Emitted transport and CO2 Emitted non green	Rotterdam	6,98%	17,65%
	Genoa	5,72%	13,45%

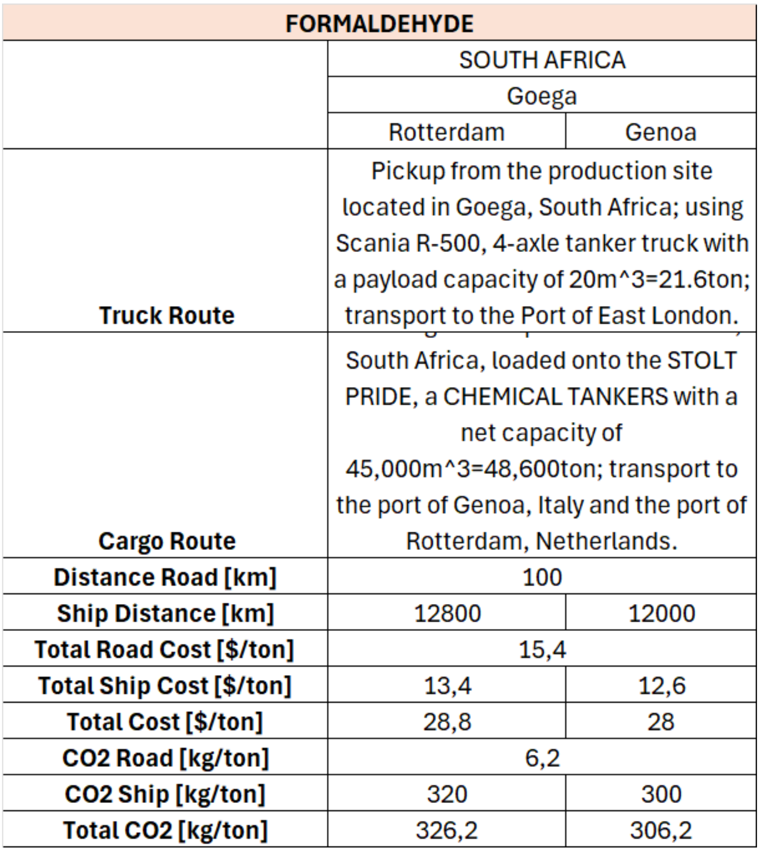
Table 14 Methanol Assessment (Benchmark between green and grey products)



336 €/t reference

Figure 35: Overall cost assessment for Methanol

5.5.7 FORMALDEHYDE



FORMALDEHYDE		
	SOUTH AFRICA	
	Goega	
	Rotterdam	Genoa
Truck Route	Pickup from the production site located in Goega, South Africa; using Scania R-500, 4-axle tanker truck with a payload capacity of 20m^3=21.6ton; transport to the Port of East London.	
Cargo Route	South Africa, loaded onto the STOLT PRIDE, a CHEMICAL TANKERS with a net capacity of 45,000m^3=48,600ton; transport to the port of Genoa, Italy and the port of Rotterdam, Netherlands.	
Distance Road [km]	100	
Ship Distance [km]	12800	12000
Total Road Cost [$/ton]	15,4	
Total Ship Cost [$/ton]	13,4	12,6
Total Cost [$/ton]	28,8	28
CO2 Road [kg/ton]	6,2	
CO2 Ship [kg/ton]	320	300
Total CO2 [kg/ton]	326,2	306,2

Table 15 Formaldehyde transport assessment

If we consider only the cost of transport by ship, it is lower per kilometre than the transport of ammonia and methanol. This is due to the higher density of formaldehyde, which allows for a higher net transport capacity. However, if we also include the cost of transport by truck, which is necessary due to the considerable distance of the production site from the nearest port of about 100 km, the overall cost increases slightly. From an environmental point of view, CO2 emissions remain high, as the only formaldehyde production site is located at a very significant distance from Europe.

FORMALDEHYDE		
		SOUTH AFRICA
		Goega
LCOH Green [$/kg H2]		6,11
Production cost [$/ton]		1047,86
% Cost H2 Green		77,00%
CO2 produced [kg of CO2/ton of product]		1490
% CO2 saving		80,54%
TOTAL COST EXPORT GREEN PRODUCT	Rotterdam	1076,66
	Genoa	1075,86
CO2 TOTAL EXPORT GREEN PRODUCT	Rotterdam	326,2
	Genoa	306,2
% COST H2 GREEN	Rotterdam	97,33%
	Genoa	97,40%
% TRANSPORT COST	Rotterdam	2,67%
	Genoa	2,60%
% CO2 Emitted transport and CO2 Emitted non green	Rotterdam	17,96%
	Genoa	17,05%

Table 16 Formaldehyde Assessment (Benchmark between green and grey products)

The total cost is relatively high compared to the overall cost of production and transport of methanol. Therefore, a possible strategy would be to transport green methanol from the previously identified production sites and subsequently convert it into green formaldehyde.

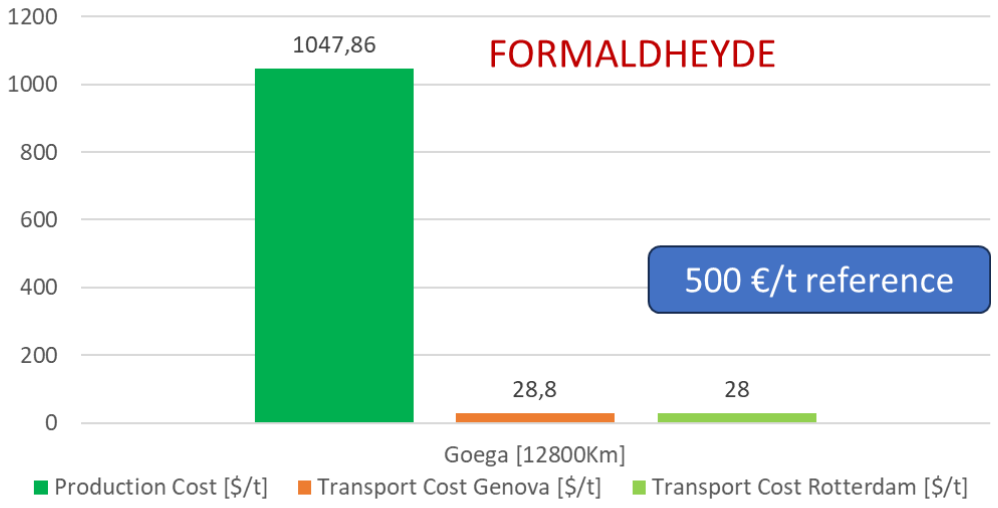


Figure 36: Overall cost assessment for Formaldehyde

However, as the impact of transport cost on the total cost is relatively small (As it can be seen in Fig.36), a reduction in the production cost of green hydrogen would help to significantly lower the overall cost, making exports more competitive.

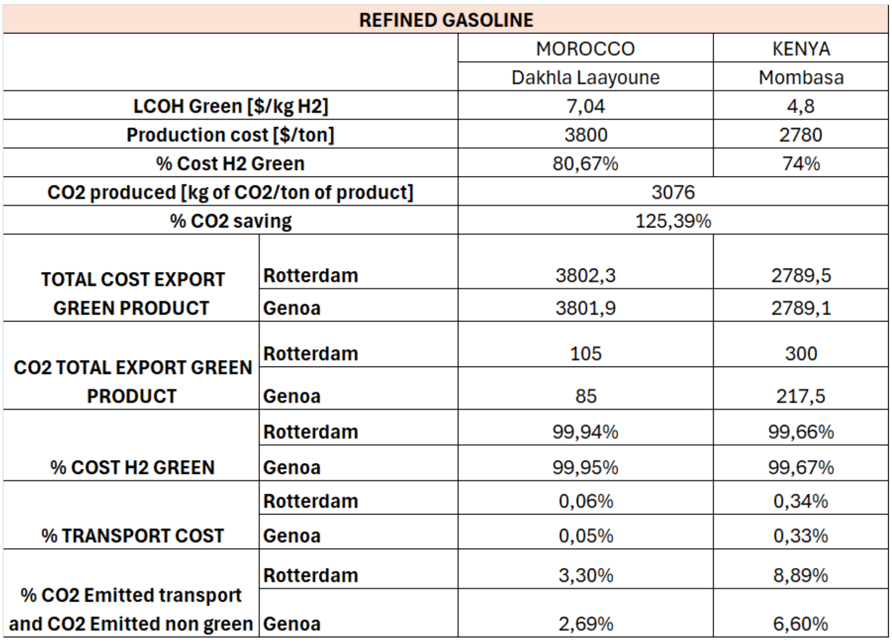
Considering that, in addition to the high costs, there are also high carbon dioxide emissions, mainly due to the long distance traveled, the production of green formaldehyde would be more advantageous if used locally. This approach would avoid transport costs and associated CO2 emissions.

5.5.8 REFINED GASOLINE

REFINED GASOLINE				
	MOROCCO		KENYA	
	Dakhla-Laayoune		Mombasa	
	Rotterdam	Genoa	Rotterdam	Genoa
Truck Route	/		/	
Cargo Route	In storage at the port of Dakhla, Morocco; embarked on the vessel TI AFRICA, OIL TANKER vessel with a net capacity of 234 thousand tons (440 thousand dwt); transport to the port of Genoa, Italy and the port of Rotterdam, Netherlands.		In storage at the port of Mombasa, Kenya; embarked on the vessel TI AFRICA, an OIL TANKER vessel with a net capacity of 234 thousand tons (440 thousand dwt); transport to the port of Genoa, Italy and the port of Rotterdam, Netherlands.	
Distance Road [km]	/		/	
Ship Distance [km]	4200	3400	12000	8760
Total Road Cost [$/ton]	/		/	
Total Ship Cost [$/ton]	2,3	1,9	9,5	9,1
Total Cost [$/ton]	2,3	1,9	9,5	9,1
CO2 Road [kg/ton]	/		/	
CO2 Ship [kg/ton]	105	85	300	217,5
Total CO2 [kg/ton]	105	85	300	217,5

Table 17 Assessment of transport for refined gasoline

Transport costs are adequate for both production sites, as they are located in close proximity to the ports. However, as highlighted in the previous cases, the CO2 emissions from the transport from the port of Mombasa to the two ports considered are high due to the long distances to be travelled.



REFINED GASOLINE			
		MOROCCO	KENYA
		Dakhla Laayoune	Mombasa
LCOH Green [$/kg H2]		7,04	4,8
Production cost [$/ton]		3800	2780
% Cost H2 Green		80,67%	74%
CO2 produced [kg of CO2/ton of product]		3076	
% CO2 saving		125,39%	
TOTAL COST EXPORT GREEN PRODUCT	**Rotterdam**	3802,3	2789,5
	Genoa	3801,9	2789,1
CO2 TOTAL EXPORT GREEN PRODUCT	**Rotterdam**	105	300
	Genoa	85	217,5
% COST H2 GREEN	**Rotterdam**	99,94%	99,66%
	Genoa	99,95%	99,67%
% TRANSPORT COST	**Rotterdam**	0,06%	0,34%
	Genoa	0,05%	0,33%
% CO2 Emitted transport and CO2 Emitted non green	**Rotterdam**	3,30%	8,89%
	Genoa	2,69%	6,60%

Table 18 Refined gasoline assessment Assessment (Benchmark between green and grey products)

The first observation that emerges from the table is the high cost of producing a ton of refined gasoline, attributable to the large amount of hydrogen needed for its production, compared to the products previously analyzed. As already indicated, the transport cost is relatively low and its impact on the total cost is negligible. From an environmental point of view, it is easy to observe that CO2 emissions are high; In this context, the use of green hydrogen would significantly contribute to reducing its impact. Therefore, until a way is found to reduce the production costs of refined gasoline, this product cannot be considered economically viable.

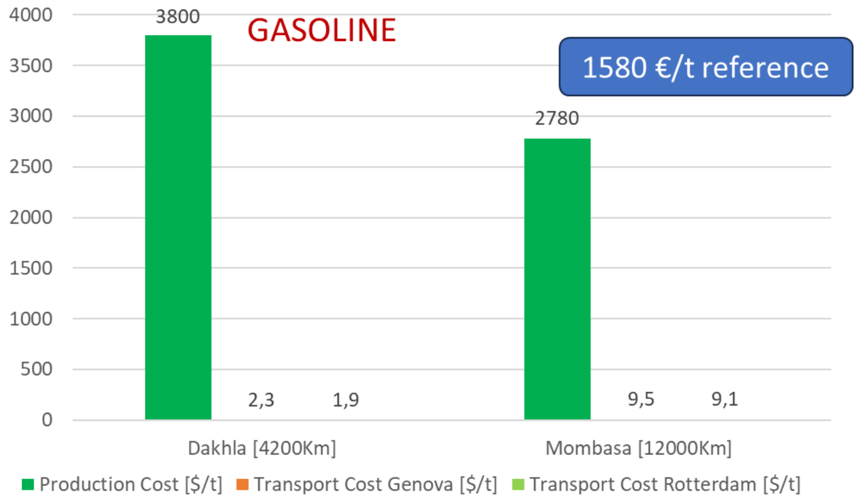


Figure 37: Overall cost assessment for Refined Gasoline

5.5.9 HYDROGEN

As far as hydrogen is concerned, the analysis conducted focused exclusively on transport, excluding production. The economic analysis of production for each site was covered in the previous thesis.

The main focus of hydrogen transport is the high cost of transport. As far as transport by truck is concerned, the use of gaseous hydrogen has been hypothesized, in order to avoid material losses. However, in the case of transport by ship, the product is transported in liquid form and the long distances result in considerable losses mainly due to the boil-off phenomenon. As a result, the quantity actually transported by ship is about half of the theoretical amount.

In addition, the cost of transporting a single tonne of green hydrogen by truck is also high, due to the low volumetric density of hydrogen gas. The density of hydrogen gas is 0.089 kg/m³, significantly lower than that of ammonia and methanol in liquid form. From an environmental point of view, the CO2 emissions associated with the transport of green hydrogen are comparable to those emitted for the transport of the products and carriers described in the previous paragraphs.

Co-funded by the European Union

The project is supported by the Clean Hydrogen Partnership and its members Hydrogen Europe and Hydrogen Europe Research.

Clean Hydrogen Partnership

	HYDROGEN																	
	MOROCCO						KENYA						SOUTH AFRICA					
	Tangier		Jorf Lasfar		Dakhla-Laayoune		Olkaria		Mombasa		Nairobi		Goega		Saldanha Bay		Boegoebaai Bay	
	Rotterdam	Genoa	Rotterdam	Genoa	Rotterdam	Genoa	Rotterdam	Genoa	Rotterdam	Genoa	Rotterdam	Genoa	Rotterdam	Genoa	Rotterdam	Genoa	Rotterdam	Genoa
Truck Route	/		Pickup at the production site located in Jorf Lasfar-Casablanca, Morocco; using the Scania R-500, 5-axle flatbed truck with a payload capacity of 20m^3; transport to the Port of El-Jadida.		/		Pickup at the production site located in Olkaria, Kenya; using the Scania R-500, 5-axle flatbed truck with a payload capacity of 20m^3; transport to the Port of Mombasa.		/		Pickup at the production site located in Nairobi, Kenya; using the Scania R-500, 5-axle flatbed truck with a payload capacity of 20m^3; transport to the Port of Mombasa.		Pickup from the production site located in Goega, South Africa; using the Scania R-500, 5-axle flatbed truck with a payload capacity of 20m^3; transport to the Port of East London.		/		Pickup at the production site located in BoegoeBaai Bay, South Africa; using the Scania R-500, 5-axle flatbed truck with a payload capacity of 20m^3; transport to the Port of Saldanha Bay.	
Cargo Route	In storage at the port of Tanger Med, Morocco; embarked on the vessel Suiso Frontier, a vessel suitable for the transport of liquid hydrogen, with a net capacity of 1250m^3=88.56 tonnes; transport to the port of Genoa, Italy and the port of Rotterdam, Netherlands.		In storage at the port of El-Jadida; embarked on the vessel Suiso Frontier, a vessel suitable for the transport of liquid hydrogen, with a net capacity of 1250m^3=88.56 tonnes; transport to the port of Genoa, Italy and the port of Rotterdam, Netherlands.		In storage at the port of Dakhla, Morocco; embarked on the vessel Suiso Frontier, a vessel suitable for the transport of liquid hydrogen, with a net capacity of 1250m^3=88.56 tonnes; transport to the port of Genoa, Italy and the port of Rotterdam, Netherlands.		In storage at the port of Mombasa, Morocco; embarked on the vessel Suiso Frontier, a vessel suitable for the transport of liquid hydrogen, with a net capacity of 1250m^3=88.56 tonnes; transport to the port of Genoa, Italy and the port of Rotterdam, Netherlands.		In storage at the port of Mombasa, Morocco; embarked on the vessel Suiso Frontier, a vessel suitable for the transport of liquid hydrogen, with a net capacity of 1250m^3=88.56 tonnes; transport to the port of Genoa, Italy and the port of Rotterdam, Netherlands.		In storage at the port of Mombasa, Morocco; embarked on the vessel Suiso Frontier, a vessel suitable for the transport of liquid hydrogen, with a net capacity of 1250m^3=88.56 tonnes; transport to the port of Genoa, Italy and the port of Rotterdam, Netherlands.		In storage at the Port of East London, South Africa; embarked on the vessel Suiso Frontier, a vessel suitable for the transport of liquid hydrogen, with a net capacity of 1250m^3=88.56 tonnes; transport to the Port of Genoa, Italy and the Port of Rotterdam, Netherlands.		In storage at the port of Saldanha Bay, South Africa; embarked on the vessel Suiso Frontier, a vessel suitable for the transport of liquid hydrogen, with a net capacity of 1250m^3=88.56 tonnes; transport to the port of Genoa, Italy and the port of Rotterdam, Netherlands.		In storage at the port of Saldanha Bay, South Africa; embarked on the vessel Suiso Frontier, a vessel suitable for the transport of liquid hydrogen, with a net capacity of 1250m^3=88.56 tonnes; transport to the port of Genoa, Italy and the port of Rotterdam, Netherlands.	
Distance Road [km]	/		30		/		350		/		480		100		/		80	
Ship Distance [km]	2500	1700	2500	1700	4200	3400	12000	8700	12000	8700	12000	8700	12800	12000	11200	10400	11200	10400
Total Road Cost [$/ton]	/		70,5		/		196,3		/		247,9		100,4		/		93,2	
Ship Cost [$/ton]	1639,6	1151,1	1639,6	1151,1	2677,8	2189,2	7441,1	5245,8	7441,1	5245,8	7441,1	5245,8	7929,6	7441,1	6952,5	6464,0	6952,5	6464,0
Total Cost [$/ton]	1639,6	1151,1	1710,1	1221,6	2677,8	2189,2	7637,4	5442,1	7441,1	5245,8	7689,0	5493,7	8030,0	7541,5	6952,5	6464,0	7045,7	6557,2
CO2 Road [kg/ton]	/		1,86		/		21,7		/		29,76		6,2		/		4,96	
CO2 Ship [kg/ton]	62,5	42,5	62,5	42,5	105	85	300	217,5	300	217,5	300	217,5	320	300	280	260	280	260
Total CO2 [kg/ton]	62,5	42,5	64,36	44,36	105	85	321,7	239,2	300	217,5	329,76	247,26	326,2	306,2	280	260	284,96	264,96

Table 19 Hydrogen transport assessment from the different UCs

CONCLUSION

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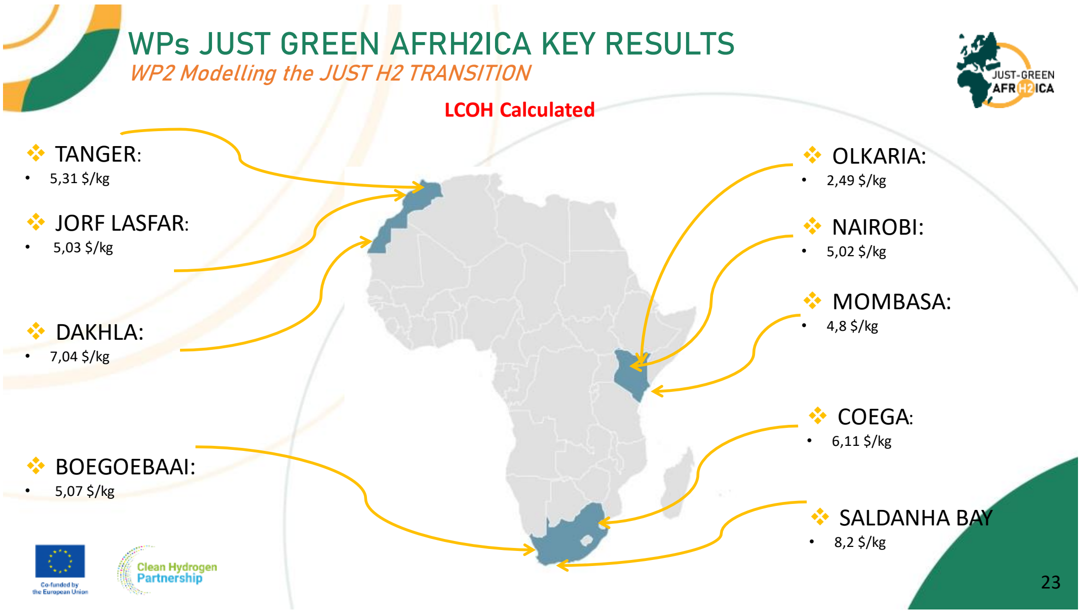
Clean Hydrogen
Partnership

In this report, UNIGE Presented a techno-economic assessment of Green Hydrogen production in the different Use Cases identified in D1.3. To do so, in concert with T2.2, UNIGE updated its model to be able to operate with African scenario, also foreseeing the evaluation of water supply costs in terms of CAPEX and OPEX (as well as of energy consumptions) of different options like ground water pumping, desalination etc. Such costs and performance curves/equations were derived from literature and market research, developing a new module dedicated to water supply as described in D2.1.

Using its own techno-economic tools, UNIGE performed two analysis, in order to investigate the techno-economic viability of the "HYDROGEN HUB" approach promoted by JGA project:

1) A first analysis in which, per each identified use case, UNIGE calculated LCOH supposing the realization of a 1 MW PEM Electrolysis plant, coupled to an off-grid local RES supply (that could be wind, solar or geothermal depending on the location) as well as with a Li-On battery whose size has been optimized by WECoMP Tool. According to this approach, UNIGE calculated the LCOH in all the project use cases, as reported in picture below



WPs JUST GREEN AFRH2ICA KEY RESULTS

WP2 Modelling the JUST H2 TRANSITION

LCOH Calculated

❖ TANGER:
- 5,31 $/kg

❖ JORF LASFAR:
- 5,03 $/kg

❖ DAKHLA:
- 7,04 $/kg

❖ BOEGOEBAAI:
- 5,07 $/kg

❖ OLKARIA:
- 2,49 $/kg

❖ NAIROBI:
- 5,02 $/kg

❖ MOMBASA:
- 4,8 $/kg

❖ COEGA:
- 6,11 $/kg

❖ SALDANHA BAY
- 8,2 $/kg

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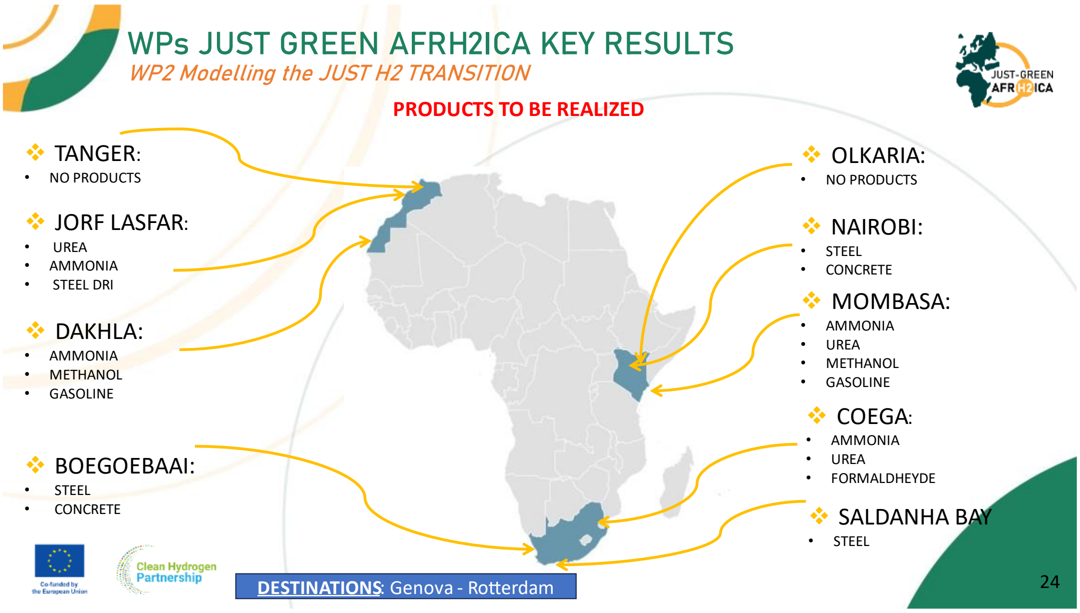
Figure 38: LCOH in JGA Use Cases according to UNIGE Techno-Economic analysis

2) Starting from these values of LCOH and considering the different products manufactured in the different hubs as reported in picture below, UNIGE estimated the cost of production of such "Green products".


WPs JUST GREEN AFRH2ICA KEY RESULTS

WP2 Modelling the JUST H2 TRANSITION

PRODUCTS TO BE REALIZED

❖ TANGER:
- NO PRODUCTS

❖ JORF LASFAR:
- UREA
- AMMONIA
- STEEL DRI

❖ DAKHLA:
- AMMONIA
- METHANOL
- GASOLINE

❖ BOEGOEBAAI:
- STEEL
- CONCRETE

❖ OLKARIA:
- NO PRODUCTS

❖ NAIROBI:
- STEEL
- CONCRETE

❖ MOMBASA:
- AMMONIA
- UREA
- METHANOL
- GASOLINE

❖ COEGA:
- AMMONIA
- UREA
- FORMALDHEYDE

❖ SALDANHA BAY
- STEEL

DESTINATIONS: Genova - Rotterdam

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Figure 39: Products analysed by UNIGE in each JGA UC in its techno-economic analysis

Thanks to a literature review cost function for the transport (via both trucks and ships) of aforementioned products were developed and then the possibility of producing green hydrogen in Africa (to be then exported to Europe even for manufacturing the assessed products) to be then transported to EU (the ports of Genova and Rotterdam were used as references arrival hubs) was evaluated and benchmarked against the costs of production and transportation of the "finite products" exploiting the existing value chains.

Obviously, transporting the "green products" is much easier and less expensive than transporting pure hydrogen (even via Natural gas pipelines) and this discrepancy is much more evident particularly for synthetized products.

Even Carbon taxes in the ETS currently paid by EU manufacturers of hard-to-abate industries (particularly for "Combustion products"), cannot compensate the advantage from an economic point of view of producing "green products" in Africa and then export them to EU using the existing trading routes and value chains.

This is a relevant result of the project because it encourages EU industries having manufacturing plants in Africa to invest on green hydrogen plants thereby to create "Higher value products": to encourage this type of investments carbon credits for emissions avoided for products traded to EU (but not produced in EU) should be considered. Such inputs will be duly valorised by UNIGE in D3.3.

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