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A model-based thought experiment on ports' energy vectors
The case of Port of Barcelona

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By

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Executive Summary

The increasing pressure on tackling climate change underlines the importance of a joint effort from all sectors towards carbon-neutral systems. Emissions from the transport sector, which is Europe's most pollutant sector, are considered to be hard to abate due to the high dependence on fossil fuels. 13.5% of the emissions of this sector are relatable to maritime transport, due to the high volumes of goods transported. The Port of Barcelona, which is the subject of this study, has announced that it aims at becoming carbon-neutral by 2050, meaning that significant changes will be necessary in the following decades. This will require a shift on multiple levels, from the infrastructural side to the necessary shift towards alternative ways of providing the required propulsion energy for vessels. Alternative fuels would allow PoB to change towards local production rather than import, by investing in fuel production capacities and avoiding the need for purchasing these from third countries. This study was developed as a thought experiment, by representing PoB and the possible evolutions that might characterize it. This was done by considering self-production of fuels, to fully capture the energy vectors of the port. Considering this, the following research question was identified:

Which energy vectors could constitute Port of Barcelona's carbon-neutral energy supply, what could be their relative importance, and how could they be produced?

Firstly, a literature review was conducted to define the main changes that might characterize future ports, considering both sides of the system: infrastructure and ships. For what concerns infrastructure, it was concluded that the main change will be represented by onshore power supply, substituting auxiliary engines used in ports with a connection to the electricity grid. On the other hand, the main portion of the overall demand is represented by fuels. To this respect, significant changes are set to happen, as a shift to alternative fuels is necessary to achieve sustainability targets. Different categories of fuels were analyzed, resulting in two alternatives: Fischer-Tropsch diesel, which has the main advantage of being usable with current engines and refuelling infrastructure, and liquefied hydrogen, which was selected for its high energy density.

Findings from the literature review were used as input to build a model, developed with the Calliope framework. This was done in two phases, the first exclusively considering the energy demand of the system, mainly composed by alternative fuels production. In the second phase, RES generation, hydrogen import from Morocco, and electricity storage were implemented. Furthermore, an alternative scenario was defined with the implementation of battery-electric ships. The demand side of the system was estimated using available data from PoB, specifically from year 2021. The parameters of the different implemented technologies were considered according to 2030 projections, wherever these were available. The model simulates hourly data regarding energy consumption and production, considering multiple carriers flowing throughout the system, such as electricity, hydrogen, or alternative fuels.

Results show how implementing RES generation implies higher production capacities, the inclusion of electricity storage to mitigate the effect of variability, as well as the adoption of a mix of fuels rather than a single alternative to increase system robustness. The impacts from implementing battery-electric ships include instead lower energy demand overall as fewer energy transformations would be required, and lower costs overall due to the minor requirements in fuel production capacities. On the other hand, electricity storage would assume a greater importance, as this serves the dual purpose of balancing RES generation and acting as fuel storage, considering this is directly used to generate propulsion.

This research shows the impact of coupling green ports with alternative fuels production and RES generation. This defined the possible energy vectors that will shape the future PoB, underlining the relative importance of the different technologies. Battery storage will be crucial in balancing the system when powered by RES, and the production of fuels will represent a significant portion of the overall demand of the system. Nevertheless, the significant uncertainties related to possible future fuels make it complex to define future energy vectors with certainty, as these mostly depend on the alternative fuels that will characterize the market in the following decades.

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List of Abbreviations

APB – Autoridad Portuaria de Barcelona
BTL – Biomass to Liquid
CAPEX – Capital Expenditures
CO_2 – Carbon Dioxide
DAC – Direct Air Capture
DWT – Dead Weight Tonnage
EU – European Union
EV – Electric Vehicle
FAME – Fatty Acid Methyl Ester
GHG(s) – Greenhouse Gas(es)
GT – Gross Tonnage
HFO – Heavy Fuel Oil
LNG – Liquefied Natural Gas
OPS – Onshore Power Supply
OPEX – Operative Expenses
PoB – Port of Barcelona
RES – Renewable Energy Sources
VLSFO – Very Low Sulphur Fuel Oil

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1. Introduction

In the last few decades, one of the main topics on a global scale, with an always increasing importance, has been that of human-induced climate change. This is mostly caused by global emissions coming from the energy sector. This includes electricity, heat, and transport, and is the one with the highest pollution levels, causing approximately 73.2% of GHG emissions worldwide (Ritchie & Roser, 2020). To respond to this, the Paris agreement was signed, with the objective of limiting climate change to a maximum of 2°C with respect to 1990 levels. Successively, in 2021, the 'fit for 55' package was issued to align European economies with joint climate strategies (European Parliament, 2022). This poses the objective on reducing GHGs emissions by at least 55% by 2030, to successively become carbon neutral by 2050 (European Commission, 2018). This set of proposals includes multi-sectorial measures, including transportation, that is EU's most pollutant sector, causing approximately 28% of GHGs in the EU (McKinsey, 2021).

Within the transport sector, approximately 13.5% of emissions are generated by the maritime sub-sector. To this respect, estimates show the Netherlands are the main contributor of GHGs emissions in Europe for maritime transportation, with a net of 17.6 Mtons of CO2 (13.7 of which from the Port of Rotterdam alone), followed by Spain at 13.9 Mtons of CO2 (Transport and Environment, 2022). Port of Barcelona, which is the subject of this research, classifies second within Spain, with net emissions equal to 2.8Mton. These consider both those emissions that can be directly linked to all port activities and/or infrastructure and those generated from the shipping itself, meaning that these were produced due to vessels' propulsion systems. These latter accounted for around 93% of the total recorded for the system, by considering all the emissions from the ships calling at the port, allocated between the port of origin and that of destination (Ajuntament de Barcelona, 2020).

In line with EU strategies, PoB has announced that it aims at becoming carbon neutral by 2050 and has started taking steps towards this. In fact, since 2017, the Port's electrical supply is 100% green, and this accounts for roughly 87% of the energy consumption of the Port's common areas, managed by APB (PoB, 2021b). In addition to this, the Port announced a €110 million investment for the installation of an OPS system (also referred to as cold ironing) to completely electrify all cruise berths, the Prat Wharf, and Ferry Terminals of Sant Bertran and Costa by 2030 (PoB, 2022a). Furthermore, PoB wishes to install a smart grid system within the port and has already set up a pilot project, to maximize the benefits offered by flexibility and keep a live-tracking of the overall energy needs. These changes, along with others that will be aimed at carbon-neutrality by 2050, will likely shape the energy demand of PoB, and thus the current energy system will need to adapt to make this possible. On the other hand, the main challenge with respect to shipping decarbonization is posed by the ships themselves. In fact, due to the massive size of the boats, great quantities of fuel are required to generate the required propulsion energy, that is the main reason for which energy-dense fossil fuels are currently dominating the markets. Literature shows that there is a multitude of possible alternatives to sustainably perform the energy transition, such as biofuels (DNV, 2023), synthetic fuels (DNV, n.d.; REDIFUEL, 2021), or even by switching to electric vessels (Fleetzero, n.d.). On the other hand, the uncertainties that these would entail remain significant barriers in most cases. For biofuels, this is mostly represented by land-use competition, which causes limited feedstock availability, due to the higher priority of other sectors such as the food industry. Synthetic fuels seem to be promising alternatives but are costly and energy intensive in most cases. Powering ships' propulsion systems with batteries, on the other hand, would suppose significant costs for ship owners, and is uncertain whether long distances could be covered due to the energy density of batteries.

This study is performed as a though experiment, in which possible setups of a carbon neutral PoB are simulated and presented. This is done by focusing on the energy vectors of the port, considering the possible technological advancements that could characterize the development of these environments. This includes both the infrastructural side and the potential means to achieve the propulsion energy to move vessels from one port to another, represented by alternative fuels and other methods. To fully represent the investments and energy consumption to obtain these, fuel production was considered to happen under the port's jurisdiction. To realize this study, an optimization model was developed through the Calliope framework, which was developed to analyze energy systems with variable generation. First, the focus was placed on representing the energy demand, to estimate the magnitude of the energy requirements of PoB as a "green port". Successively, sustainable energy supply was implemented to identify the possible setups considering different combinations of methods for generating propulsion energy together with the optimal energy supply systems. This study was developed by exclusively considering the perspective of the port, meaning that this does not take into account the costs that fleet owners might face to sustain the resulting changes.

1.1. State-of-the-art literature and knowledge gaps

The concept of "green" ports is becoming common among scholars, due to the increasing importance of sustainability in planning and developing new infrastructures (Yun et al., 2018; Peng et al., 2020; Johnson & Styhre, 2015). Generally, electrification is considered as one of the most effective ways to reach this, as if this is powered by RES no CO_2 is released into the atmosphere. Because of the complexity of port environments, various technologies are being studied to change their different subsystems. Among these, OPS is one of the most promising, mostly because of ships being the main source of GHGs emissions, even when they are not travelling (Sifakis & Tsoutsos, 2021; Yun et al., 2018). Other measures include microgrids (Sifakis & Tsoutsos, 2021), electric cargo handling equipment, such as shore-to-ship cranes, and actions aimed at improving the overall energy efficiency of the system, such as automation of operations (Yun et al., 2018) or peak shaving (Doudounakis & Kanellos, 2015). Electrification is also being studied as a possibility for ships themselves, with the first full-electric container ship at sea in 2021 (Rapid Transition Alliance, 2022). Although, given the current limitations regarding electricity storage, different fuel alternatives are also being studied.

One of the main categories of fuels that are being considered is that of biofuels (DNV, 2023). These are generally drop-in fuels, meaning that they are produced with the objective of using them with current infrastructure and engines, by either replacing fossil fuels completely or mixing them together (Hsieh & Felby, 2017). This would imply lower capital expenditures for ship owners, increasing the acceptability of the option from their side. The main portion of the market is covered by bioethanol, that is mostly obtained by microbial fermentation of glucose-based biomass. Bioethanol is currently used for road transport, as it is not compatible with current marine engines, but multifuel diesel engine technologies might open the maritime sector to this biofuel. Amongst the options already in use, FAME (fatty acid methyl ester) is the most common type of biodiesel, that is produced by a process of transesterification of oils, mostly of vegetable origin. Other examples include BTL (biomass to liquid), produced from biomass via either the Fischer-Tropsch or the methanol-to-gasoline processes, or HVO/HDRD (hydrogen vegetable oil/hydrogenation derived renewable diesel), made by hydrotreating and refining fats or oils (DNV, 2023). Other solutions are instead still in study phase or are currently not economically viable for various factors. Methanol, for instance, is usually produced from methane due to its low costs but can also be produced via biomass. Although, most of the major projects worldwide to realize this have stopped, possibly because of the high costs to produce it in a renewable way (Helgason et al., 2020). Another category of alternative fuels that is increasingly represented in literature is that of synthetic fuels. These are produced by using renewable energy in the form of electricity, as well as a feedstock of carbon dioxide and water (DNV, n.d.). These can be produced by using electricity from the grid, with a dedicated energy system, or with a mix of both (Franz et al., 2021). A first example is methanol, produced via an electroreduction process in which carbon dioxide and hydrogen undergo a catalytic reduction. This fuel has high volumetric density and is easy to transport and store, but a new generation of engines would be needed to use this as marine fuel (*Methanex*, n.d.). Ammonia, when produced in a green way, is also being considered to decarbonize shipping. This is produced via the Haber-Bosch process combining hydrogen with nitrogen (Royal Society, 2020). This fuel has several advantages, as it is energy dense, easy to store and transport, and has an already established global market given its multitude of uses (DNV, n.d.). On the other hand, there are multiple barriers such as the need to refurbish or to change engines to the current fleet (DNV, n.d.), or the possibility of posing a threat for the world's nitrogen balance (Wolfram et al., 2022). Another option of synthetic fuels is represented by e-Diesel, that can be produced with the Fischer-

Tropsch process, similarly to BTL for biofuels (Elobio, n.d.). This fuel has several advantages, as it is compatible with existing engines, and it is more energy-dense when compared to other options. On the other hand, compared to other e-diesels in the market, this represents one of the most energy-intensive alternatives to produce (REDIFUEL, 2021). Hydrogen is also being associated with the energy transition of shipping, given its high gravimetric energy density, that is higher than that of fossil fuels (World Nuclear Association, n.d.). Furthermore, as hydrogen is used as feedstock for different alternative fuels, this option would likely require less conversion steps, and therefore lower investment requirements (DNV, 2021). On the other hand, the volumetric energy density of this element poses a significant barrier for its deployment as a marine fuel, due to the large volumes that would be needed for bunkering (Van Hoecke et al., 2021). The richness of available opportunities contributes to the uncertainties about which of these will prevail. Some studies even consider that fuel supply will possibly need to vary on a regional basis, given the limitation of resources and the simultaneous need to decarbonize other hard-to-abate sectors (DNV, 2022a). All these changes, in which the objective is to reduce fossil-based energy use as much as possible, will inevitably shape the overall power demand of the system. Therefore, additional generation will need to be installed, and to effectively decarbonize the system this will necessarily be based on RES. These will cause a certain degree of uncertainty to the system, given their characteristic resource variability in time (Koutsoyiannis, 2016). Further analyses were performed on the possible evolution of PoB towards a green port concept, as presented in the following chapters.

Many scholars have developed models with different objectives and scopes for what concerns ports. In the research of Yun et al., a model was developed to simulate operation processes in a container terminal under a quantitative perspective (2018). Peng et al. on the other hand adopted a different perspective, developing a machine learning method to predict energy demands of ships in green ports (2020). Another study by Ekmekçioğlu et al. developed a model to estimate the emissions from container traffic (2022). The common point of the three studies is the fact that they considered one portion of the port, being this the infrastructure, vessels, or the overall traffic of a certain category of goods. The current state-of-the-art literature does not present studies considering port systems as a whole, possibly because of their complexity, and therefore the difficulty of representing these with current methods. Furthermore, uncertainties related to renewable fuel production make it difficult to select realistic ways to represent this. Taking a more general perspective, other complex energy systems of different types or nature have been studied with different methods throughout the years. These have been developed using models such as Temoa, based on multi-state stochastic optimization to address uncertainties (*Temoa*, 2010), PyPSA, focused on planning the energy transition (Brown et al., n.d.), or Calliope, that was designed to analyze energy systems with high shares of renewables or other types of uncertainties (Pfenninger & Pickering, 2018). The latter has specifically been designed in a way for it to be suitable to represent systems of any size, from an urban to an intercontinental level. Different studies have been performed by using Calliope, such as Euro-Calliope, modelling possible pathways to decarbonize the European power system (Tröndle et al., 2020), or Bangalore-Calliope, modelling a district of the Indian city to deal with decision-making when faced with uncertainties (Pickering & Choudhary, 2019). Nevertheless, a representation of a port system on Calliope has not yet been developed. To build a model of a port, different factors need to be considered, such as the specifics of the different potential technologies to be adopted, as well as the energy vectors. Currently, the system receives RES-based electricity from the national grid and imports fuel, such as HFO, that is either fed to the vessels or stored for later use (PoB, 2022a). With the objective of decarbonization, the changes that the port will go through are multiple, and this will shape energy requirements as well. Additional inputs such as electricity to power up OPS, but also feedstock to produce alternative fuels could be needed (DECHEMA, 2017).

In conclusion, the lack of published studies in which a model of a port as a whole is developed, together with the lack of consideration of alternative fuels production, set the knowledge gap in literature. Calliope, a framework that was specifically created for analyzing complex energy systems, was identified as a viable tool to represent the future energy system of the PoB. Defined this, the main research question of this project is presented:

Which energy vectors could constitute Port of Barcelona's carbon-neutral energy supply, what could be their relative importance, and how could they be produced?

1.2. Research Questions

Given the primary research question, presented in the previous section, the following sub-questions were derived to structure the development of the project:

Sub-Question 1: ***What could be the total energy demand of a carbon-neutral Port of Barcelona, by considering the production of alternative fuels and other changes the port may undergo?***

Sub-Question 2: ***What could be needed in terms of energy storage, transmission, and RES generation capacities to sustain the total energy demand of the Port of Barcelona, by achieving carbon neutrality?***

1.3. Research Approach

This project is divided into three main phases: firstly, a literature review was performed to define the current state-of-the-art technologies, which systems might face the main changes, and how these changes could happen. This includes both the current state of the system, in which different activities are already facing changes towards more sustainable ways, and future changes, such as new technologies (i.e., OPS), new means of achieving marine propulsion (i.e., hydrogen-based methods), measures to improve efficiency of the (sub-) system(s), and possible ways to power up the system.

Secondly, the overall energy demand of the system is characterized by considering the current system and its inherent energy requirements, as well as the changes that are most likely to happen. Research was aimed at recreating PoB as realistically as possible, requiring both quantitative and qualitative research to identify the proper locations for the system. This subsists both for the definition of the geographical characteristics of the port in the model, and for the identification of the suitable locations for energy generation or import.

Lastly, the model development, which is done in three different phases, first considering only the energy demand, then by implementing energy generation, and lastly by including an additional means of generating marine propulsion energy, battery-electric ships. To represent this on Calliope, it was necessary to define the different locations, technologies and links composing the system. The outcomes from the model were analyzed and discussed to provide insights on the possible relations between technologies in future carbon-neutral ports.

1.4. Data Gathering, Research Methods, & Data Analysis Tools

Sub-Question 1: What could be the total energy demand of a carbon-neutral Port of Barcelona, by considering the production of alternative fuels and other changes the port may undergo?

This sub-question's main objective is to build up a representation of PoB's energy demand, considering both the current system, and thus the current traffic, and the possible changes that this could face. As the new technologies to replace fossil-based ones to perform activities are likely to be mostly electricity-based, overall electrical demand is set to increase. Because of the many uncertainties characterizing marine transport, the additional required energy has not been quantified yet. Furthermore, it was decided to include alternative fuels production within the scope of the system, as these create the opportunity of being produced locally rather than being imported, as happens with fossil fuels. Thus, both quantitative and qualitative research was performed to define the different aspects characterizing such a complex environment. This was carried out through desk research, exploring both the potential changes that could break through in the future, and the current state of things to define the base scenario to transform accordingly. Due to the complexity of the system, involving a multitude of actors and a wide array of potential technologies, elaboration of data was necessary in case of information gaps.

The main data analysis tool for this project was the model itself, which was developed with Calliope. Firstly, the model was built exclusively by considering the changes in energy demand, to define which technologies might be deployed given current characteristics. The outcomes of this phase were used as an input to develop the complete model, in which the focus shifted to the supply side, and thus to the effects of introducing variable generation into the system.

Sub-Question 2: What could be needed in terms of energy storage, transmission, and RES generation capacities to sustain the total energy demand of the Port of Barcelona, by achieving carbon neutrality?

The second sub-question focuses on the supply side of the system, with the objective of defining the necessary technologies and their capacities to support the energy demand of the system. Again, both quantitative and qualitative research was needed to define the ways in which this energy might be obtained, together with the potential locations to host the new systems, and the technologies to be considered. Defined these, the base model was taken and modified accordingly to provide it with the different identified options. The model is therefore again the data analysis tool, by implementing the different alternatives to supply energy to the system. Moreover, sensitivity analyses were performed to test the reliability of the data and assess the parameters affecting the most in the definition of the outcomes. The results from the two scenarios, together with the ones with the previous phase, were used as basis for a comparative analysis of the results.

1.5. Structure

This paper is structured as follows: Chapter 2 explores the state-of-the-art literature regarding different topics which were deemed to be meaningful for this project, represented by green ports, sustainable propulsion technologies, and energy systems modelling. In Chapter 3 the build-up of the demand model is explained, together with how the data was handled in order to make this possible, given the structure of Calliope. Additionally, the outcomes of the base model are presented and analyzed, to improve this towards the development of the refined model. Chapter 4 presents the supply system optimization and the changes that were made to the previously presented demand model. First, the changes that were made are explained and justified, and then the focus shifts to the explanation of the model refinement and presentation of the outcomes. In Chapter 5, the different obtained outcomes in the previous phases are discussed and compared. Furthermore, a reflection on the limitations of the model is provided. Lastly, Chapter 6 wraps up the project, by pointing out the main findings together with future research recommendations to give continuity to this work.

2. Literature Review

2.1. Green Ports

As introduced in the previous chapter, the current global landscape is characterized by increasing attention to the topic of sustainability. To this respect, the sustainability of shipping has emerged as a crucial concern. Maritime transportation plays a pivotal role in facilitating the movement of goods across vast distances. However, the environmental impact of traditional shipping practices, characterized by significant GHGs emissions, calls for a necessary transition. The different aspects impacting on this sector can be split into two sides: shore-side, represented by the infrastructure to process goods passing through the port, and seaside, in which ships require a determinate amount of energy, in the form of different fuels, in order to transport goods between ports.

For what concerns port infrastructure, OPS is arguably the most significant change that might be happening in the following years, probably representing the most promising technology to be introduced in future port environments (Sifakis & Tsoutsos, 2021). This consists in providing a connection between the boats and the electricity transmission system, with the final aim of powering vessels while they are at berth. While in port, vessels need less energy as this is not needed for generating propulsion, but a certain amount is required to perform in-port operations, such as (un-)loading, or keeping refrigerated cells at the proper temperature. Currently, this is done with an installed auxiliary engine, that is generally fossil fueled, thus emitting GHGs. OPS substantially consists in replacing these engines with a direct connection to the electricity grid. By doing this, emissions are avoided if the provided electricity is green (Bergqvist & Monios, 2019). Currently, there appear to be no clear alternatives for this technology, unless significant advancements are made in the development of alternative, carbon-neutral fuels. Given the magnitude of the share of the avoided emissions, this poses a great importance on the adoption of OPS worldwide. There are several ports which have started providing electricity with shore-side OPS. In Europe, Sweden's Port of Gothenburg was the first installing OPS, but the main example to this respect is represented by Norway, in which more than 50 ports are offering this service (Tariq, 2022). The recognition of the importance of this technology is reflected in the agreements reached on FuelEU Maritime, making OPS a requirement for certain ports by 2030 (ESPO, 2023).

By taking a deeper look at this technology, it is important to note that the requirements of installed capacity might significantly differ between different terminals. This is mostly due to the wide variety of ships calling at ports (PoB, 2022b), which have different sizes and different energy consumption levels. To this end, research from Gutierrez-Romero et al. (2019) theorized a set of formulas to calculate the power requirements of ships in function of their gross tonnage. This was done by analyzing a set of observations in the Cartagena Port (Spain) from 2010 to 2016, in which the focus was that of correlating energy consumption from the auxiliary engines while at berth with the gross tonnage of the ships (Gutierrez-Romero et al., 2019). Additionally, the study underlines how the current electrical transmission network does generally not have enough capacity to issue the required energy through OPS. Therefore, in order to successfully install this technology, the energy system needs to be adapted first.

Other than OPS, several technologies and measures are being studied as possible solutions towards reducing the environmental impact of the shipping sector. Among these, many are aimed at improving the energy efficiency of different subsystems, such as implementing data analytics to optimize system operations (Grosche & Haid, 2022; Soone, 2023), or hull optimization for vessels, while others are aimed at substituting existing polluting systems with sustainable ones, mostly through electrification. Nevertheless, these were not considered in the development of the model, and therefore a brief analysis is provided in *Appendix A1*.

2.2. Sustainable Propulsion Systems

While changes to the infrastructure are set to be quite significant, the main contribution can be achieved by substituting current fuels in use with sustainable alternatives. In fact, the majority of GHGs emitted within the shipping sector can be related to ships (Transport&Environment, 2022). Currently, the most common fuel in the sector is HFO. This is fossil-based, and therefore this contributes significantly to shipping emissions as this undergoes combustion in engines to generate energy. These can either be characterized by a dual-stroke, or a quad-stroke cycle, depending on the target speeds for the specific vessel (Ocean's Technology, n.d.). Starting from 2020, the International Maritime Organization has set a 0.5% limit on sulfur levels in fuels in determinate areas. This has brought the market to define a new category of fossil fuels, including different blends that respected this limit: VLSFO (Einemo, 2021). At the same time, the increasingly urgent changes that are needed to shape the shipping market in view of 2050 objectives made it necessary to explore different options. One of the fuel options that is currently experiencing a major growth phase is LNG. Its availability, together with low sulfur contents (Hsieh & Felby, 2017), made it a dominant alternative amongst fuels (Soone, 2023). This is reflected in the Alternative Fuels Infrastructure Directive (European Parliament & European Council, 2014), that states that "a core network of refueling points for LNG at maritime and inland ports should be available at least by the end of 2025 and 2030, respectively", setting an obligation for member states. Nevertheless, considering that these are fossil-based options, it was decided to rule these out from this study. This is because of the scope of this research, that is to find ways to decarbonize the whole port system by 2050, and therefore fossil based ways are not considered due to their carbon intensity. In contrast with fossil fuels, many different options can be found in literature, as already anticipated in the previous chapter.

2.2.1. Biofuels

The first category of alternative fuels to be analyzed is that of biofuels. These are fuels which derive in a direct or indirect way from biomass and can be divided into: solid biofuels (i.e., wood), liquid biofuels (i.e., biodiesel), and biogases (i.e., biogas from anaerobic fermentation). Due to the low sulfur content of biomass, and its renewable nature, these are currently regarded as one of the main possibilities for transitioning the shipping sector. Generally, liquid biofuels are the main category that is connected to maritime transport. The main reason for this is that these can be used as drop-in fuels. This means that these fuels are engineered with the objective of using the current infrastructure, by either replacing fossil fuels completely or mixing them together, without needing to adapt to new technologies, that would entail high capital expenditures for all involved parties (Hsieh & Felby, 2017).

Biofuels include different alternatives, such as FAME, BTL from Fischer-Tropsch or methanol-to-gasoline processes, or methanol. The breakthrough of biofuels is although likely to be limited, due to the barriers that these could face in the following decades. The main problem is that of feedstock availability, that might be caused by different factors. As the global population is constantly growing, food demand also is, and this means that more space for agriculture and farms is necessary. Another example is presented by plastic production, which can be bio-based, representing a potential new demand of biomass, and therefore of land as well (Philibert, 2017). Other forms of RES, such as solar panels, require land as well, and if the two are compared it can be noted how solar is significantly more efficient in energy generation. This is given by the fact that, while photovoltaic panels have an average efficiency of 20% (Centre for Sustainable Systems, 2021), biomass growth is based on plants photosynthesis. This process is characterized by a maximum efficiency that might range between 4.6% and 6%, depending on the type of plant, but with values that are generally significantly lower (Zhu et al., 2008). The issue of depending on the growth of plants is enlarged by the seasonality of most of the crops, that can be generally cultivated in determinate seasons. This problem might be solved by finding the proper combination of crops to optimize the overall energy output. On the other hand, attention needs to be paid to tackling soil depletion to avoid negatively impacting the environment (EUBIA, n.d.). Furthermore, biomass-based fuels are also considered as a possible option for decarbonizing other means of transport, increasing the pressure on land availability on a global scale (DECHEMA, 2017).

After carefully considering the option of including biofuels in the model, it was decided to rule these out. This is mostly because of the high uncertainties and barriers related to biomass availability, subject to the evolution of other sectors that might be prioritized.

2.2.2. Hydrogen

Hydrogen as a maritime fuel is an option that is gaining more momentum as a potential solution for the shipping industry's decarbonization challenges. Hydrogen not only represents a potential maritime fuel, but also a feedstock that serves as base to produce other types of fuels. At the same time, if hydrogen is directly used environmental and economic impact could be reduced, as fewer conversion steps would be involved (DNV, 2021). Hydrogen can be used either in gaseous or liquid form, and the decision depends on the requirements of the specific case.

Using hydrogen in its gaseous form, also known as compressed hydrogen, is the first option. Compressed hydrogen can be stored in high-pressure tanks on board of ships and used in fuel cells to generate electricity for propulsion. However, compressed hydrogen is not suitable for long-distance shipping, as the amount of compressed hydrogen required to power the vessel would take up too much space on the ship, making it impractical (Van Hoecke et al., 2021). Additionally, the safety concerns associated with the high-pressure storage of hydrogen must also be addressed before it can become a viable option for the shipping industry.

The second option is to use hydrogen in its liquid form, also known as cryogenic hydrogen. Cryogenic hydrogen is stored at very low temperatures, around -253 degrees Celsius, in insulated tanks. This method provides a higher volumetric energy density than compressed hydrogen and is more suitable for long-distance shipping. However, cryogenic hydrogen requires specialized infrastructure to store, transport, and handle the fuel. Moreover, there is a significant energy cost associated with liquefying hydrogen, which needs to be considered when assessing the feasibility of this option. *Figure 1* shows the differences in energy inputs to obtain the same output, when comparing compressed and cryogenic hydrogen with proton exchange membrane (PEM) or internal combustion engines (H2SHIPS, 2020). As can be seen, compressed hydrogen gas combined with PEM fuel cells is the most energy efficient way of using hydrogen as fuel. This implies an overall efficiency of 0.306, with electrolysis and fuel cells being the least efficient processes. The other two options, considering liquid hydrogen in combination with PEM fuel cells and internal combustion engines, are less energy efficient, with values equal to 0.276 and 0.225, respectively. On the other hand, liquid hydrogen would imply lower spatial requirements on board, given the lower volumetric density of its gaseous counterpart.

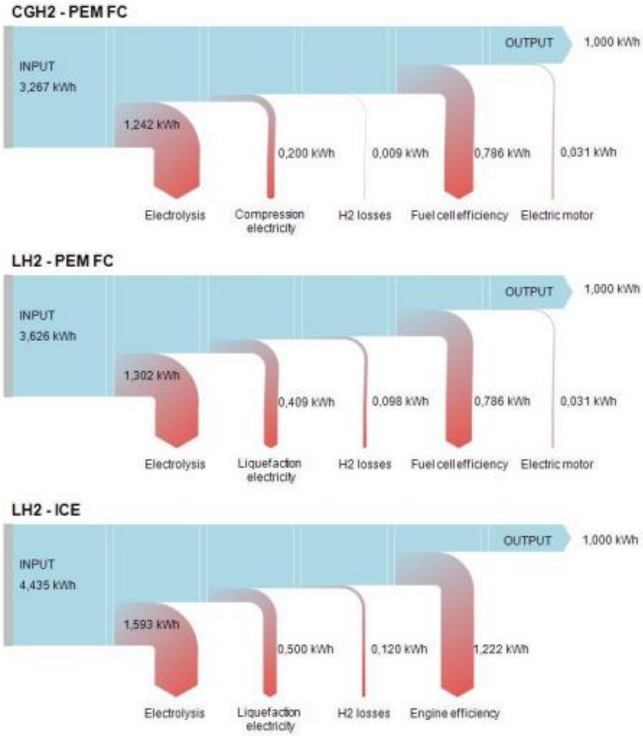

Figure 1: The energy efficiency of pure hydrogen options
Source: H2SHIPS, 2020

Switching to hydrogen as a maritime fuel would require significant infrastructural changes. These changes would include developing the infrastructure necessary for the production, storage, and transport of hydrogen, as well as the installation of hydrogen fuel cells and storage tanks on board of ships (Van Hoecke et al., 2021). The hydrogen infrastructure would need to be able to supply enough fuel to support the shipping industry's needs, which are significant. Additionally, the infrastructure would need to be built in a way that allows for safe and efficient handling of the fuel (Alternative Fuels Data Center, n.d.).

In conclusion, either gaseous or liquid hydrogen could be viable fuel options to decarbonize the shipping sector. Although, given the higher volumetric density of liquid hydrogen with respect to its gaseous form, makes the former a more credible option, also in view of the length of international shipping routes and the subsequent additional space to provide for hydrogen storage. Therefore, it was decided that liquid hydrogen would be included in the model as one of the fuel options. This was considered to be used in fuel cells, as shown in *Figure 1*.

2.2.3. Synthetic Fuels

Synthetic fuels, also known as electrofuels, have the potential to play a crucial role in the decarbonization of the transportation sector. These fuels are produced using renewable electricity, carbon dioxide, and water, providing a sustainable alternative to conventional fossil fuels (DNV, n.d.). For this study, three types of synthetic fuels were initially considered: e-methanol, green ammonia, and Fischer-Tropsch Diesel. As a carbon feedstock is necessary for producing e-methanol and Fischer-Tropsch Diesel, this was assumed to be gathered via Direct Air Capture.

E-methanol is a synthetic fuel produced by combining carbon dioxide and renewable electricity in a chemical process called electroreduction. The process involves the use of an electrolyzer to convert water into hydrogen and oxygen, followed by the catalytic reduction of carbon dioxide with hydrogen to produce methanol (*Methanex*, n.d.). E-methanol has several advantages as a fuel, including easy transportation and storage. On the other hand, it has higher volumetric density if compared to similar options such as hydrogen or ammonia, but lower when compared to current fuels in use, as a methanol bunkering would take up approximately 2.5 times the volume of an HFO storage on board (DNV, 2022b).

Green ammonia is another synthetic fuel produced using renewable electricity, water, and nitrogen. The process involves the use of an electrolyzer to generate hydrogen from water, followed by the Haber-Bosch process to combine hydrogen with nitrogen to produce ammonia (Royal Society, 2020). Green ammonia has several advantages, including high energy density, easy storage and transportation, and compatibility with existing infrastructure. Moreover, ammonia is a well-established commodity, with a global market already in place. Nevertheless, ammonia would require the fleet to change in order to be able to switch, as current engines cannot run on ammonia without incurring refurbishment (DNV, n.d.), as well as posing a potential threat due to its toxicity. Additionally, there is a fundamental problem that might be caused in the event of a significant switch towards this option. In fact, by deploying ammonia on a large scale, there is a chance that issues could arise because of a destabilization of the global nitrogen balance (Wolfram et al., 2022). Moreover, ammonia as a maritime fuel might end up emitting significant levels of N_2O, that could contrast the benefits from decarbonization efforts (Wolfram et al., 2022).

E-Fischer-Tropsch Diesel is a synthetic fuel produced from hydrogen and carbon dioxide. The process involves converting these reactants into liquid hydrocarbons using the Fischer-Tropsch process (Elobio, n.d.). Fischer-Tropsch Diesel has several advantages as a fuel, including high energy density and compatibility with existing infrastructure. At the same time, high energy consumption needs to be considered, as this process requires different steps and transformations. In fact, the Fischer-Tropsch process involves a series of steps in which different products are obtained. These are almost entirely represented by hydrocarbon chains with different lengths, and thus different properties. In order of ascending length, these include synthetic methane, synthetic gasoline, synthetic diesel, and waxes. The proportions between the different products are represented by the Flory-Schulz-Anderson distribution, and these depend on the process conditions, including temperature, pressure, time, and the selected catalysts (Kayfeci et al., 2019). For what concerns shipping, only diesel is generally considered, due to its lower cost with respect to gasoline, as well as its higher volumetric energy density, which is similar to that of fuels in use (Marchese et al., 2022).

The main differences between e-methanol, green ammonia, and Fischer-Tropsch Diesel are their production processes, energy densities, and compatibility with existing infrastructure. On the other hand, all these options generate from hydrogen, that is then combined with different compounds and undergoes different steps. E-methanol is produced by combining carbon dioxide and hydrogen, as well as Fischer-Tropsch Diesel, while green ammonia is produced by combining hydrogen with nitrogen. In terms of energy density, Fischer-Tropsch Diesel has the highest calorific value, ranging from 9.89 to 43.29 MJ/kg but an average of around 35 (Doustdar et al., 2016), followed by e-methanol at 22.7 MJ/kg (World Nuclear Association, n.d.), and then green ammonia at 18.72 MJ/kg (Fricke, 2018). This means that Fischer-Tropsch Diesel can provide a higher amount of energy per unit of mass than e-methanol and green ammonia. Moreover, e-methanol and green ammonia have the disadvantage of not being compatible with the existing fleet, while Fischer-Tropsch Diesel can be used in existing engines and fuel systems.

By comparing and analyzing these options and considering that at least one of these options should be included in the research given their importance and potential, it was chosen to include Fischer-Tropsch Diesel, considering the carbon feedstock to be obtained with DAC. Ammonia was ruled out mostly due to the possible risks related to its use. Threats for humans and for the global nitrogen balance make the feasibility of deploying ammonia as maritime fuel on a large scale highly uncertain. Methanol, on the contrary, would represent a safer option, but its lower calorific value with respect to Fischer-Tropsch Diesel and the need to refurbish the existing fleet to deploy this led to the decision of discarding this option.

2.2.4. Battery-Electric Ships

Other than fuels, batteries are also currently being studied as a potential solution for powering vessels. By directly using electricity for propulsion systems, the number of conversion steps would be minimized, increasing the overall efficiency of the system as less energy would be consumed overall to achieve the final objective. Nevertheless, the higher barriers in storing electricity when compared to liquid or gaseous fuels represent a challenge to this respect. Currently, different ways to make this feasible are being analyzed, with few examples already present in the market, generally represented by smaller vessels, but also bigger ships are being developed (Macola, 2020). Current market developments present different prototypes of large vessels, with innovative solutions such as installing RES on the boat (Maxwell, 2020), or by engineering interchangeable battery packs (Coldewey, 2022). In addition to the higher energy efficiency, if battery-electric ships were powered with renewable energy this technology would have no direct emissions as no combustion would be needed. Therefore, this could possibly represent the most effective option for decarbonizing the shipping sector, together with hydrogen-powered vessels. Furthermore, if costs for producing batteries were successfully driven down in the near future, this technology could become cost competitive when compared to other alternatives, as lower costs would be faced by fleet owners.

On the other hand, there are multiple barriers that this option would need to overcome to be able to successfully break into the market. Firstly, this type of vessel is currently limited in range, due to the use of batteries, that are limited in energy density and are more suitable for short-term rather than long-term storage (Coldewey, 2022). This represents a major issue when considering intercontinental shipping routes, in which voyages might last multiple weeks. Another major issue is that of providing the required charging infrastructure for two main reasons. First, all terminals should be equipped with charging points, and all vessels would need to be either refurbished or changed to fit the switch (Fleetzero, n.d.). This would clearly entail high costs for all involved parties, representing a major barrier without subsidies, especially for ship owners. Second, recharging times would need to be sufficiently low to avoid excessive waiting times or delays, according to the average stay of vessels when they call in at ports (Gutiérrez-Romero et al., 2019).

To address the range and charging challenges of electric ships, one of the solutions that is being engineered is based on the use of interchangeable battery packs (Coldewey, 2022). By using multiple containers as batteries and replacing these with recharged ones for each port call, vessels should theoretically be able to travel for longer routes. By doing so, recharging times would not represent a problem, as there would be a constant turnover allowing for lower lead times. Furthermore, this could represent an opportunity for ports to reduce their required capacities for electricity storage. Lastly, once these batteries are not suitable for use on ships anymore (i.e., due to their reduced capacity), these can be reused for other purposes, potentially providing a business case for these even when they stop being used.

In conclusion, battery-electric ships represent a potentially revolutionary option for the shipping sector, but at the current state of things these are not feasible yet. Although, it is possible that in the following decades technological advancements will make it possible to see these vessels deployed on a large scale. Therefore, it was decided to take these into account for the development of the model, but in a separate scenario in which these are included alongside the other two selected options.

2.3. Energy Systems Modelling

As mentioned in the previous chapter, there is currently a lack of studies considering port systems in a comprehensive way, meaning that these generally focus on specific subsystems. Nevertheless, given the complexity of ports, such an approach is limiting, as it is likely that it will fail to capture interactions between the different system components. Goods which need to be handled are constantly brought in by ships, which need to be hosted in terminals and refueled. The fuels that are fed into vessels could potentially be produced and stored locally, given the need to transition to non-fossil alternatives. Furthermore, future ports will likely be powered with RES, implementing a high degree of variability, and creating a necessity for electricity storage. All these subsystems need to be constantly balanced to allow for the proper functioning of the port, increasing the overall degree of complexity of the system. Such complexities require proper tools to be dealt with. Energy system models are tools aimed at recreating such environments, providing insights on the implications of applying determinate technologies or constraints to a system. The importance of these tools is underlined by the high degree of adoption among institutions, such as the IEA (Chiodi et al., 2015), as well as companies operating in the energy sector. Other than institutional models, aimed at developing more comprehensive and complex analyses, a multitude of alternative energy system modelling tools were developed.

Calliope is the first proposed example of energy systems modelling tools. This was designed to analyze energy systems of different sizes with high shares of renewables or other types of uncertainties (Pfenninger & Pickering, 2018). This allows for analyses with high spatial and temporal resolution, considering any type of manipulation that could be applied to energy. This has been used in multiple projects, ranging from districts, such as Bangalore-Calliope (Pfenninger & Pickering, 2018), to whole continents such as Euro-Calliope, representing decarbonization pathways for the European energy system (Tröndle et al., 2020). Python for Power System Analysis, or PyPSA, was developed to provide a tool to plan the energy transition (Brown et al., n.d.). This was used for multiple projects aimed at analyzing different aspects of energy systems. Research from Millinger et al. was aimed at assessing the cost efficiency of different categories of fuels in future scenarios (2022), underlining the barriers in the adoption of biofuels and the higher cost efficiency of electrofuels, or fossil fuels paired with CCS systems or negative emissions technologies. MARKAL and TIMES models are instead used by the IEA to develop analyses aimed at defining energy and climate policies (Labriet et al., 2018). These are generally used for exploring global technology roadmaps, energy and carbon prices, and others. Kim et al. developed a model-based study for analyzing decarbonization pathways for jet fuel production (2021). This involved the development of multiple models, including the TIMES model, to define the market shares of jet fuels in a net-zero scenario, including multiple sustainable routes to satisfy the overall demand. Results from this model show how in most cases the cheapest alternative involves a combination of fossil fuels and negative-emissions technologies. Other energy systems modelling tools include Tools for Energy Model Optimization and Analysis, or TEMOA, or SWITCH. TEMOA is formulated as a linear programming model based on multi-state stochastic optimization to address uncertainties. It allows for representing a wide range of systems, with the main objective of minimizing system-wide cost of supply given a determined time horizon (Hunter et al., 2013). SWITCH is instead an open-source system planning model, with the objective of analyzing the integration of RES into energy systems (Johnston et al., 2019). This was tested on different systems and aims at a minimization of system costs based on the net present value of the alternative options (Fripp, 2018).

As previously mentioned, few studies in literature focus on port decarbonization, and none of these comprehensively consider port systems. The work from Peng et al. was aimed at applying machine learning methods to predict the energy consumption of ships in green ports (2020). In doing so, the authors identify possible strategies to reduce the energy consumption of a portion of the system, although not considering this in relation with other systems composing the demand and the supply side of the energy system. Other studies focused instead on the optimization of ship layouts. Barone et al., for instance, developed a dynamic simulation approach to optimize the energy consumption of ships, resulting in savings of up to 18.1% of primary energy consumption (2021). From a port perspective, this would imply lower fuel demand, and thus lower costs.

3. Energy Demand Characterization

3.1. Data Collection

The focus is now posed on the definition of the model to represent PoB on Calliope. This was realized by considering available information, and by taking assumptions wherever it was deemed necessary to make up for knowledge gaps. As previously mentioned, the model was developed by considering the perspective of the PoB, and therefore does not account for any cost that is incurred by ship owners.

3.1.1. Port of Barcelona

As a starting point, traffic statistics for the year 2021 for PoB were considered for goods traffic (PoB, 2022b). There is a wide range of goods being moved through the PoB, which are grouped under three main categories: Containerized General Cargo, Non-Containerized General Cargo, and Bulk Cargo. Together, these totaled 64.99 Mtons of total traffic, of which 57.6% corresponded to containers, 25.9% to bulk, and the remaining 16.5% to general cargo. Data from companies operating with different types of goods shows how the energy consumption to process these once they arrive at the port can significantly vary, as shown below.

Containerized General Cargo accounts for more than half of the total tonnage of goods passing through the PoB, with a total of 37.46 Megatons. All of this is managed in two terminals: APM Container Terminal and Hutchison Ports BEST. Both are parts of bigger organizations managing a rich portfolio of terminals worldwide (A.P. Moller-Maersk Group and CK Hutchison Holdings), and therefore information was available on a global level rather than for the terminals themselves. Therefore, given that the total quantity of goods moved through the port was known, this was allocated in the two terminals according to their size, the overall container traffic numbers reported by APB (PoB, 2022b), and information provided by the two companies on a global level (CK Hutchison Holdings Limited, 2021; Maersk, 2022). Then the total energy consumption was calculated by considering the global performances of the two parties, which corresponds to 41.99 kWh per processed TEU for APM Container Terminal and to 50.83 kWh per processed TEU for Hutchison Ports BEST.

The second category in terms of magnitude is represented by Bulk Goods. These can be divided into two subcategories: liquid and dry bulk. Under liquid bulk, goods such as fossil fuels and chemicals are considered, while dry bulk is mostly composed of goods such as soybeans and cement (PoB, 2022b). In total, these account for 16.83 Megatons, 12.37 of which are relatable to liquid bulks. Given the size of the port system, it is consequential that multiple companies operate within its jurisdiction. For what concerns traffic of bulk goods, this is covered by 15 different companies. Among these, only three had publicly available information: Enagás SA (Enagás, 2022), operating with LNG; Tepsa (Tepsa, 2022), operating with Chemicals & Oil; and Cargill España SA (Cargill SLU, 2020), that imports and processes soybeans (PoB, n.d.-a). For each of these companies, energy consumption per ton of processed goods was calculated by combining the total volume of goods with the total energy consumption for in-terminal activities. This resulted in a unitary energy consumption of 14.2 kWh per ton of LNG (Enagás, 2022), 264.7 kWh per ton of soybeans, which are processed, and the end-product is stored in the terminal (Cargill SLU, 2020), and 2.5 kWh per ton for oils and chemicals (Tepsa, 2022). Nevertheless, as the above-mentioned companies do not cover all types of goods moved in the Bulk Terminals, assumptions were necessarily taken to define the total energy consumption characterizing these. It was chosen to consider Tepsa's unitary energy consumption, mostly due to the nature of the goods being moved by the other two companies. Enagás SA deals with LNG, which needs to be stored under specific conditions (Bahadori, 2014), and therefore has higher energy requirements when compared to similar goods. On the other hand, Cargill España SA has been found to be the company with the highest energy use per ton of goods, due to the processing of soybeans into refined goods.

The third and last category of goods is non-containerized general cargo, which is again characterized by a significant variety of goods, including cars, frozen fish, and others. For this reason, this subsector is characterized by a high number of companies. Furthermore, the data reported for this subsector has caused many goods to be grouped under a single name in the traffic statistics (PoB, 2022b). Therefore, given the low availability of information and the granularity of this sub-sector, it was decided that the energy consumption of non-containerized cargo would be considered equal to that of containerized. As the unit of measurement for Containerized General Cargo is TEUs, the average tonnage per TEU was calculated, and the average consumption was computed accordingly. This resulted in a final value of 4.59 kWh of electricity consumed for each moved ton of this type of goods in the PoB.

The information presented above is summarized in *Table 1*. For each category of goods that was considered, the tonnage and the unitary energy consumption were specified. These were used to compute the total consumption on a yearly basis, which was used as an input in the model.

Table 1: Overview of Goods Traffic in PoB (2021)
CGC: Containerized General Cargo; NCGC: Non-Containerized General Cargo; LB: Liquid Bulk; DB: Dry Bulk

Type of Goods	Quantity of Goods	Unitary Energy Consumption	Yearly Consumption (Goods Handling)	References
CGC – APM	873,122 TEUs (*9,260,332 t*)	41.99 kWh/TEU	36.66 GWh	Maersk, 2022; PoB, 2022b
CGC – Hutchison	2,658,202 TEUs (*28,195,689 t*)	50.83 kWh/TEU	135.12 GWh	CK Hutchison Holdings Limited, 2021; PoB, 2022b
NCGC	10,713,157 t	4.59 kWh/t	49.13 GWh	PoB, 2022b
LB – Enagás SA	2,798,790 t	14.2 kWh/t	39.74 GWh	Enagás, 2022; PoB, 2022b
LB – Others	9,571,790 t	2.5 kWh/t	23.93 GWh	Tepsa, 2022; PoB, 2022b
DB – Cargill SA	1,603,242 t	264.7 kWh/t	424.39 GWh	Cargill SLU, 2020; PoB, 2022b
DB - Others	2,856,502 t	2.5 kWh/t	7.14 GWh	PoB, 2022b
Total	**64,999,056 t**	**11.02 kWh/t**	**716.11 GWh**	

The above-mentioned calculations made it possible to quantify the total energy consumption required to handle all goods transported through PoB. On the other hand, to represent these numbers into the model, it was necessary to define a seasonality of traffic to allocate the energy requirements throughout the year. The above-mentioned reports of the port provided a breakdown of the total traffic into monthly totals, divided into containers and rest of goods (PoB, 2022b). In *Figure 2* the variation of the traffic of goods throughout the year is shown. The blue line, reflected to the left axis, presents the quantity of containers that pass through the PoB each month, expressed in thousands of TEUs. The orange line represents the rest of the traffic, namely bulk goods and non-containerized cargo, expressed in Mtons and reflecting on the right axis. It can be observed that in both cases traffic reaches its lowest levels in October, but the peaks of the two curves are different. The traffic of containers peaks in April at 317.5 thousand TEUs, while the rest of traffic peaks in July at 5.73 Mtons of goods overall.

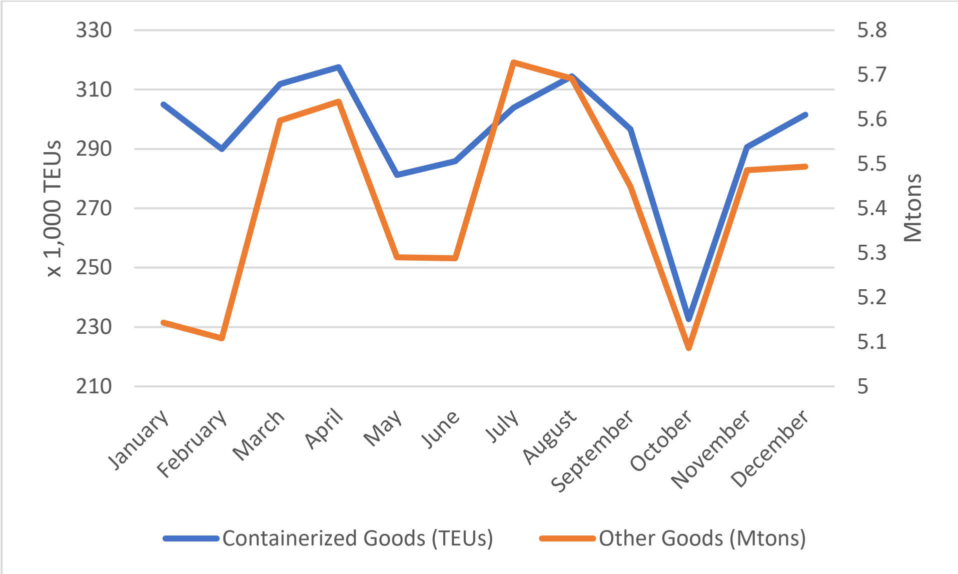

Figure 2: PoB Goods Traffic Seasonality – Containerized Goods & Other Goods

Other than the traffic of goods, another aspect of interest characterizing the port is that of passengers' traffic. This includes two categories of boats: cruises and ferries. Contrarily to what was done with Goods Traffic in the previous section, different years have been compared to recreate a realistic quantification of ship calls. This choice was taken because of the drastic changes in the number of passengers due to the Covid-19 pandemic (PoB, 2021a; PoB, 2022b). Furthermore, a different approach has been taken to calculate the number of calls for the two categories, given the different impacts of the global crisis in these. In fact, when comparing 2021 with 2020, the year in which the restrictions were present for most of the time, a 161.9% increase can be seen for cruises, against a 48.4% that has characterized ferries' traffic. This is mainly reflected in the thirteen straight months, starting in May 2020, in which the port reported no monthly calls for cruises, while in the same period ferries never stopped traveling (PoB, 2022b).

To represent the traffic of cruises it was chosen to consider the latest year that was not affected by Corona, 2019. This is justified by the fact that tourism rates have dropped significantly during the pandemic, mainly due to the impossibility of traveling. The overall number of passengers totaled almost three million that year, with 800 cruise calls in the port (PoB, 2020). The monthly breakdown of these shows how October has been the month with the most overall and daily calls, respectively 109 and 3.5. On the other limit, January has been the month with the smallest value in daily calls, 0.92, and together with February the one with the least overall calls, 29.

On the other hand, ferries' traffic was impacted in a different way with respect to cruises. This is mostly because of the nature of this type of transport, generally serving a line to connect closer (marine) locations. In the case of Barcelona, most of the ferries are used to connect the city with the nearby Balearic Islands daily (PoB, 2020). Whereas this might look like a touristic line, it serves as one of the main ways to connect the habitants of the islands to mainland Spain. Due to this, during Covid-19 the drop in ferry traffic was lower when compared to cruises. For this reason, to represent the traffic of ferries it has been chosen to compare the number of passengers of 2020 and 2021, and for each month the maximum between the two values has been considered.

To conclude the energy requirements for the current port infrastructure, the energy consumption for general purposes was considered. For the considered year, 2021, this equaled 7,764 MWh. Of these, 6,719 MWh corresponded to electricity, whose main end-use was to satisfy the electricity demand of the numerous administrative buildings and to grant the necessary outdoor lighting throughout the port area. The second highest reported value for energy consumption is related to vehicles' fuel consumption, with a total of 666 MWh of consumed energy split between diesel fuel and gasoline. Lastly, 372 MWh of natural gas were consumed. This is used exclusively for heating and domestic hot water in buildings. Being the energy demand for these significantly lower with respect to all other subsystems in the Port, it was assumed that these systems would switch to fully electric in a net-zero scenario. This can be done by substituting those parts still running on fossil-based energy for more modern ways. For what concerns vehicles, this is easily done by switching to EVs. Similarly, heating can be considered to switch to electric heat pumps (IEA, n.d.-b).

3.1.2. Marine Fuel Demand

Enlarging the perspective taken to analyze the system, it is easy to notice how vessels represent the bigger part of the system when it comes to energy requirements. This is almost entirely represented by a wide array of fossil-based fuels that vessels require to move goods between ports (IEA, 2022a). On average, roughly 80% of this energy is needed for propulsion, but this may vary depending on the type of ship (Sinha, 2021). For this reason, energy requirements of ships are significantly lower when in port, but while at berth the engines need to keep running to make it possible to operate, i.e., to unload the boat in case of crane-equipped vessels, or to keep cooling refrigerated goods.

Given the nature of PoB, in which various types of goods are moved, different types of vessels were considered to define the marine fuel demand characterization. These have different characteristics, summarized in *Table 2*. For what concerns fuel consumption, information was found about Container Ships (Windstar Cruises, 2020), Oil Tankers (Whittier, 2022) and Cruises (FreightWaves, 2020). These values were transformed, where considered necessary, to fit other types of vessels, and thus to make up for information gaps. The average gross tonnage of ships was provided by research from Gutiérrez-Romero et al. (2019). Lastly, yearly calls and total tonnage of goods were taken from PoB's traffic reports (2021a; 2022b), and by allocating the tonnage evenly between each call for each type of ship, the tons of transported goods per call were calculated.

Table 2: Vessel Types Specifications

Vessel Type	**Daily Fuel Consumption**	**Average GT *(Gutiérrez-Romero et al., 2019)***	**Tons per Call - own calculations based on *PoB (2022b)***	**Yearly calls *(PoB, 2021a; PoB, 2022b)***	**References**
	Liters HFOeq	*Tons*	*Tons of goods*	*#*	
Container Ships	2,652,343	7,905	17,308	2,164	*FreightWaves, 2020*
Ro-Ro Ships	*684,563*	5,197	10,432	1,027	
Chemical Tankers	*2,652,320*	1,304	59,248	18	
Oil Tankers	2,652,320	69,729	8,882	707	*Whittier, 2022*
LNG Carriers	*2,652,320*	51,875	8,885	315	
Bulk Carriers	*2,652,320*	8,152	60,143	95	
Cement Carriers	*273,182*	3,877	2,360	412	
Cruises	122,669 per trip	53,226	-	800	*Windstar Cruises, 2020*
Ferries	10,720 per trip	N.A.	-	2,510	

The numbers presented above were used to allocate marine fuel demand into the different terminals for the model, defining the proportions with respect to the overall numbers. For goods transport, it was assumed that the average distances to be covered by ships were constant for all ship types. By doing so, the difference between terminals' fuel demand is impacted by the average daily fuel consumption, and the number of calls in the port. For what concerns passengers' traffic, instead, a "base scenario" was considered to quantify the fuel requirements. For cruises, this is defined as a 12-hour travel to move towards other ports in the Mediterranean Sea. Differently, for ferries the main route was considered, corresponding to the Barcelona-Ibiza line, which serves tourism as well as providing the habitants of the islands of a connection to the mainland. This resulted in the following percentages, with respect to the total marine fuel demand: 46.86% is relatable to bulk goods, 45.87% to containers, 7.20% to non-containerized cargo, 0.06% to cruises, and finally 0.02% to ferries.

Once the proportions of the marine fuel demand were computed, fuel demand needed to be quantified. The most recent information that could be found in this respect accounted for the consumption of 2018, in which 1.5 million tons of fuel were consumed (Observatorio de los Servicios Portuarios, 2020). By comparing the total traffic of 2018 with 2021, which was selected as reference, it can be seen how these are almost equal, with a 1.4% greater value for the earlier year. Therefore, this decrease with respect to 2018 was accounted for in the calculation of the total, resulting in 1.479 million tons required for 2021. By considering the energy content of HFO of 11.36 kWh/kg, this can be translated into 16.80 TWh of energy. Additionally, HFO engine efficiency was combined with this value to define the actual energy that is required to generate the required propulsion, resulting in 8.40 TWh of effective propulsion energy demand.

By combining the total demand together with the previously calculated proportions between terminals, the total demand for each one was calculated. This is summarized in *Table 3* below.

Table 3: Propulsion Energy Demand Allocation

Terminals	Portion of Total Demand	Total Propulsion Energy Demand
Bulk Terminal	46.86%	3.936 TWh
Container Terminal	45.87%	3.853 TWh
Non-Containerized Cargo	7.2%	0.605 TWh
Cruises	0.06%	0.005 TWh
Ferries	0.02%	0.002 TWh

An additional factor that needs to be considered in the definition of the model with respect to marine fuel demand, is related to spatial requirements for what concerns the different fuel options. The current main fuel, HFO, has a volumetric energy density of 38.3 MJ/l (Aronietis et al., 2016). For what concerns the considered alternative fuels, this value is equal to 34.38 MJ/l for Fischer-Tropsch Diesel (*Fossil and Alternative Fuels – Energy Content,* n.d.), and to 8 MJ/l for liquefied hydrogen (Department of Energy, n.d.). Considering the volume required to store the same amount of energy, this translates to a 11.40% increase for Fischer-Tropsch Diesel. For liquefied hydrogen, the amount of required space would be 378.75% higher than for HFO. This difference underlines the necessity of considering a spatial factor for what concerns liquefied hydrogen. On the other hand, this variation in the spatial requirement for storing fuel does not impact in the same way for all types of ships, as these have significantly different characteristics. Therefore, it was deemed necessary to make estimations based on the actual size of the vessels calling at the port, and their specific fuel consumption. The calculations and the assumptions that were taken to reach the results are reported in *Appendix A2*. These resulted in terminal-specific spatial factors, differing depending on the quantity of transported goods. The resulting values are the following: 0.85 factor for container ships, 0.7265 for non-containerized general cargo, and 0.603 for bulk traffic. As the increased volume will have the effect of increasing the necessary number of boats to transport the same quantity of goods, it was decided to combine the spatial factors with the engine efficiency of hydrogen. This implies higher fuel requirements to satisfy the same traffic, reflecting the additional vessels that will likely need to be deployed to satisfy the same demand.

3.1.3. Onshore Power Supply

By analyzing the current setup of PoB, it appears that all terminals could be suitable for installing this technology, given the high degree of utilization. At the same time, the requirements of OPS systems could vary significantly depending on the type of ships, the average number of calls for each terminal and the mean time per call. Gutiérrez-Romero et al. (2019) theorized regression formulas to calculate auxiliary power requirements for different ships. These include most of the ships considered in this study, except for ferries.

For these, the requirements have been considered as the cruises', but proportioned to the average passengers these usually carry. This proportion was calculated by comparing the total numbers of passengers reported by APB (PoB, 2020). The different formulas that were used for calculations are presented in *Table 4*.

Table 4: OPS Regression Formulas per Vessel Type
Source: Gutiérrez-Romero et al., 2019

Vessel Type	**Regression Formula**
General Cargo	$1.328(GT)^{0.7321}$
Chemical Tanker	$108.6(GT)^{0.3062}$
LNG Ship	$2.597*10^{-11}(GT)^3 – 4.131*10^{6}(GT)^2 +0.2040(GT) + 422.6$
Bulk-Carrier	0.06610(GT) + 335.2
Oil-Tanker	$70.86(GT)^{0.3317}$
Container Ship	$4.217*10^{-6}(GT)^2 + 0.1331(GT)$ *or* $0.0003(TEU)^2 + 1.562(TEU)$
Cruise Ship	$-1.119*10^{-6}(GT)^2 + 0.3692(GT)$
Ferry	*Cruise Ship * (Average Pax Ferry/Average Pax Cruise)*

It can be seen how the demand of auxiliary power for in-port operations depends on the gross tonnage of the considered ship. Because of the quantity of ships calling at PoB, and the potential difference between them, average values for gross tonnage were taken. The same rationale was applied in defining the mean time per call per type of ship. Defining these two, it was possible to define the average consumption per call, and thus the total predicted consumption for each of the considered terminals. The results of these calculations are summarized in *Table 5*.

Table 5: OPS Requirements per Vessel Type

Vessel Type	**Auxiliary Power**	**Yearly calls *(PoB, 2021a; PoB, 2022b)***	**Call Time *(Gutiérrez-Romero et al., 2019)***	**Consumption**	
	kW		*Hours*	*MWh* **(per call)**	*MWh* **(yearly)**
General Cargo	697.4	1,027	46	32.1	32,946.6

Chemical Tanker	1,973.8	18	42	82.9	1,492.2
LNG Ship	3,513.8	315	49	172.2	54,235.5
Bulk-Carrier	874.0	95	38	33.2	3,155.1
Oil-Tanker	2,863.9	707	49	140.3	99,214.1
Container Ship	1,315.7	2,164	16	21.1	44,554.8
Cruise Ship	16,480.9	800	8	131.8	105,477.8
Ferry	1,871.6	2,510	3	5.6	14,093.1

To ease a comparison between these numbers, the consumption can be expressed in terms of kWh per ton of goods (or per passenger in the case of cruises and ferries). By doing so, considerable differences can be seen between different vessel types. For example, the lowest consumption per ton can be seen in bulk carriers, in which this equals 0.55 kWh. Contrarily, LNG ships consume 19.38 kWh per ton, roughly 35 times higher. These represent the highest difference for goods traffic. For what concerns passengers the relative difference is lower (13.46 kWh per passenger on ferries, 35.90 kWh on cruises), but this is caused by the assumptions taken to compute the gross tonnage, and thus the auxiliary power requirement, for ferries. By considering all the potential energy consumption in the different terminals exclusively for OPS, it can be seen how by installing this, 368.13 GWh would be provided in the form of green electricity, rather than using fossil-based engines. To provide a clearer image, if HFO was used to provide this energy, with an energy content of 11.36 kWh/kg (Aronietis et al., 2016), more than 64 ktons would be needed (considering a 50% engine efficiency). The yearly totals reported in *Table 5* were considered in the calculation of the electrical demand of the different terminals, allocating it proportionally to the seasonality of traffic of goods as presented in *Section 3.1.1.*

3.2. Demand Model

EX-Post Correction:

Following the obtained feedback from the Green Light Meeting, a few changes were made to the model to correct determinate errors which were identified. These are represented by the heat exchanges characterizing the model, as well as in the quantification of the hydrogen required to feed the calciner unit in the DAC-SOEC system. After considering the different temperature ranges at which the chosen technologies operate, it was concluded that no heat exchanges needed to be considered. Initially, exothermic reactions' waste heat, relatable to PEM electrolyzers and Fischer-Tropsch reaction plants, was considered to be reusable for the DAC-SOEC system. Nevertheless, after considering the required temperatures, it was concluded that this could not be the case. PEM electrolyzers result in low-temperature waste heat up to 90°C (Scheepers et al., 2021), while Fischer-Tropsch reaction results in medium-temperature heat, ranging from 220°C to 350°C (NETL, n.d.). On the other hand, this heat was initially considered to be reused for the calciner unit, operating at high-temperature heat ranging from 900°C to 1,600°C (Daniel et al., 2022). The same rationale is applied to the initially included industrial electric boilers, which can reach medium-temperature heat levels up to 350°C (TNO, 2018), but this cannot be used to achieve the target ranges. For this reason, electric boilers were excluded from the model. Moreover, given the initially neglected fact that H_2 enters the calciner unit to be burnt in combination with O_2, it was concluded that no heat input is required to obtain high-temperature heat. Furthermore, as this is directly connected to the SOEC co-electrolysis cell by providing the required reactants, operating in a range between 500°C and 900°C (Elder et al., 2015), these are transferred at the required temperature. On the other hand, the other error which was corrected is related to the amount of hydrogen to be fed into the calciner unit of the DAC system. In fact, for Fischer-Tropsch Diesel production, a syngas H2:CO ratio of 2 is ideal (Marchese et al., 2021). For this reason, the amount of hydrogen required for producing it was doubled.

The above-mentioned changes to the setup of the model have an impact on the previously reported results, as a technology was excluded and some energy exchanges were modified, either by taking them out of the model or changing the proportions between products. For what concerns the costs that were initially relatable to electric boilers, the changes are somehow limited, as reflected in *Table 6* below. As can be seen, the maximum CAPEX reduction due to this change can be related to the complete model, in which 448.1 MW of electric boilers were initially installed. This totals €62.7 million, which needs to be split among the 50 years of lifetime characterizing the technology. Compared to the objective function value, in the order of the tens of billions, this alone causes negligible changes. On the other hand, there are multiple factors that need to be considered in the identification of the changes to the results. First, the heat that was produced using electric boilers also represented electricity consumption, with the totals reported in *Table 6*. On the other hand, this needs to be put in relation to the total electricity consumption, equal to 86.9 TWh for the base scenario of the refined model. Another important factor is represented by the heat that was produced with other technologies. As heat balances were necessarily enforced in the model, it is possible that this led the system to favor technologies yielding waste heat, as this could have reduced the requirements for electric boilers' capacity.

Table 6: Electric Boilers - Impact on Results

Model Phase	Installed Capacity	Total CAPEX	Produced Heat	Required Electricity
Demand Model	140.0 MW	€ 19,600,000.00	83.7 GWh	84.5 GWh
Refined Model – Base Scenario	448.1 MW	€ 62,734,000.00	18.6 GWh	18.8 GWh
Battery-Electric Ships Scenario	4.2 MW	€ 588,000.00	4.3 MWh	4.3 MWh

On the other hand, the changes related to the hydrogen requirements for producing syngas might be decisive in the definition of the main fuel option to produce propulsion energy. In fact, by doubling the amount of required hydrogen to produce syngas, and subsequently Fischer-Tropsch Diesel, the costs for producing this significantly increase. On one hand, if Fischer-Tropsch Diesel is still chosen as the main option, this would require twice as much hydrogen, and the same for the energy required for its production, or the costs related to its purchase. Furthermore, this would possibly require a higher installed capacity, increasing overall investment requirements. On the other hand, by requiring higher amounts of electricity to produce the required hydrogen, the requirements for electricity storage might be lowered, partially compensating for the higher costs. Moreover, it is possible that, due to the higher costs associated with this option, liquefied hydrogen becomes more important, as this route did not change with respect to the previously presented model.

In consideration of these aspects, the model was changed to evaluate the differences between results. This was realized exclusively for a chosen reference case: the base scenario of the refined model. The choice fell on this scenario as this includes RES and the inherent variability of these technologies and is more impacted by the changes with respect to the battery-electric ships scenario, in which alternative fuels are less important due to the presence of battery-electric ships. *Table 7* presents a comparison of the main aspects of the model, underlining the changes caused by the corrections.

Table 7: Ex-Post Corrections, Reference Case Results Comparison

Technology	Capacity - before corrections	Capacity - after corrections	Change
Wind Onshore	21.8 GW	48.1 GW	+120.6 %
Solar PV	13.6 GW	29.9 GW	+119.9 %

DAC-SOEC	1.6 GW	489 MW	*-69.4* %
PEM Electrolyzers	615 MW	3.7 GW	+501.6 %
Hydrogen Liquefaction Plants	470 MW	2.3 GW	+389.4 %
Fischer-Tropsch Production Plants	2.5 GW	713 MW	*-71.5* %
Electricity Storage	4.6 GW	224 MW	*-95.1* %
Fischer-Tropsch Diesel Storage	4.4 GW	34.3 GW	+680.5 %
Hydrogen Storage	2.9 GW	17.9 GW	+518.3 %
Electricity Lines	2.3 GW	5.8 GW	+152.2 %
Hydrogen Pipelines	1.0 GW	Not installed	*-100.0* %
Total Costs	**€27.97 Billion**	**€28.80 Billion**	**+2.97** %

As can be seen from the results above, there are substantial changes in the strategy assumed by the model to satisfy the overall energy demand. In the reference scenario, total costs increased by 2.97% to €28.80 billion. This is because of the higher energy requirements to produce Fischer-Tropsch Diesel, as well as the increased importance of liquefied hydrogen. Before the corrections, its production efficiency was lower with respect to Fischer-Tropsch diesel's. This is not the case anymore, as the increased amount of hydrogen gas for e-diesel production made the system shift to liquefied hydrogen as the main fuel option. This is reflected in the capacity of hydrogen liquefaction plants, which increased by 389.4% up to 2.3 GW, and that of Fischer-Tropsch production plants, which decreased by 71.5% to a total of 713 MW. As the production of Fischer-Tropsch diesel dropped, it can be seen how also DAC-SOEC's capacity decreased by 69.4%. Given the increased energy demand overall, an increase in the RES generation capacity can also be observed, equal to 120.6% for onshore wind (up to 48.1 GW) and to 119.9% for solar PV (up to 29.9 GW). Subsequently, a 152.2% increase in electricity lines' capacity is required to accommodate the additional generation. The overall increase in consumption relative to fuel production, due to the lower efficiencies, also impacted on the installed capacity for electricity storage. The strategy adopted by the model leads to a tendency towards directly using electricity to produce fuels that are cheaper to store with respect to electricity. This is reflected in the 95.1% decrease in batteries' capacity, resulting in 224 MW. Moreover, this also impacts the capacity for fuel storage, increased by 680.5% for Fischer-Tropsch diesel, and by 518.3% for liquefied hydrogen. Lastly, a major change is seen in the installation of hydrogen pipelines, which are not installed after the correction of the model. The main consequence of this is reflected in the total installed capacity for PEM electrolyzers. This in fact increases by 501.6% to 3.7 GW, which is required to feed the production of the two fuel alternatives.

In view of the described changes, the results from all the three modelling phases would be different. Nevertheless, it was not possible to change all the phases, including the sets of results and the subsequent sensitivity analyses. Due to the characteristics of the three phases, the one chosen as reference is the one in which the impacts are more meaningful. The results as presented in the previous version of this document are kept in this version, as well as the sensitivity analyses that were previously shown. The previous sets of results provide a picture of the changes as described above and show some aspects that remain valid after the corrections. These are part of the reflections and conclusions from *Chapters 5* and *6*. The sensitivity analyses provide insight into the impact of the different technologies on the results of the three scenarios. Certain impacts might vary in view of the changes in the importance of the technologies, i.e., liquefaction plants would probably be more impactful with respect to the previous results set, while the opposite would be seen for Fischer-Tropsch reaction plants. On the other hand, these still provide information regarding the technology groups of the system and their impact on overall costs. These include fuel production technologies, RES generation technologies, energy storage, or energy transportation infrastructure. In practical terms, the set of results regarding the base scenario of the refined model was also updated in *Chapter 4*, but the rest of the results and the sensitivity analyses remain the same as the previous version of this report, with some small adaptations in the text to improve their clarity.

3.2.1. Technologies

Having defined the demand of electricity, as well as that for marine propulsion energy, the different technologies which might shape the future of ports need to be modelled. These are summarized in *Table 8* below. For the technologies aimed at manipulating energy, the energetic values for inputs are specified to provide more clarity on the definition of the respective process efficiencies. For what concerns costs originally reported in US dollars, a fixed change rate of 0.91 US dollars per euro was considered.

Table 8: Technology List – Demand Model

Technology	Cost	Efficiency	Inputs	Outputs	References
DAC + SOEC	€3,762.00/kW	37.8%	H_2(gas) 2 kWh Electricity 0.64 kWh	Syngas 1 kWh	Daniel et al., 2022
PEM Electrolysers	€978.00/kW	68.6%	Electricity 1.46 kWh	H_2(gas) 1 kWh	Danish Energy Agency, 2023b
Fischer-Tropsch Reactor	€477.00/kW	68.5%	Syngas 1.44 kWh Electricity 0.02 kWh	FT Diesel 1 kWh	Decker et al., 2019; Danish Energy Agency, 2023a
Hydrogen Liquefaction Plant	€2,650.00/kW	82%	H_2(gas) 1.22 kWh	H_2(liquid) 1 kWh	IEA, 2020; Connelly et al., 2019
Hydrogen Refuelling Station	€2,518.00/kW	65% (Hydrogen Fuel Cells)	H_2(liquid) 1.54 kWh	Propulsion Energy 1 kWh	IEA, 2020
e-Diesel Refuelling Station	n.a.	50% (Marine Diesel Engines)	FT Diesel 2 kWh	Propulsion Energy 1 kWh	-
e-Diesel Storage	€24.00/m^3-year	-	FT Diesel	FT Diesel	Edwards, 2022
Hydrogen Storage	€46.87/kgH2-year	-	H_2(liquid)	H_2(liquid)	Gaffney Cline, 2022
Electricity Supply	€0.0779/kWh	-	Variable Cost	Electricity	Fernández, 2022

As cost projections might present inaccuracies, especially if considering a longer time span, a decision was taken to consider projections for 2030. Net-zero targets are currently set for 2050, and thus the chosen numbers might be overestimations of reality. Nevertheless, given the significant timeframes for approving projects and their installation, 2030 could be representative of the moment in which investments will need to be made in view of PoB's decarbonization objectives. Given that this study represents a thought experiment, which does not aim at representing what will happen, but rather define possible net-zero scenarios, previous projections were taken to take a conservative approach and avoid underestimations of the possible costs for achieving this. For better clarity, a short overview of the different technologies is presented below.

The overall costs of the system are based on the capital expenditures that are required for each technology. These are reported in the table above and define the main costs for the system. Operating expenses (OPEX) are automatically dealt with by the model, as these depend on a combination of the capital expenditures and the capacity factors of the different technologies. To make a practical example, Fischer-Tropsch reaction plants are taken as reference. This technology requires a determinate quantity of syngas and of electricity, so that the reaction can take place. Both carriers are a result of deploying other technologies, which are characterized by a certain capital investment. Depending on the degree of usage of these, the cost of producing the different carriers might vary, as the lifetime is fixed for the model and the overall investment is allocated on each unit of obtained output. Therefore, OPEX for Fischer-Tropsch diesel production depends on the cost of production of the required inputs: syngas and electricity.

PEM Electrolyzers

Given the choice of fuels characterizing the model, represented by Fischer-Tropsch Diesel and Liquid Hydrogen, it is necessary for the system to produce hydrogen gas. In fact, this is required to produce both options. PEM electrolyzers were chosen for different reasons with the objective of satisfying hydrogen demand. With respect to alkaline electrolyzers, PEM are more compatible with the variability of RES, as these are not negatively affected by ramping up and down. Furthermore, the maturity of the technology makes it a potentially cheap alternative, as reflected in the cost projections (Danish Energy Agency, 2023b). In the model, PEM electrolyzers basically consist in a transformation of electricity into hydrogen, with an efficiency of 68.6%. This technology also yields a small amount of low-temperature heat, coming from the operating temperatures ranging between 70°C and 90°C. Nevertheless, this would not be reusable for other considered technologies. As it was chosen to not consider any export to systems external to PoB this was neglected, but in reality this could be sold to improve the business case and lower the costs for the port. The CAPEX of €978 per kW of installed capacity was taken from reports of the Danish Energy Agency (2023b), representing the average between the lower and higher values for 2030 projections.

Direct Air Capture + Solid Oxide Co-Electrolysis Cells

To produce e-Diesel with the Fischer-Tropsch reaction, a carbon dioxide feedstock is necessary. In fact, this is used as a basis to produce syngas, which is the main reactant in the production of Fischer-Tropsch Diesel. In the study from Daniel et al. (2022), direct air capture (DAC) is paired with a solid oxide electrolysis cell (SOEC) for co-electrolysis, as shown in *Figure 3*. In this system, DAC is used to extract CO_2 directly from the atmosphere, by using a series of reactions which involve different catalysts which first combine with CO_2 to take it out from the atmosphere, to then retransform it into carbon dioxide. Unlike the traditional DAC systems in which the calciner releases CO_2, this system considers hydrogen combustion to yield a mixture of CO_2 and water. Moreover, the high temperatures that are obtained with this method, ranging between 900°C and 1,600°C, allow for obtaining the necessary heat for the SOEC co-electrolysis cell, which operates between 500°C and 900°C. The reactions in the SOEC cells result in oxygen, which is re-used for the ignition of H_2 in the calciner unit, and syngas (H_2 + CO), which is the target product of this reaction.

As the technologies in the model and the parameters defining these are expressed in relation to the installed capacities, it was necessary to transform this technology in similar terms. For this reason, the values in *Figure 4* were considered to transform energy flows of different carriers into a quantity per MW. An H_2:CO ratio of 2 needs to be considered, this being optimal for obtaining a higher amount of diesel with respect to other products. Therefore, a ton of syngas is composed of 0.77 tons of CO (equal to 7.7 GJ, according to *Figure 4*), and 0.23 tons of H2 (equal to 27.6 GJ). This energy content was used to define the value in terms of MW for the model, resulting in 1 MW of capacity being equal to a production of 0.102 tons of syngas per hour. The CAPEX of €3,762 per kW of installed capacity was taken from Daniel et al. (2022).

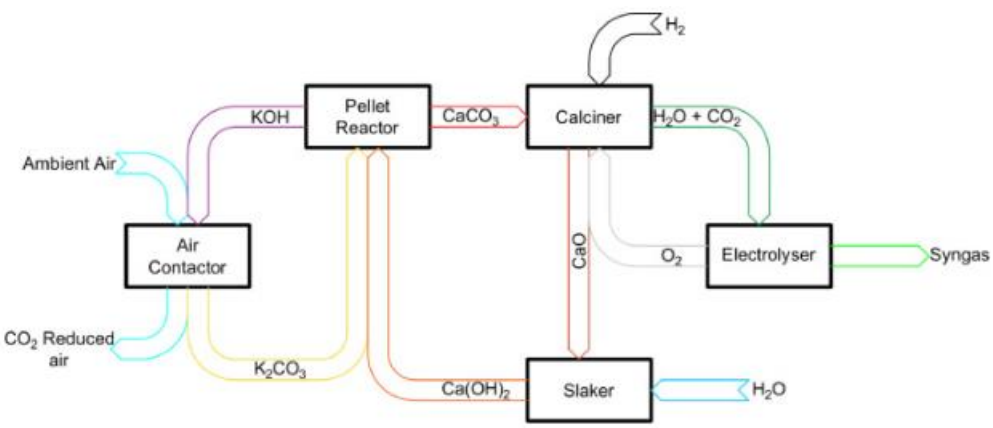

Figure 3: DAC + SOEC - Process Overview
Source: Daniel et al., 2022

Fischer-Tropsch Reaction Plants

After obtaining syngas, it is possible to transform this into e-Diesel via the Fischer-Tropsch reaction. This process, which takes place at high temperatures, yields a range of products, which consist in hydrocarbon chains with differing carbon numbers, as anticipated in Chapter 2. Nevertheless, for marine propulsion systems e-Diesel is the only product that would be considered. Shorter hydrocarbon chains, such as methane or synthetic gasoline, are more valuable than diesel as these can be used for fueling light vehicles, making it worth selling these rather than to use them for marine propulsion. Differently, longer hydrocarbon chains, which are waxes, are instead useful for other processes in the chemical industry. The proportions between the different products depend on the process conditions, such as the temperature or the catalyst chosen. Nevertheless, as these other products are not useful for the scope of the project, it was chosen to only consider part of the process. The ideal process conditions for Fischer-Tropsch Diesel production, according to the Flory-Schulz-Anderson distribution (Flory, 1936), would yield approximately 22.60% of Fischer-Tropsch Diesel with respect to the total products. In the model, other products have not been considered, and for this reason it was chosen to consider only the portion of the Fischer-Tropsch process proportionate to Fischer-Tropsch diesel, with the same proportions as *Figure 4* below. Therefore, to produce 1 kWh of Fischer-Tropsch Diesel, a total of 1.44 kWh of syngas and 0.02 kWh of electricity are required. While this might be an oversimplification, this decision was taken to avoid considering export from the system, as the alternative would have been to consider the whole spectrum of products and set a selling price for those which could not be used in the port. This could clearly improve the business case of this technology, as other products such as synthetic gasoline have a higher value due to their properties. Nevertheless, given the possible inaccuracies brought by the lack of information on price evolutions throughout the following years, it was chosen to avoid this method to not overestimate the value brought by this process. As Fischer-Tropsch reaction is a highly exothermic process, medium-temperature heat is also obtained from fuel production, ranging from 150°C to 300°C. The rationale that was applied is the same as the one introduced in the case of PEM electrolyzers, meaning that no export of any form of energy is considered in the model. Nevertheless, this can be taken into account for later studies. To define the capacity corresponding to 1 MW for the model, the values that were mentioned in the previous section were considered (with 0.102 tons of syngas corresponding to 1 MWh). The CAPEX of €477 per kW of installed capacity was taken from Decker et al. (2019), which represent current CAPEX values. Therefore, this was combined with cost reductions between now and 2030, considering the values provided by reports of the Danish Energy Agency (2023a).

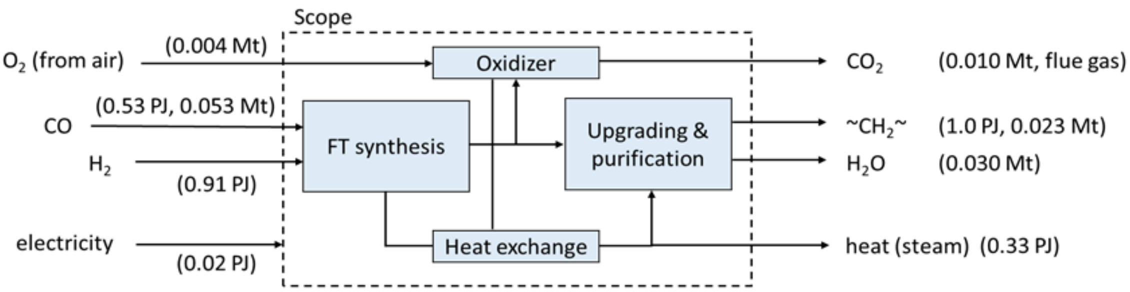

Figure 4: Fischer-Tropsch Reaction - Process Overview
Source: Detz, 2019

Hydrogen Liquefaction Facilities

For what concerns liquid hydrogen, liquefaction plants need to be considered to transform gaseous hydrogen. This is done to improve hydrogen's characteristics for using it in vessels, in which spatial availability is a crucial factor. In the model, this is represented as a simple transformation of hydrogen from its gaseous to its liquid form. The energy required for the system is considered to be in the form of hydrogen and is effectively reflected as a carrier loss during the process. Practically, for each kW of installed capacity in the model, 1 kWh of gaseous hydrogen can be transformed into 0.82 kWh of liquefied hydrogen for each timestep. The CAPEX of €2,650 per kW of installed capacity was calculated by taking the average between values reported by IEA (2020) and Connelly et al. (2019), which were later used as high and low values for the sensitivity analyses.

Fuel Storage

For both fuel options selected, storage technology was included, as not doing so would have resulted in unnecessarily high production capacities for fuel and lower capacity factors for these. For what concerns hydrogen, salt cavern storage was taken as reference, due to the large availability of salt deposits nearby PoB (Blanco & Faaij, 2018). For what concerns e-Diesel storage, normal tanks were considered, taking as reference the rates applied in the ARA zone (Amsterdam-Rotterdam-Antwerp) (Edwards, 2022). To model these, no losses were considered.

Refueling Infrastructure

Refueling infrastructure was included in the model as a way to transform fuels into "marine fuel", a fictional carrier that was used to unite the fuel options into a single demand. As costs were not found for diesel refueling infrastructure, these were initially neglected and later implemented in the sensitivity analyses. Furthermore, as the quantity of required fuels depends on the efficiency of the engines using these, this was included as a parameter characterizing refueling infrastructure, which is the last step towards the satisfaction of marine fuel demand. The CAPEX of €2,518 per kW of installed capacity for hydrogen refueling infrastructure was taken from IEA (2020).

Electricity Supply

In this phase energy generation is not considered, as this is introduced in the following chapter to explore the effect of variable generation supplying energy to ports. Therefore, in this phase electricity supply has been assumed to be unlimitedly available at a fixed cost. By doing so, the overall minimization of the objective involves minimizing the CAPEX and the energy use.

3.2.2. Demand Model Overview

Figure 5 represents a graphical overview of the different components of the model. The blue boxes represent the locations that were included to represent the structure of the PoB, including the different terminals, common areas, and a fictional location in which alternative fuels are produced. For each location, the technologies that compose this are indicated, including production technologies and demand technologies. Following the corrections that were made to the model, electric boilers were taken out, which were previously placed in the "Fuel Production Centre". The arrows connecting the different blocks represent the transmission system that allows for energy flows aimed at satisfying the overall system demand. In this phase, this is limited to electricity, represented in red, and the two considered alternative fuels, indicated with green arrows. In this phase, all of the energy that is fed to the system is provided at constant conditions, as the price per kWh is fixed and this is unlimitedly available in the form of electricity. The connection to the grid was assumed to happen in the "Common Areas", with in-port transmission infrastructure making it possible to move the electricity from here to all other identified locations.

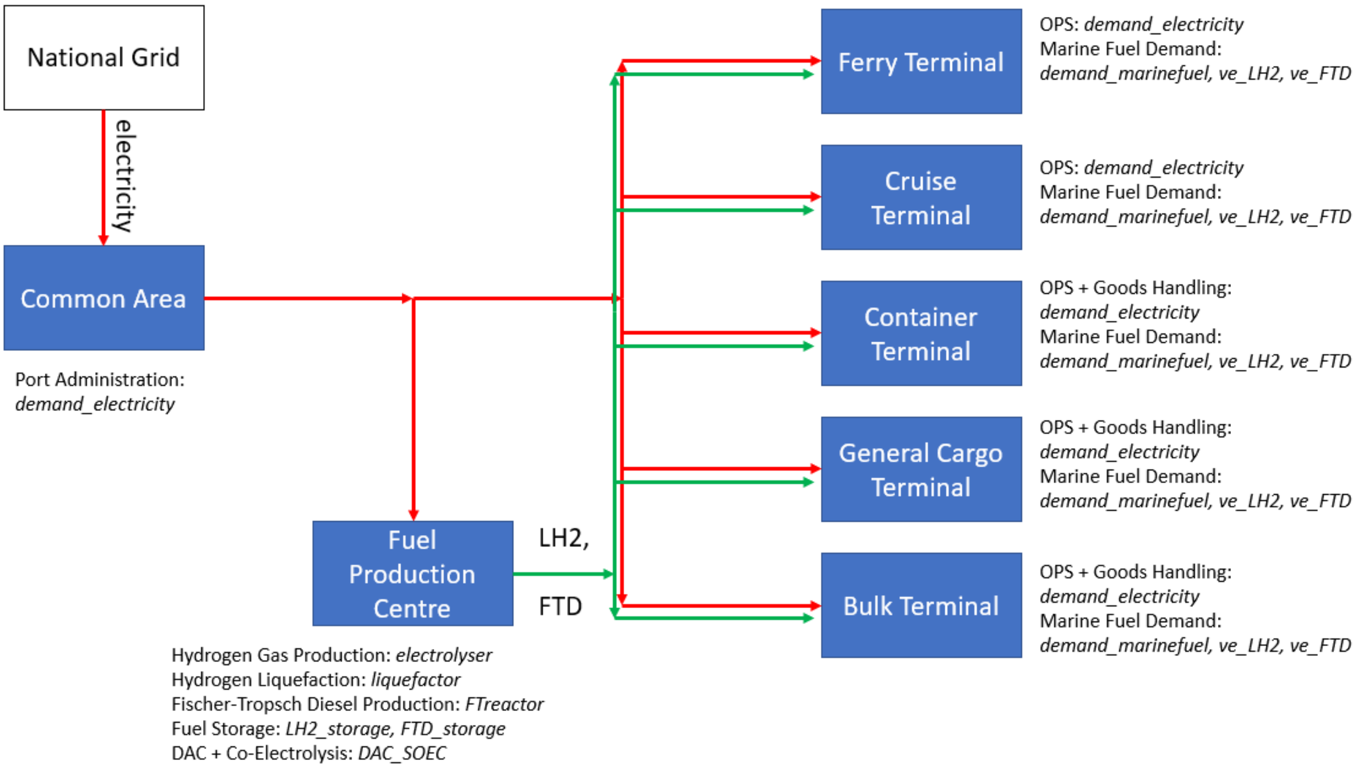

Figure 5: Demand Model Overview

For what concerns the different terminals, electrical demand is caused by two factors: the necessity of powering up the processes aimed at moving or processing different kinds of goods, so an infrastructural electricity demand, and on the vessels' side the requirements caused by the installation of OPS systems in the terminals. These were allocated according to the estimations as previously presented in this chapter, and by considering the seasonality of traffic. Thus, the granularity of this allocation was determined monthly, resulting in a constant value throughout each month. Differently, in the "Fuel Production Centre" the electrical supply is entirely used for generating the second energy stream characterizing this project, represented by marine fuels, including both Liquid Hydrogen and e-Fischer-Tropsch Diesel. After being produced, these are first stored in the same location, and then are transported to all terminals to satisfy marine fuel demand, as shown by the green arrows connecting the locations in *Figure 5*. For both demand streams the time definition of the model was set to be hourly, and marine fuel demand was allocated with the same principle as electrical demand, according to the traffic and its seasonality.

As the demand for propulsion systems was calculated in general terms, by considering current consumption levels and losses due to efficiency factors, the hourly demand was defined to represent the effective amount of required energy in kWh. As two fuel alternatives were considered, each with different characteristics, the demand was modelled as a single stream, and a fictional carrier was used to represent this, "marine fuel". This was coupled with the refueling infrastructure, which transforms alternative fuels into this fictional carrier, satisfying the propulsion energy demand. For a better understanding of the Calliope framework, additional information is provided in *Appendix A3*.

3.3. Results - Demand Model

The base model resulted in a value of the objective function equal to €36.17 billion, reflecting the expense that PoB might need to face each year according to current projections. This represents the costs for purchasing electricity, as well as the proportion of the capital expenditures, which depends on the lifetime of the technologies. Nevertheless, electricity prices are merely indicative, and are not present in the following chapter as generation is implemented. *Figure 6* shows the installed capacities for the different technologies that were considered. It can be seen how little capacity was installed for producing liquid hydrogen, showcasing the higher cost-efficiency of Fischer-Tropsch diesel production. The highest capacity is in fact installed to produce this, totaling 2,038.50 MW. In consequence, DAC-SOEC to produce syngas is necessary, totaling 1,395.60 MW, as well as PEM electrolyzers to provide the required hydrogen for this system, for a total of 1,402.40 MW. Lastly, the installed capacity for refueling infrastructure remarks the higher importance of Fischer-Tropsch diesel when compared to liquefied hydrogen.

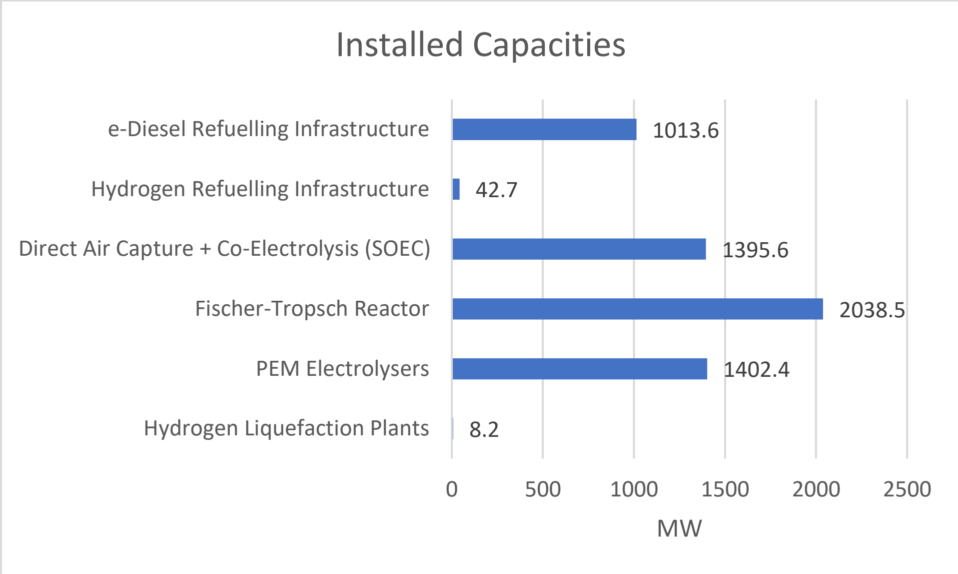

Figure 6: Installed Capacities, Demand Model

Figure 7 shows the installed capacities for fuel storage technologies. Again, this remarks the significant difference between the two, as up to 2,593.10 MWh of Fischer-Tropsch Diesel could be stored with the resulting capacities, against a mere 1.9 MWh for hydrogen.

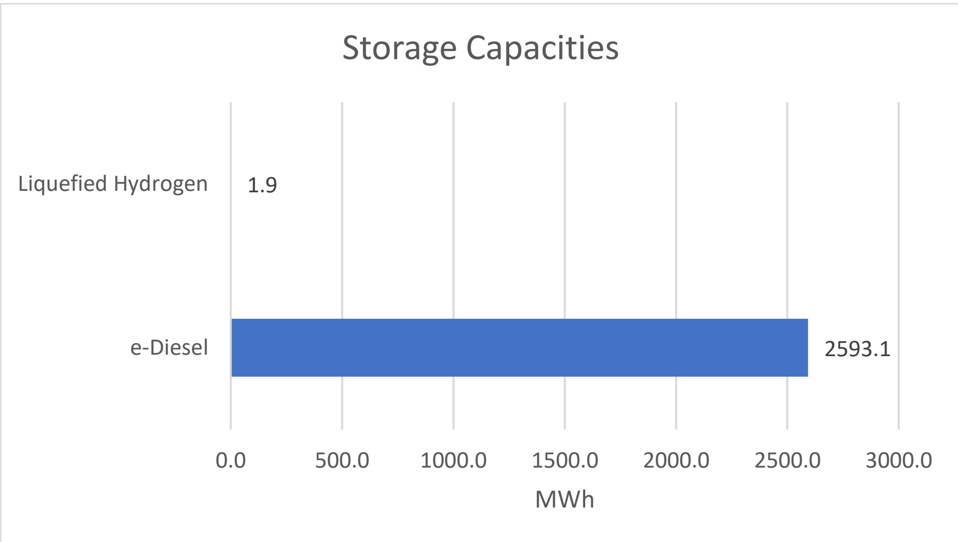

Figure 7: Storage Capacities, Demand Model

Figure 8 shows the total electricity consumption from the different subsystems considered in the model. It is important to underline how, in this phase, demand and supply are equal. This is due to the static price of electricity, which allows the model to minimize costs based on capacities. This explains how the consumption of electricity is nearly constant throughout each month, with slope variations when transitioning between these.

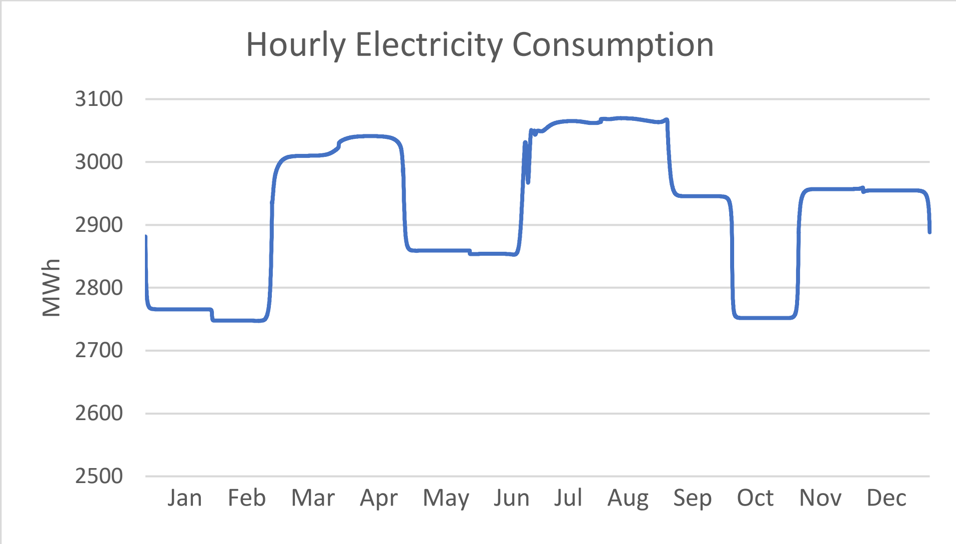

Figure 8: Hourly Electricity Consumption, Demand Model

Figure 9 shows the levels of fuel production throughout the year. As previously mentioned, Fischer-Tropsch Diesel volumes are significantly higher than the alternative. For this reason, liquefied hydrogen's production values are reflected in the secondary axis on the right. It can be noted that the curve representing e-Diesel production follows almost the same pattern as total hourly electricity consumption, as shown in *Figure 8*. The difference between these shows the portion of the electricity demand that is related to other systems, such as boilers, electrolyzers, or the DAC-SOEC system.

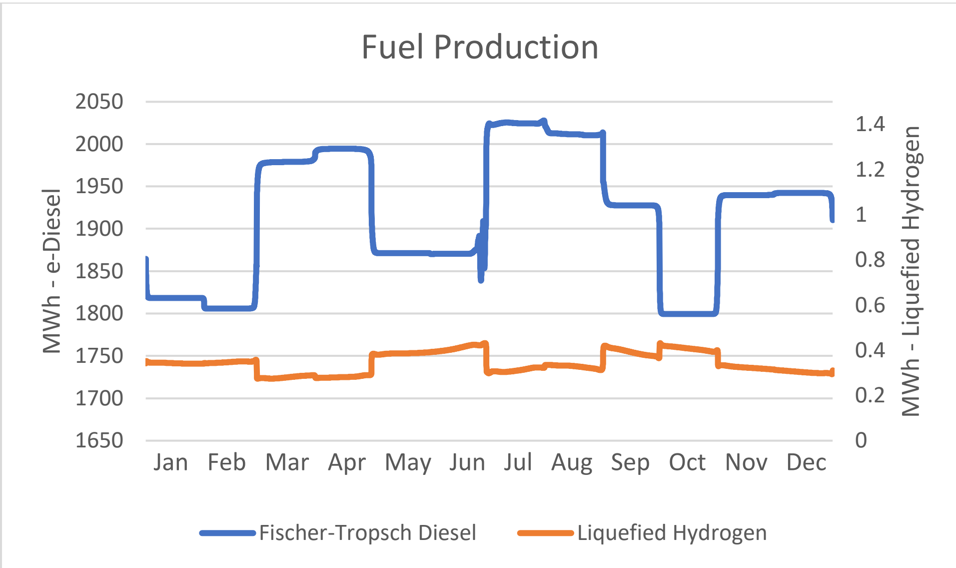

Figure 9: Fuel Production, Demand Model

For what concerns Fischer-Tropsch Diesel, *Figure 10* shows how its production and consumption impact the levels of storage throughout the year. Analyzing the trend, it is evident how summer is the period in which consumption is the highest, as storage is almost completely drained by the end of August. Furthermore, the almost constant levels of storage during determinate months underline how, in these periods, it is likely that production and consumption tend to be equal. Another important observation can be made regarding the months in which marine fuel demand is the highest, July and August. The storage level is gradually decreasing until this is fully depleted. This underlines how, unlike other months in which fuel production and consumption tend to be equal, during this period production levels cannot sustain the demand, and thus the system recurs to using previously stored amounts of Fischer-Tropsch diesel.

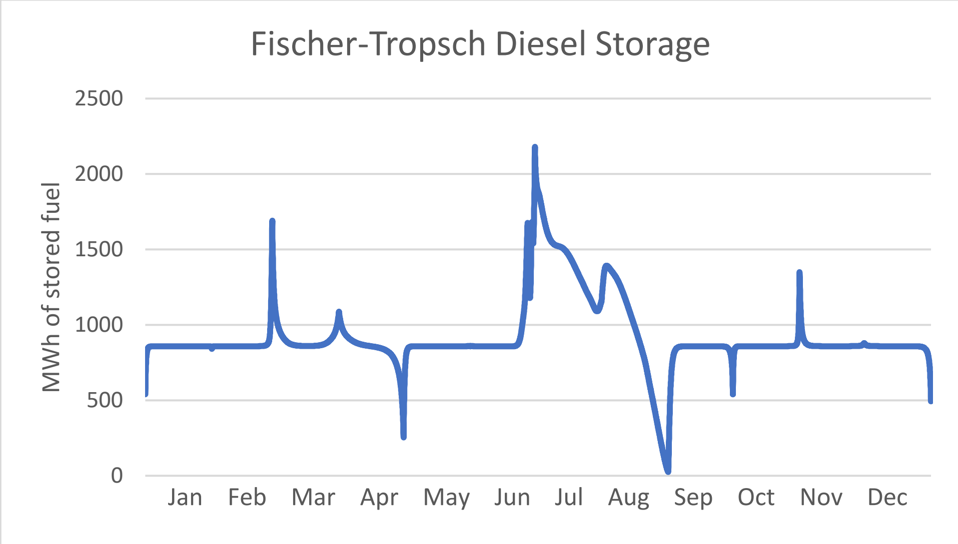

Figure 10: Fischer-Tropsch Diesel Storage, Demand Model

The hourly consumption of Fischer-Tropsch diesel is depicted in *Figure 11*, underlining what was mentioned above. Consumption and production levels tend to equal throughout each month, except for July and August as shown in *Figure 10*.

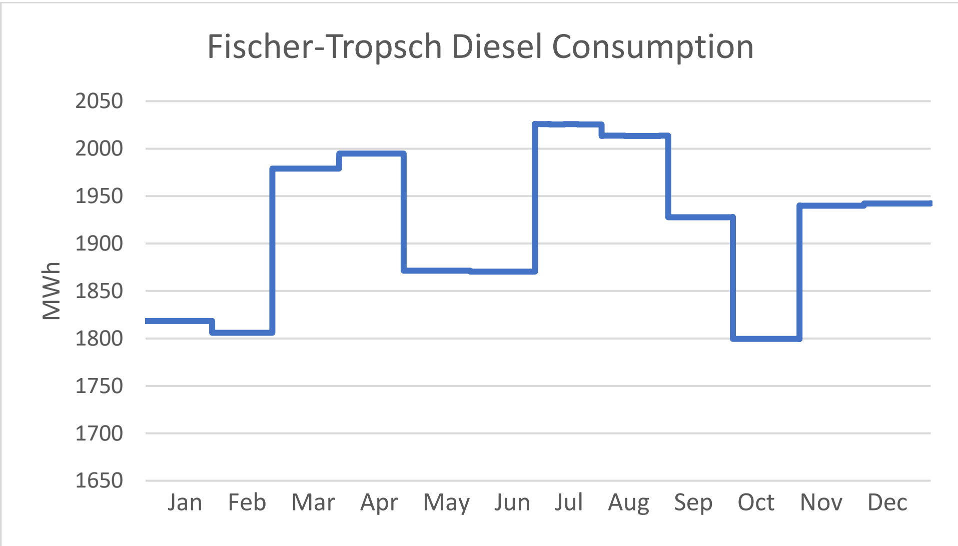

Figure 11: Fischer-Tropsch Diesel Consumption, Demand Model

For what concerns liquefied hydrogen, *Figure 12* shows the consumption throughout the year. As can be seen, the higher values are present in summer, with an increase of around 60% with respect to the start of the year. This is possibly the case as hydrogen is used as a back-up for periods with higher fuel demand. Nevertheless, this is used throughout the whole year, but the levels are almost insignificant with respect to e-Diesel.

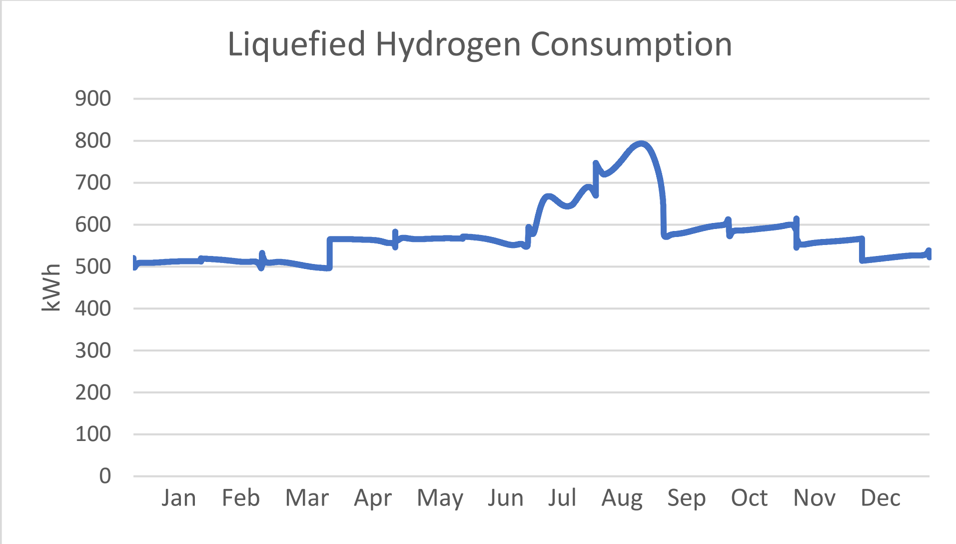

Figure 12: Liquefied Hydrogen Consumption, Demand Model

Lastly, *Figure 13* shows the levels of hydrogen storage throughout the year. As can be seen, this is almost constant in values, with a change of slope happening at the end of each month, showing the change in marine fuel demand.

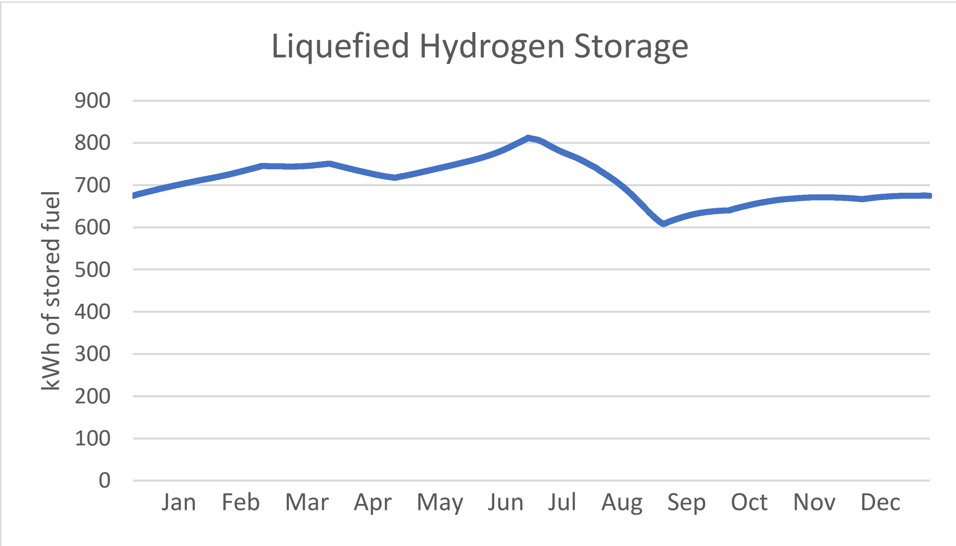

Figure 13: Liquefied Hydrogen Storage, Demand Model

3.4. Sensitivity Analyses – Demand Model

The purpose of sensitivity analyses in the context of the Calliope model is to assess the robustness and reliability of the preliminary outcomes. This involves systematically varying the input parameters of the model to evaluate their impact on the results. Furthermore, these might provide insights on the limitations of the model, as well as potential uncertainties. Analyses were performed by considering different parameters which were considered in the building of the model. *Table 9* presents an overview of these, showing the impact of the different parameters on the model. This showcases the parameters which have the highest impact on the value of the objective function. The parameters that were considered for these analyses are exclusively of economic nature, represented by CAPEX of the different technologies and electricity prices.

Table 9: Sensitivity Analyses - Overview, Demand Model

Technology	Base Value	Unit	Changed value	Reference	Variation	Objective Function	Variation	OF Base
						€ Billions		***€ Billions***
DAC+SOEC	3,762.00	€/kW	1,881.00	n.a.	-50.00%	35.765	-1.12%	**36.171**
			5,643.00	n.a.	50.00%	36.330	+0.44%	
PEM Electrolyzers	978.00	€/kW	591.00	Danish Energy Agency, 2023b	-39.53%	36.016	-0.43%	
			1,365.00		39.53%	36.207	+0.10%	
H_2 Liquefaction Plant	2,650.00	€/kW	1,417.00	IEA, 2020	-46.53%	36.081	-0.25%	
			3,883.00	Connelly et al., 2019	46.53%	36.199	+0.08%	
Fischer-Tropsch Reaction Plant	*477.00*	€/kW	423.00	Decker et al., 2019; Danish Energy Agency, 2023a	-11.28%	36.087	-0.23%	
			530.00		11.02%	36.229	+0.16%	
Electric Boilers	140.00	€/kW	100.00	Danish Energy Agency, 2023a	-28.57%	36.171	0.00%	
			150.00		7.14%	36.171	0.00%	
Electricity price	0.078	€/kWh	0	n.a.	-100.00%	34.039	-5.89%	
			0.156	n.a.	100.00%	38.211	+5.64%	
H_2 Refueling Infrastructure	2,518.00	€/kW	1,259.00	n.a.	-50.00%	34.039	-5.89%	
			3,777.00	n.a.	50.00%	37.469	+3.59%	
Fischer-Tropsch Diesel Refueling Infrastructure	-	€/kW	364.00	n.a.	n.a.	40.532	+12.06%	
			1,259.00	n.a.	n.a.	43.668	+20.73%	

DAC+SOEC

As shown in *Table 9*, the CAPEX of the DAC+SOEC system has a limited impact on the overall cost efficiency of the system. As can be seen, reducing this value by 50% only causes a 1.12% variation, while increasing it by the same percentage raises the objective function by 0.44%. By analyzing the differences between installed capacities of the two options, only minor changes can be identified, such as a slight increase in DAC+SOEC capacity (+2.35%) in the case of lower CAPEX, and the opposite (-3.44%) in the other alternative.

PEM Electrolyzers

For PEM Electrolyzers, the starting parameter was computed as the average between low and high estimates for 2030 (Danish Energy Agency, 2023b). Therefore, the two values that have been considered represent the two limits of the said range. These changes resulted in an even lower change of the objective function with respect to DAC+SOEC, equal to -0.43% and +0.10% when changing the CAPEX by 39.53%. Considering the installed capacities for the different technologies, a slight difference can be seen in fuel production. In fact, with a higher CAPEX value, liquefaction capacity is lower (-23.1%) and Fischer-Tropsch production higher (+0.4%). With a lower CAPEX value, the opposite situation is present, with similar proportions.

Hydrogen Liquefaction Plants

The analysis on the CAPEX of hydrogen liquefaction plants is based on two different estimates. The lower value was theorized by IEA and used to develop a report on global hydrogen markets in the future (2020), while the higher value was provided by Connelly et al. (2019). By focusing on the impact of changing this parameter, there is almost no difference in the objective function. This is reflected in the changes to the installed capacities. In fact, the only significant difference is in the installed capacities for liquefaction, with a variation of approximately 2 MW (+24.4%) for the low CAPEX value, and 1.2 MW (-14.6%) for the higher CAPEX.

Fischer-Tropsch Reaction Plants

For what concerns Fischer-Tropsch Reaction, the impact is again limited with respect to the objective function value, as this ranges from -0.23% to +0.16%, despite a 11% variation of the parameters. Considering the behavior of the system given this change, little difference can be seen due to it. In fact, a lower CAPEX caused a slight increase in Fischer-Tropsch Reaction plant, as well as a low decrease in liquefaction capacity, and vice versa in the case of a higher value.

Electricity Prices

Electricity prices were included to avoid having a CAPEX minimization in this phase, as resource availability is not considered. For this analysis, the base value of €0.078 per kWh, included in the model, was changed to €0 per kWh for the lower bound, and to €0.156 per kWh for the higher bound, doubling the base value. If electricity is free, the objective of the optimization shifts towards minimizing CAPEX. On the other hand, raising electricity prices means increasing the magnitude of OPEX within the system, and thus the optimization will shift towards minimizing energy use. It is noteworthy that, by considering the decrease and the increase, the variation of the objective function remains almost linear with respect to the variation in prices. This shows that the cost of electricity makes up for nearly 6% of the total yearly system cost.

Refueling Infrastructure

Lastly, for what concerns refueling infrastructures, different impacts can be seen when comparing hydrogen's and e-Diesel's. This is also due to the different nature of this analysis. For what concerns hydrogen, the cost reduction due to lower CAPEX (-5.89%) is higher than the increase caused by the higher parameter value (+3.59%). For what concerns capacities, the main difference is present in hydrogen liquefaction capacity, which is almost eliminated in the case of higher CAPEX, reaching a value of 0.5 MW. On the other hand, almost no change can be observed for what concerns the lower CAPEX, as refueling capacity only grows by +3.65%.

For what concerns Fischer-Tropsch Diesel refueling infrastructure, this analysis was structured differently due to the lack of information regarding the CAPEX for this. This led to the initial choice of not considering any cost related to this technology, to then explore the implications of implementing this in a sensitivity analysis. As shown in *Table 9*, this resulted in a +12,06% increase using the lower value, and in a +20.73% increase with the higher value. This underlines how the cost of this technology might represent a significant aspect that should be considered.

4. Supply System Optimization

4.1. Refined Model

This phase builds upon the previous focus on the demand side of the system, and primarily addresses the challenge of satisfying the additional energy demand. Considering the substantial amount of additional required energy to substitute fossil fuel demand, it is unrealistic to assume that the national energy system can meet this demand without significant changes. Therefore, in this phase the main focus is on the supply side of the energy system. This was considered in two possible ways, which are further explained below. Furthermore, an additional means of generating marine propulsion was considered in a separate scenario, battery-electric ships, to define the potential impact that this choice might have on the system. The additional technologies that were introduced in this phase are summarized in *Table 10* below. For each technology, CAPEX is reported, as well as the inputs and the outputs as these were modelled, and additional information such as efficiencies.

Table 10: Technology List – Optimization Model

Technology	***Cost***	***Others***	***Inputs***	***Outputs***	***References***
Onshore Wind	*€978.00/kW*	*η = 40%*		*Electricity*	*Danish Energy Agency, 2023a*
Solar PV	*€534.00/kW*	*η = 25%*		*Electricity*	*Danish Energy Agency, 2023a*
Battery Storage	*€622.00/kW*	*Min. charge: 20%; η = 95%*	*Electricity*	*Electricity*	*Danish Energy Agency, 2020*
Recharging Infrastructure – Battery-Electric Ships	*€728.00/kW*	*η = 95%*	*Electricity 1.05 kWh*	*Propulsion Energy 1 kWh*	*PwC, 2019*
Hydrogen Import	*€0.042/kWh (€1.40/kg)*			*H_2(gas)*	*IRENA, 2022a*
Electricity Transmission	*€0.849/km-kW*	*η = 99.7%*			*DeSantis et al., 2021*
Hydrogen Transmission	*€0.094/km-kW*				*DeSantis et al., 2021*

As in the previous phase, cost projections for 2030 were considered were possible. The technologies presented above are further explained below.

4.1.1. Electricity Generation and Transmission

The first option that was considered to supply energy to the system is that of installing new RES generation. To this respect, two technologies were considered: onshore wind and solar photovoltaic. These were chosen due to their maturity, as well as the high availability of the resources these are based on in the vicinity of the port. The presence of the sea makes the Mediterranean coast of Spain a regularly windy area. More importantly, Spain is amongst the EU countries with the highest solar irradiation levels. This is represented in the solar and wind maps of Europe in *Figure 14*.

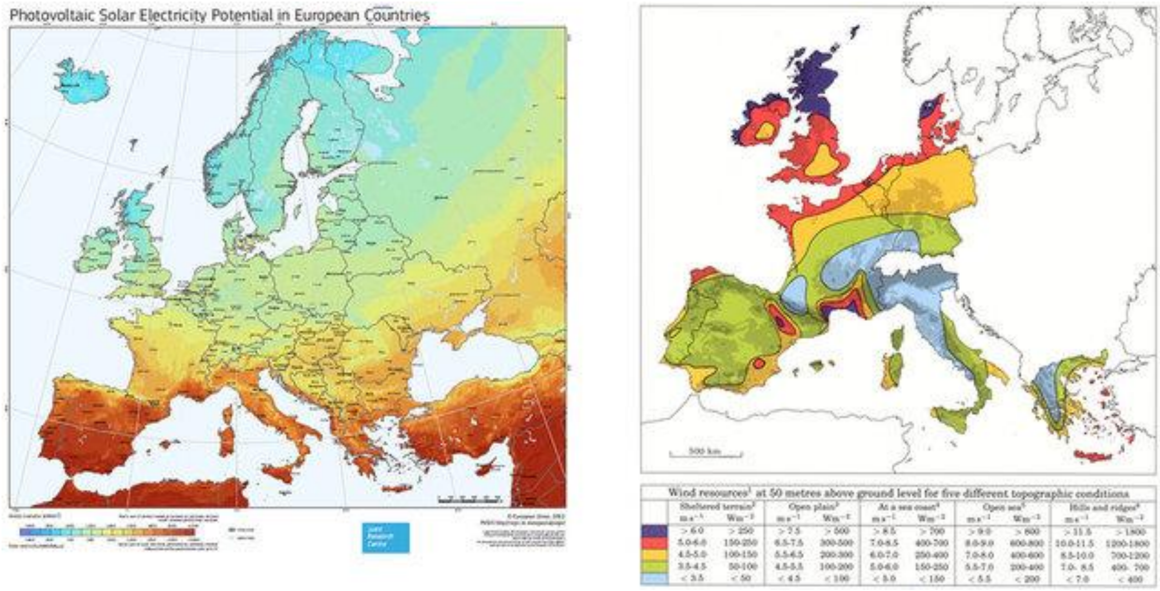

Figure 14: Left, Solar Map of Europe; Right, Wind Map of Europe
Source: Talebi et al., 2016

To represent this, a location near Barcelona was chosen as a reference point. However, it is important to note that this location does not fully capture the actual locations where these systems could be installed. Considering the limited availability of space around the city, it is unlikely that enough generation capacity could be accommodated to support the entire energy demand of the port. Therefore, the modelling approach was designed to provide insights into the scale and magnitude of the generation systems required to support the energy demand of the port, rather than its specific location. To represent RES availability, data from 2021 was gathered from Renewables Ninja (n.d.), setting the coordinates of the location that was chosen as reference. This is in the hills North of the city, and the coordinates are the following: latitude of 41.4796, and longitude of 2.0113. Moreover, said coordinates were used by the model as well to compute the distance between supply and demand. For this reason, CAPEX for transmission system has been considered in the form of €/km-kW, taken from DeSantis et al. (2021). The CAPEX for RES generation capacity was instead taken from Danish Energy Agency (2023a), representing the projections for 2030.

4.1.2. Hydrogen Import and Transmission

The second option that was considered to account for energy supply in the model is that of importing hydrogen from Morocco. Several factors contributed to the selection of Morocco as the potential source country for hydrogen gas importation. First and foremost, the relative proximity of Morocco to the PoB makes it a geographically favorable option. This proximity facilitates efficient and cost-effective transportation of hydrogen gas, reducing logistical complexities and associated expenses. Moreover, the cost projections for green hydrogen production in Morocco make it an attractive choice. Current cost estimations range from €0.70 to €1.40 per kilogram of green hydrogen (IRENA, 2022a), translating into 0.021 and 0.042 €/kWh, respectively. These cost considerations, alongside Morocco's significant potential in the near future, make it an appealing candidate for hydrogen gas importation. Importing hydrogen gas from Morocco was considered as a more feasible alternative compared to transporting electricity. The challenges associated with transmitting electricity over long distances, particularly across natural barriers such as the Mediterranean Sea, are substantial. Additionally, electrical transmission has a higher cost when compared to hydrogen, when considering it in terms of cost per distance per capacity, measured in € per km-kW (DeSantis et al., 2021).

To represent the import of hydrogen gas from Morocco, several modelling considerations were taken into account. Firstly, the location of the hydrogen production facility was situated in the Moroccan side of the Sahara Desert, chosen due to its high solar irradiation, which allows for efficient and abundant renewable generation. The abundant solar resources in this area make it an ideal location for harnessing solar power to produce green hydrogen (Hydrogen Council & McKinsey, 2021). In terms of costs, the model incorporated the projections for green hydrogen production costs in Morocco. As a starting point, the estimates of €1.40 per kg were considered, while other values were kept in consideration later while developing the sensitivity analyses. Furthermore, the transmission infrastructure required for importing hydrogen gas from Morocco to Barcelona was considered. This was considered to happen exclusively via pipelines to ease the representation of this in the model. These would need to be partly offshore, given the presence of the Mediterranean Sea between the two locations. Estimates from Desantis et al. (2019) were considered to calculate the costs of installation, resulting in an investment requirement of €0.094/km-kW for installing such a system. Considering the current situation of the Maghreb-Europe pipeline, which is unused due to international tensions, the prices could be driven down, as refurbishment could be chosen rather than new installations. Nevertheless, this goes out of the scope of this research, and was therefore not considered.

4.1.3. Battery Storage

The introduction of RES generation makes it necessary to introduce some form of electricity storage into the system, with the main objective of balancing variable generation. As energy export was not considered within the system, storage makes it possible to balance the trade-off between over-installing generation and production capacity. Furthermore, with the introduction of battery-electric ships, this has an additional use, as this could also be considered as fuel storage. For this reason, in the alternative model with battery-electric ships, this was included in all terminals, in addition to a general storage, which is present in the base scenario as well. For what concerns the model, batteries were represented to be used only for 80% of their capacity, to maximize their lifetime. The CAPEX of €622 per kW of installed capacity was taken from reports of the Danish Energy Agency (2020).

4.1.4. Battery-Electric Ships

Battery-electric ships offer the advantage of directly utilizing electricity for propulsion systems, minimizing conversion steps, and enhancing overall system efficiency. Although examples of smaller vessels utilizing this technology already exist in the market, larger ships are also being explored, with innovative solutions such as integrating renewable energy systems on board or engineering interchangeable battery packs. Battery-electric ships powered by renewable energy sources have the potential to be amongst the most sustainable options for decarbonizing the shipping sector since they produce no direct emissions due to the absence of combustion (Infineon, 2021). Furthermore, as costs of battery production decrease in the future, this technology may become more cost-competitive compared to other options, as shipowners would face lower variable costs. However, there are significant barriers that battery-electric ships must overcome to penetrate the market successfully. One major limitation is their current range due to their energy density, which makes them more suitable for short-term rather than long-term storage. This poses challenges for intercontinental shipping routes that span multiple weeks. Another significant hurdle is the establishment of adequate charging infrastructure. This entails equipping all terminals with charging points and retrofitting or replacing vessels to accommodate the switch to battery-electric power. The associated costs pose a significant barrier, particularly for ship owners, but current technological developments are improving the business case for these (Kersey et al., 2022).

Given the perspective taken by this project, which aims at defining the costs for the PoB, the only cost that was considered in addition to already present components is that of recharging infrastructure. This clearly puts this option in advantage with respect to the other alternatives, as fewer conversion steps are required, and this implies that no production facilities are needed for this. Nevertheless, the requirement of high quantities of energy for marine propulsion, as well as the variability of RES generation, could significantly increase the costs of the system due to the necessity of installing battery storage. The objective of this inclusion is to assess the effect of variability towards the optimal combination of marine propulsion systems, as well as providing an estimation of the potential savings for PoB. The CAPEX of €728 per kW of installed capacity of refueling infrastructure was taken from Pwc (2019).

4.1.5. Refined Model Overview

Figure 15 shows an overview of the refined model, considering the changes as previously introduced. The main changes with respect to the previous phase are represented by the supply side, as RES generation and hydrogen import are considered. For the former, it was necessary to also include battery storage. Furthermore, transmission systems for these were considered, taking into account current cost projections to represent these in the model. For what concerns the battery-electric ships scenario, also the technologies written in red in the figure are included in the model.

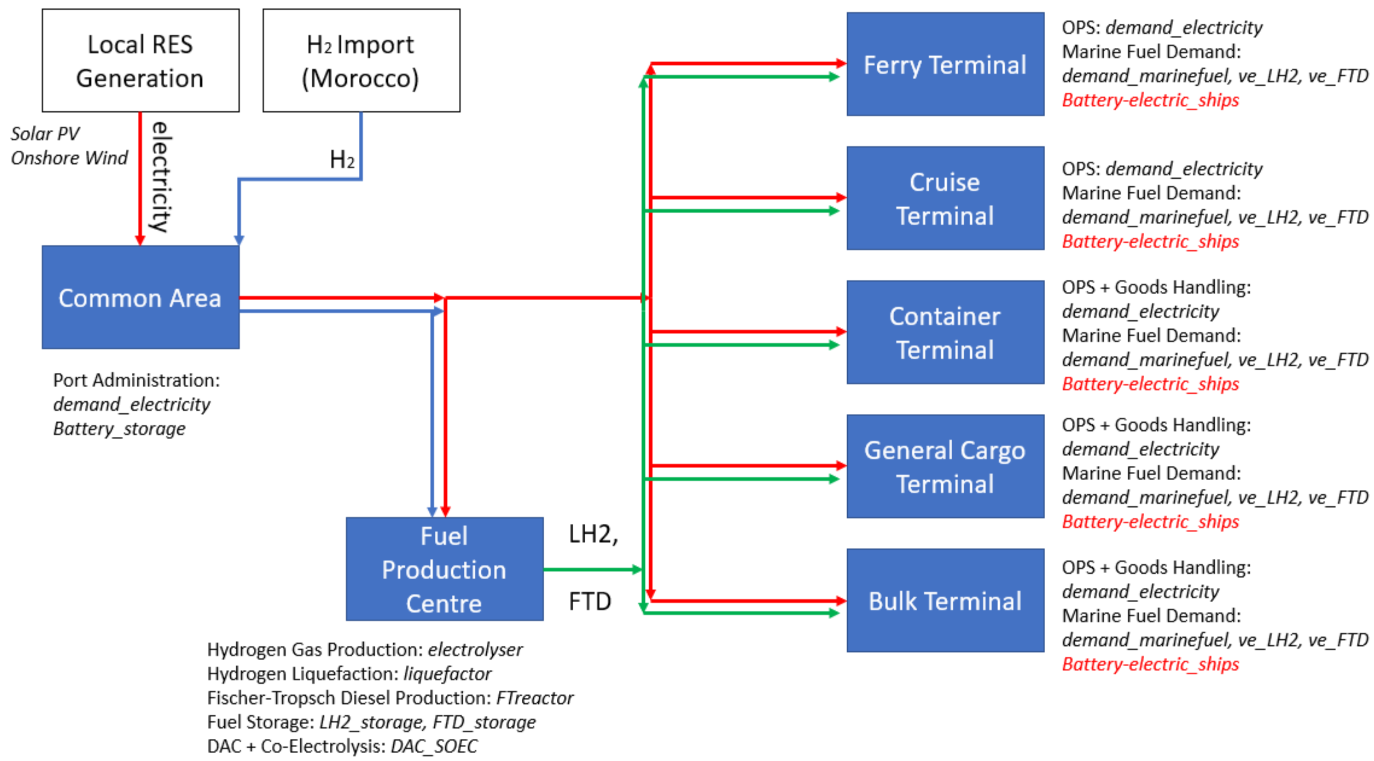

Figure 15: Refined Model Overview

While the model blocks remain the same as the demand model for what concerns the production of alternative fuels, the implementation of the two alternatives to supply the system significantly changes the observable behaviors, as is shown in the following sections. For what concerns the implementation of battery-electric ships, this was developed with the same rationale as the alternative fuels in the previous phase. In fact, the recharging infrastructure aimed at feeding electricity into the boats transforms this into "marine fuel". As happened for the previous phase, this was done to group all alternative propulsion systems under a single demand stream.

4.2. Results – Refined Model

4.2.1. Base Scenario

With respect to the demand model presented in the previous chapter, this base scenario is characterized by the implementation of RES generation, as well as the possibility of importing hydrogen from Morocco. This additional feature resulted in an objective function value equal to €28.800 billion, representing the yearly costs for sustaining such a system. *Figure 16* shows the resulting installed capacities of this phase. It can be seen here that liquefied hydrogen, after correcting the model, becomes the main option to generate propulsion energy. While there is still significant capacity for producing Fischer-Tropsch Diesel, liquefaction capacity is more than triple that amount. As a consequence for the lower Fischer-Tropsch diesel production, the capacity of DAC-SOEC is significantly reduced. On the other hand, it can be seen how PEM electrolyzers are widely used. This is the consequence of two main factors: firstly, using liquefied hydrogen as marine fuel requires higher loads of hydrogen gas as feedstock with respect to the previously dominant alternative; secondly, the amount of required hydrogen per unit of produced Fischer-Tropsch diesel was doubled to consider a proper H_2:CO ratio in the production of syngas. This shift in marine propulsion generation is also reflected in the refueling infrastructure, which equals to 540 MW for e-diesel and 1.11 GW for hydrogen across all terminals.

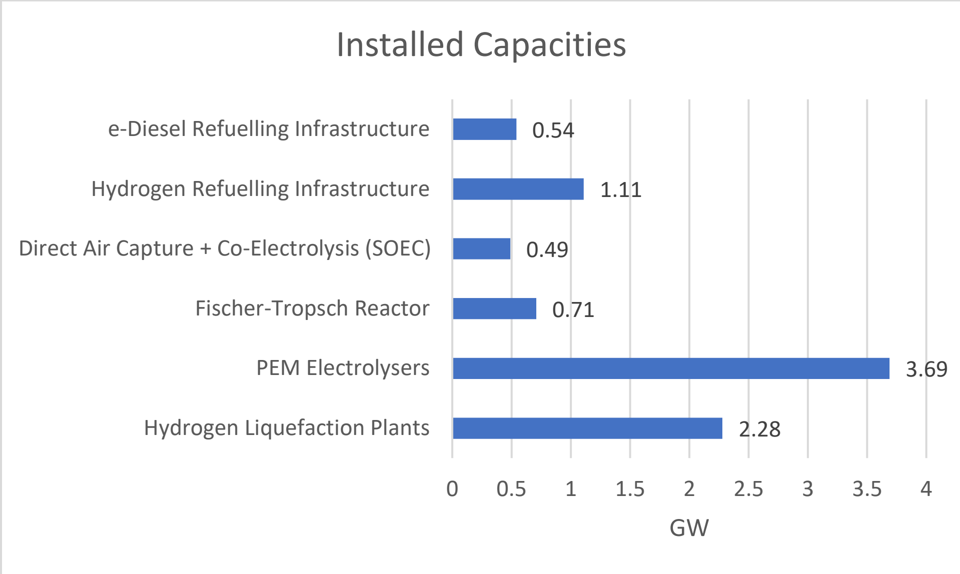

Figure 16: Installed Capacities, Base Scenario

Figure 17 shows the installed capacities for energy transmission infrastructure. As can be seen, hydrogen pipelines were not installed in the system, showcasing the higher cost efficiency of PEM electrolyzers for providing the required hydrogen feedstock. This implies that all the energy required by the system arrives in the form of electricity, to then be transformed into other carriers. For this reason, electricity lines with a capacity of 5.83 GW were installed by the model, to transport energy coming from RES to the port system.

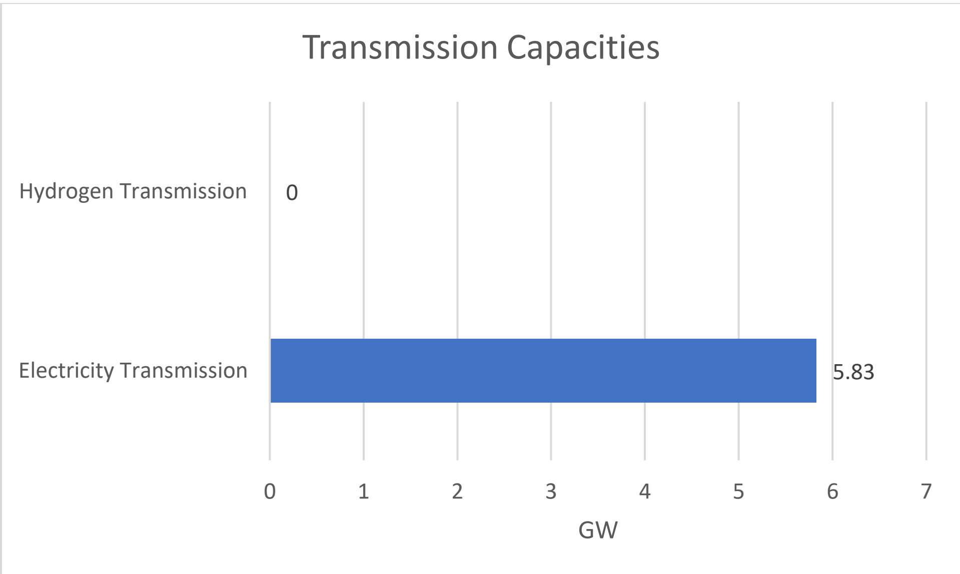

Figure 17: Transmission Capacities, Base Scenario

The transmission capacity is reflected in the capacity for energy generation, equal to 48.1 GW of onshore wind and 29.87 GW of solar photovoltaic, as shown in *Figure 18*. These supply the whole electrical demand of the system and the technologies composing it, including fuel and feedstock production.

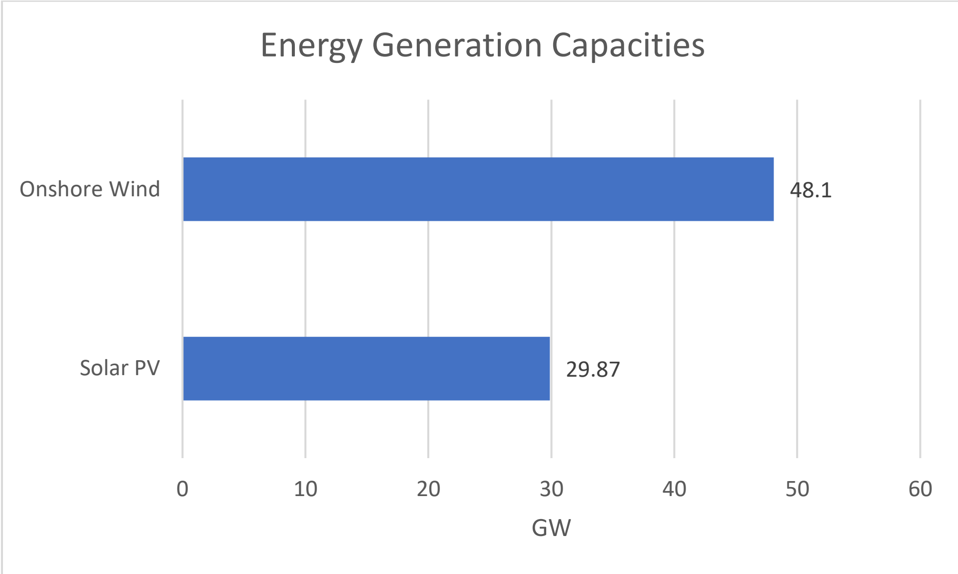

Figure 18: Energy Generation Capacities, Base Scenario

Figures 19 and 20 show the production of electricity from these two resources throughout the year. The main difference is clearly given by the complete lack of production during the night in the case of solar PVs, while wind energy is potentially available all the time. It is interesting to note that, while solar availability is higher during summer, wind speeds are generally higher and more consistent throughout winter. This underlines the importance of deploying both technologies to mitigate the effects of seasons on RES availability.

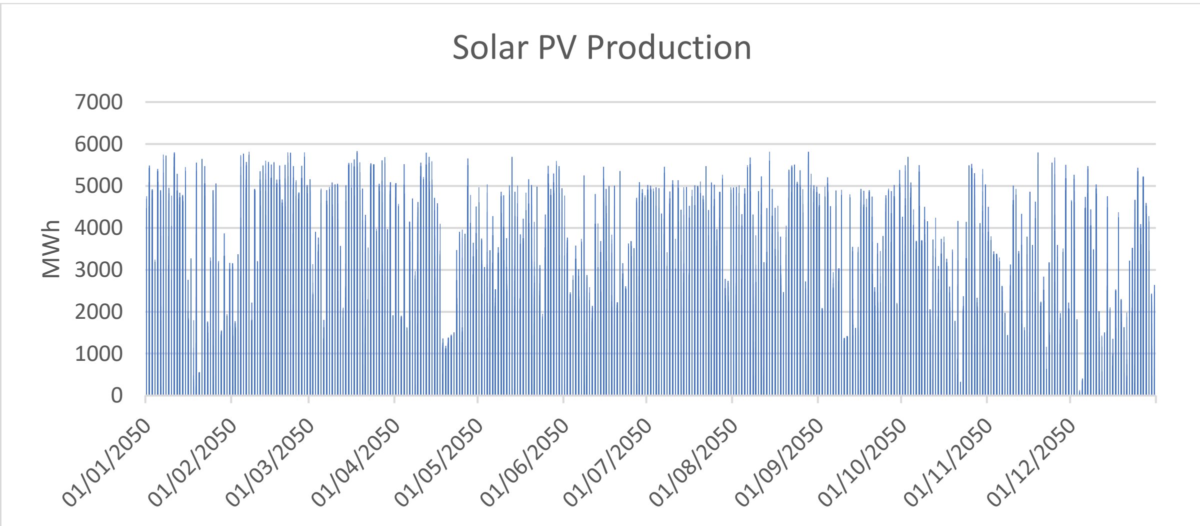

Figure 19: Solar PV - Production, Base Scenario

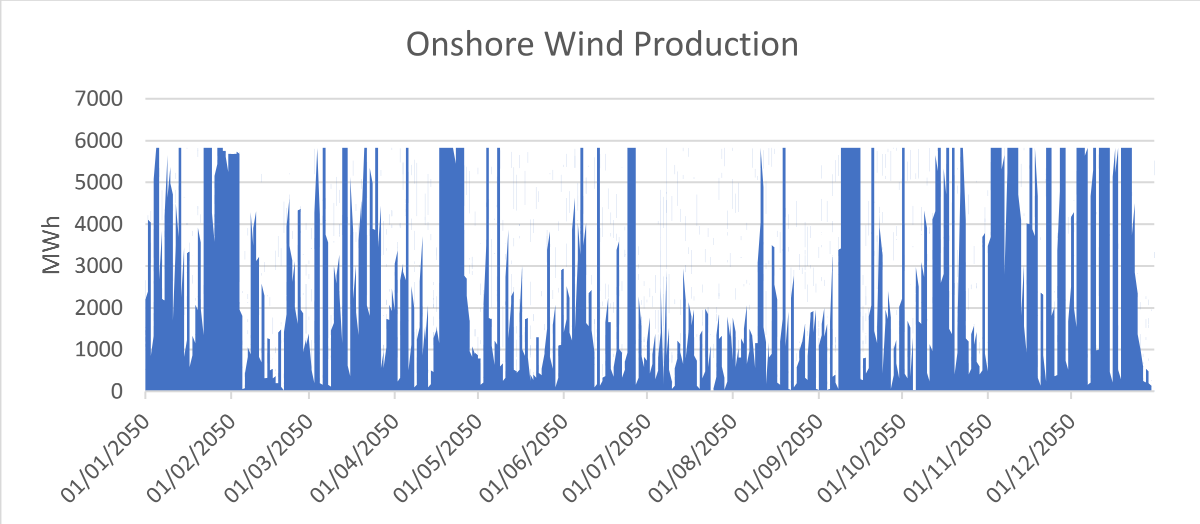

Figure 20: Onshore Wind - Production, Base Scenario

Figure 21 shows fuel production levels throughout the year, which depend on RES availability and the variable patterns characterizing it. Liquefied hydrogen production is dominant, this being the main fuel option for the system. The curve representing its production shows how, whenever RES generation is high enough, the system tends to produce this by using the full 2.28 GW of capacity. On the other hand, this is not always possible as when RES generation is lower the production drops to lower values. Contrarily, Fischer-Tropsch diesel production is characterized by significantly lower levels, as this takes place whenever RES generation is above average.

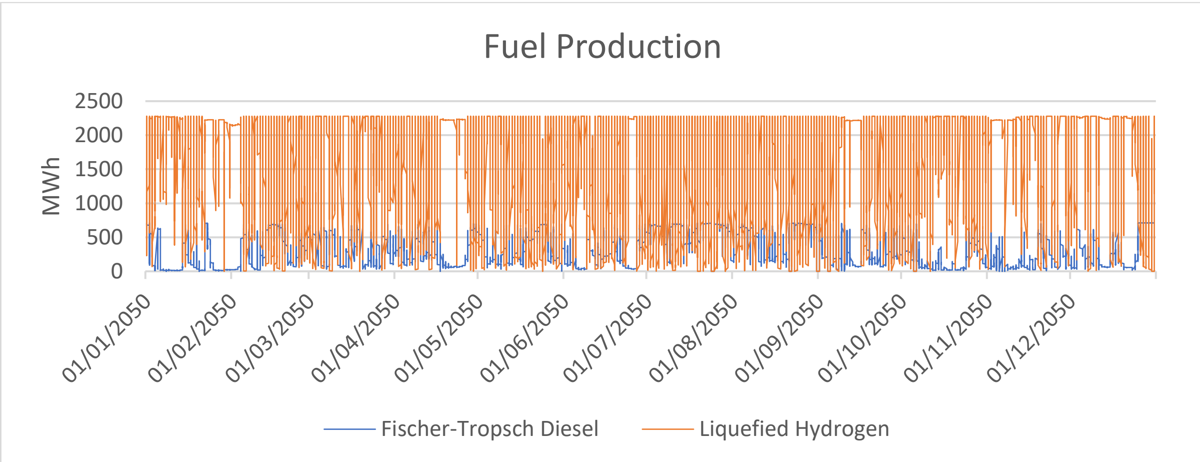

Figure 21: Fuel Production, Base Scenario

To mitigate the effect of variability on production levels, and attenuating peaks, which would require additional capacity, and lows, which would force non-production, battery storage was installed in the system, for a total capacity of up to 224 MWh. *Figure 22* shows the level of storage throughout the year, showcasing the effectiveness of this technology in balancing variable generation. This is particularly evident in the last months of the year, in which the frequency of charging and discharging of the batteries becomes higher, possibly due to the patterns of wind availability.

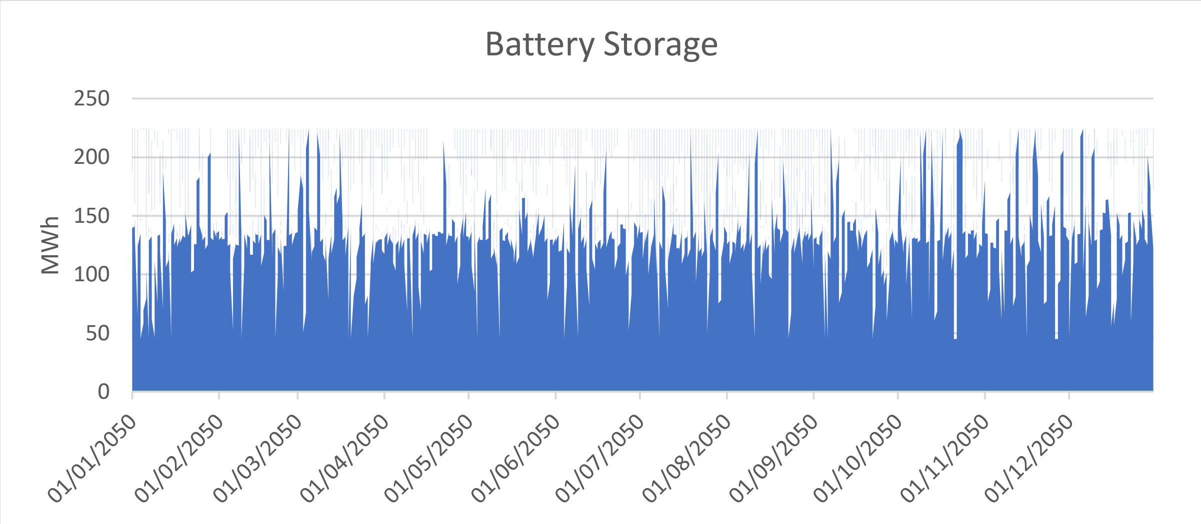

Figure 22: Battery Storage, Base Scenario

Figure 23 shows the electricity supply throughout the year, including RES generation, and battery storage variations. Considering the installed capacity, battery storage is barely noticeable when compared to RES generation, only contributing to a minor extent when it comes to provide energy to the system. As shown in the supply curve, the system often reaches the maximum transmission capacity of 5.83 GW, alternating this to moments in which the generation does not reach this level. Whenever it occurs that both solar and wind availability are high enough there is a peak in the curve. In this case, it is possible that a certain amount of electricity is wasted, considering the generation capacity. The model does not account for this amount, but in reality this would represent a possibility for feeding this energy to other systems, improving the business case for the RES generation facilities and lowering production costs.

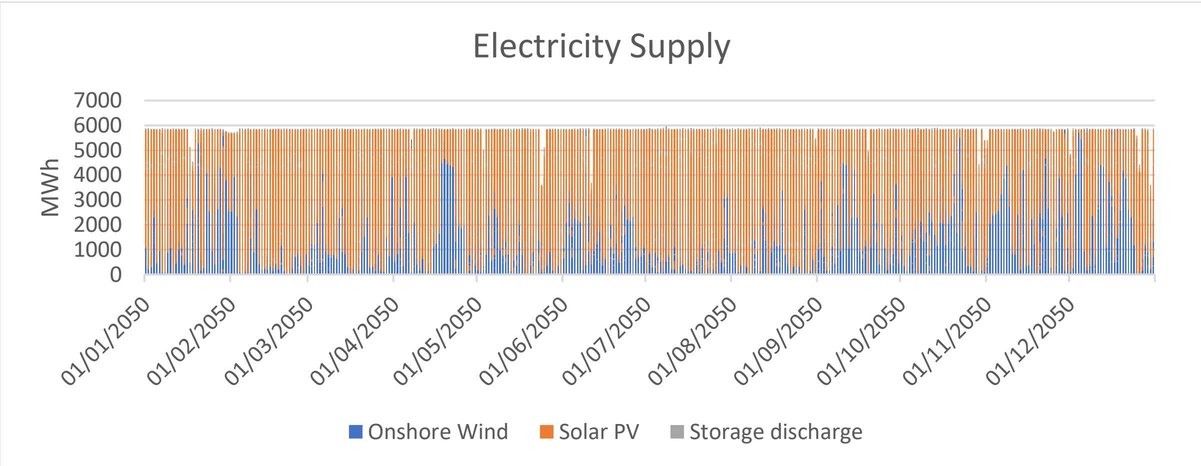

Figure 23: Electricity Supply, Base Scenario

Figure 24 shows the installed capacities for the different storage technologies. For what concerns battery storage, this reflects the values shown in the previous figures, with a total capacity of 224 MW. For what concerns fuel storage, Fischer-Tropsch Diesel has higher storage capacity with respect to liquefied hydrogen, despite being less used overall. This is possibly caused by the different uses of the two alternatives: while liquefied hydrogen is constantly used to satisfy propulsion energy demand, Fischer-Tropsch diesel is produced when there is an energy surplus and stored for later use. Additionally, e-diesel storage is cheaper when compared to hydrogen's, favouring this behaviour from the system.

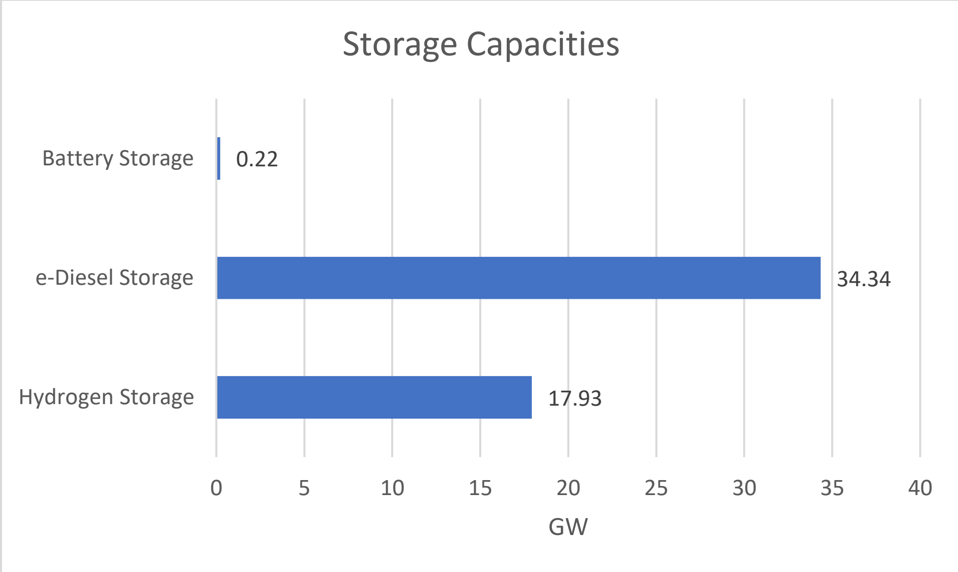

Figure 24: Storage Capacities, Base Scenario

Lastly, for what concerns fuel consumption, the trends throughout the year are shown in *Figure 25*. As can be seen, liquefied hydrogen is constantly used throughout the year, with Fischer-Tropsch diesel being used whenever hydrogen availability cannot sustain propulsion energy demand. There are a few periods in which hydrogen is used at constant levels, satisfying the whole demand of the system. This is likely to happen whenever RES availability is higher. Throughout the whole year, liquefied hydrogen has higher consumption rates with respect to Fischer-Tropsch diesel, with the exception of the last days of December. This period is characterized by lower wind speeds and little solar availability, making it necessary to switch to e-diesel, which was previously accumulated.

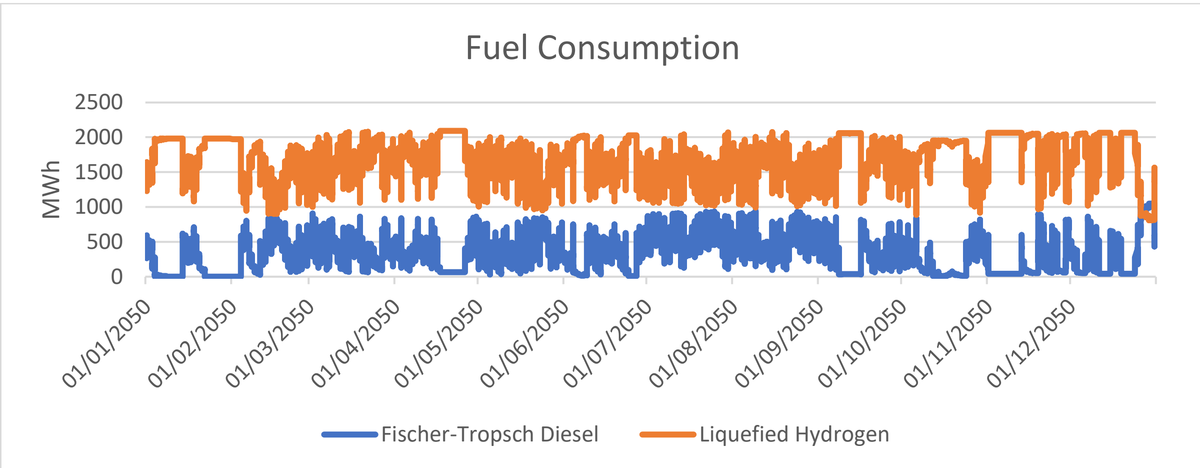

Figure 25: Fuel Consumption, Base Scenario

4.2.2. Battery-Electric Ships Scenario

By implementing battery-electric ships to the base scenario, the objective is that of assessing the cost savings for PoB. This change caused the objective function to decrease by 73.28% (compared to the previously presented set of results), equalling to €7.474 billion per year. Besides being a significant reduction, this is not fully unexpected. In fact, the fewer conversion steps necessary to provide energy to ships with Battery-based propulsion systems allow the system to reduce its overall energy requirements. Additionally, this also reduces the necessary capacities for other technologies, as shown in *Figure 26*, lowering the capital investments to this respect. Fischer-Tropsch production capacity, which was previously the dominant technology in terms of capacity, in this case has an installed capacity of 124.8 MW, roughly 20 times lower than the base scenario. Similarly, all other technologies are reduced in capacity as well, showing how battery-electric ships are largely deployed. This is shown in the recharging infrastructure, which is in this case the conversion technology with the highest installed capacity, equal to 1.01 GW. Nevertheless, Fischer-Tropsch Diesel recharging infrastructure sees a significant capacity as well, totalling 871.00 MW.

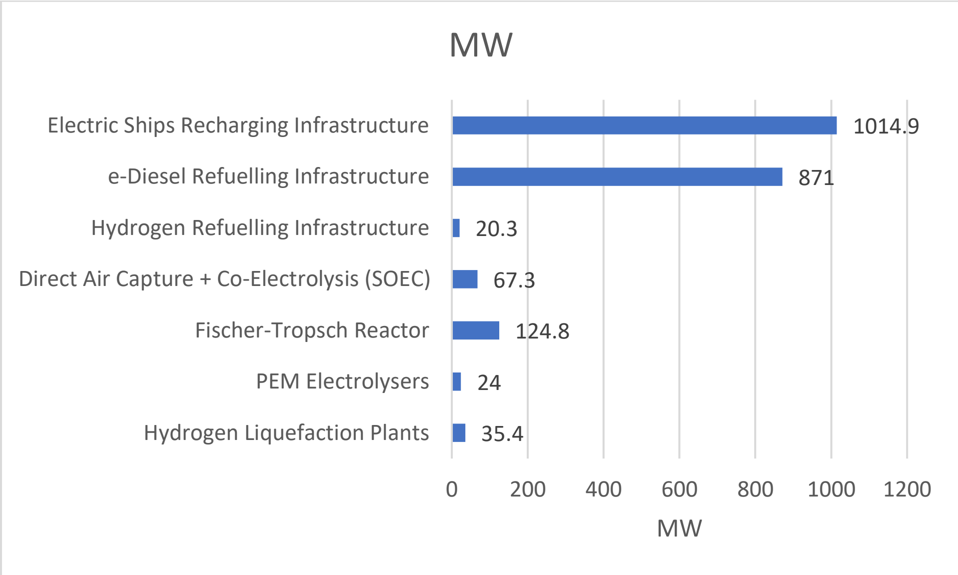

Figure 26: Installed Capacities, Battery-Electric Ships Scenarios

For what concerns transmission capacities, a big difference between carriers can be noted, as shown in *Figure 27*. As battery-electric is the most used alternative to generate propulsion energy, hydrogen demand significantly lowered in this phase, reflected in the 43.40 MW of transmission capacity. This is used as a nearly constant supply, with an hourly flow of 1.3 tons of hydrogen and allows for lower PEM electrolyzers' capacity. For what concerns electricity transmission, in this phase this equaled 1.82 GW, aimed at transporting electricity from RES generation plants to the PoB.

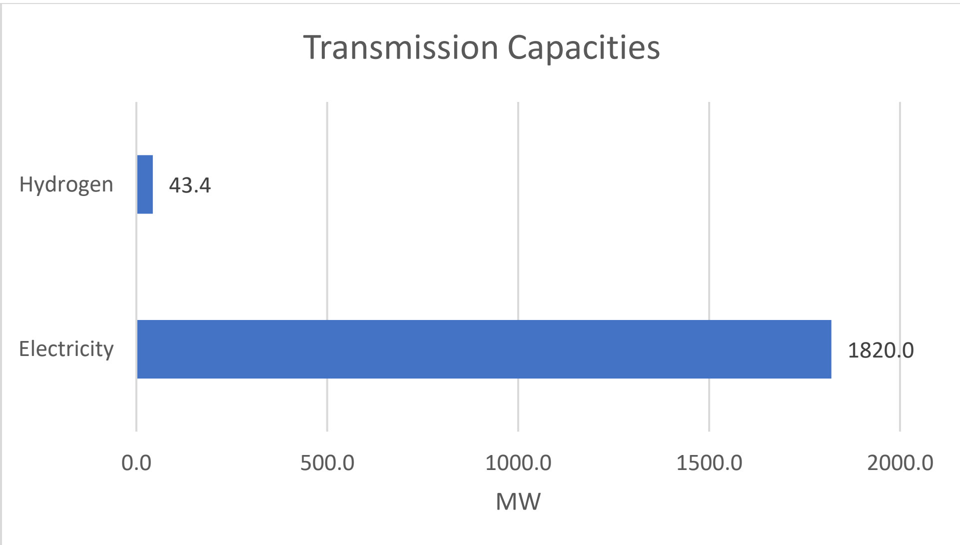

Figure 27: Transmission Capacities, Battery-Electric Ships Scenario

The total installed capacities for RES generation in the system are shown in *Figure 28*. The higher value is that of onshore wind, with a total generation capacity of 19.3 GW, against 12.3 GW of solar PV capacity. These are reflected in the production levels for these two technologies, represented in *Figures 29* and *30*. Besides the lower installed capacity, solar production is characterized by higher production peaks, showcasing the higher resource availability in the area. Nevertheless, this is only present during the day, increasing the importance of installing storage capacity.

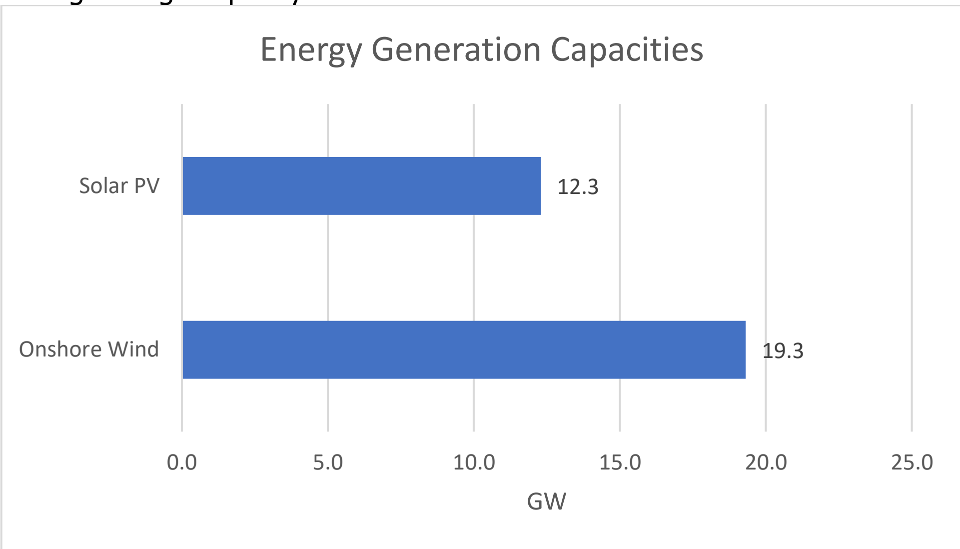

Figure 28: Energy Generation Capacities, Battery-Electric Ships Scenario

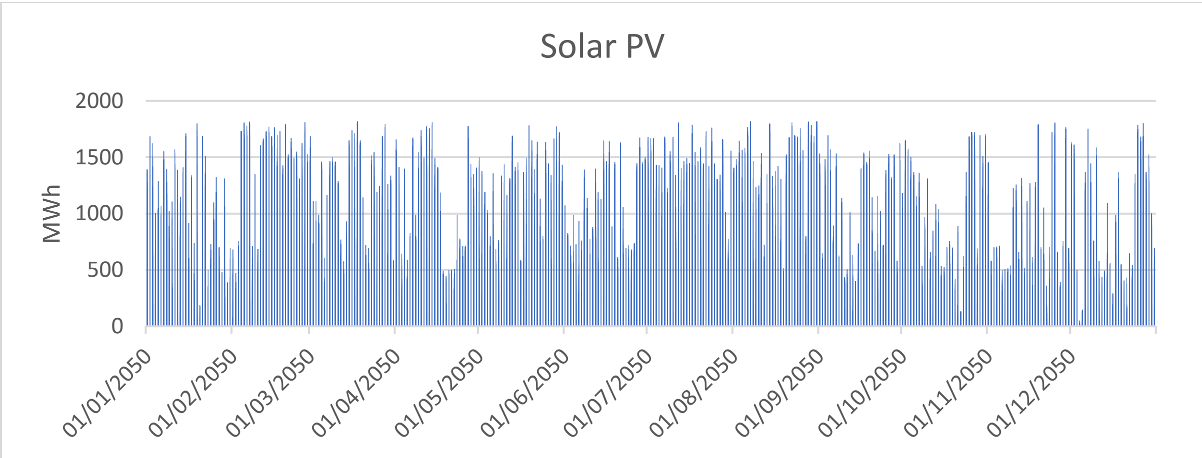

Figure 29: Solar PV - Production, Battery-Electric Ships Scenario

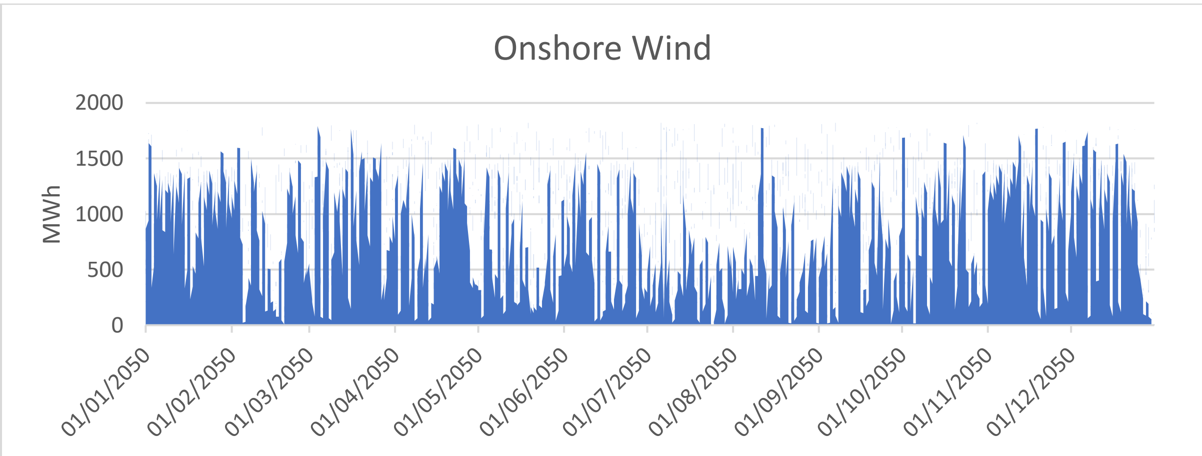

Figure 30: Onshore Wind - Production, Battery-Electric Ships Scenario

For what concerns electricity consumption, the main contributor to this respect are battery-electric ships, as expected from previously shown data. *Figure 31* shows the pattern of electricity consumption in this respect throughout the year. Whenever electricity production reaches a certain threshold, corresponding to the total propulsion energy demand, a horizontal trait of the curve is observed. The remainder of the produced electricity can then be used otherwise, such as producing fuels. On the other hand, when electricity generation is insufficient to satisfy marine fuel demand, the system shifts to using other fuels as well, produced when there is an excess of production. In the figure below this is represented by the local minimums of the function.

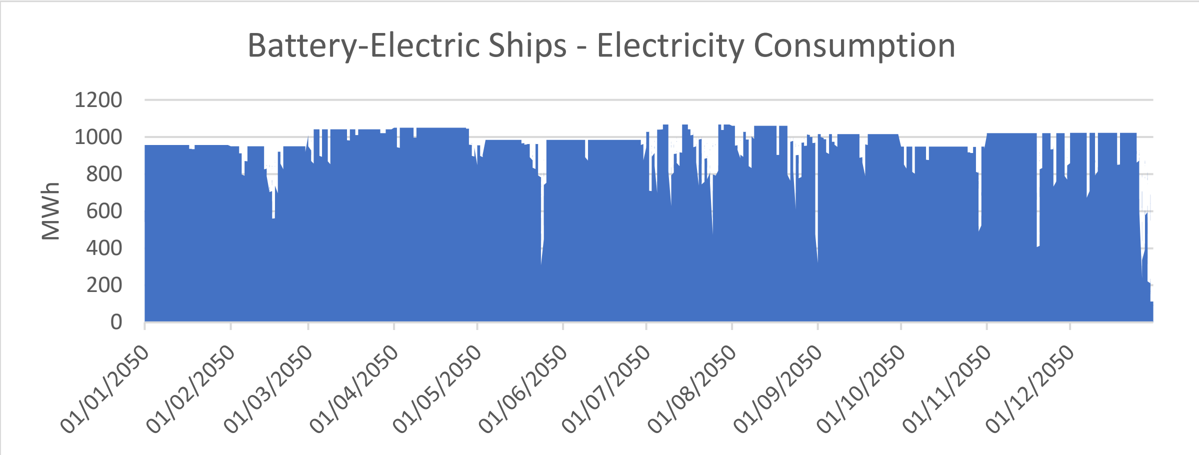

Figure 31: Battery-Electric Ships - Electricity Consumption

Figures 32 and *33* show the production and consumption patterns for Fischer-Tropsch diesel and liquefied hydrogen. For what concerns *Figure 33*, liquefied hydrogen is depicted on the right axis for better clarity. Consumption patterns underline what was previously mentioned: these fuels are used exclusively when electricity production is not high enough to sustain the whole propulsion energy demand. This is mostly present in July and August, as well as at the end of December. For what concerns summer, this is possibly caused by the insufficient electricity production during the nights, which causes the shift of propulsion system. Differently, the last period of December is characterized by lower wind speeds, and therefore the system is forced to switch. On the other hand, for what concerns production the rationale is the opposite: whenever electricity production exceeds propulsion energy demand, fuels are produced to make use of the unused electricity. This phenomenon is particularly present in July and August, in which solar is abundantly available during the day, and fuels are instead required during the night, as well as in the winter months, in which overall marine fuel demand is lower, and wind availability is higher.

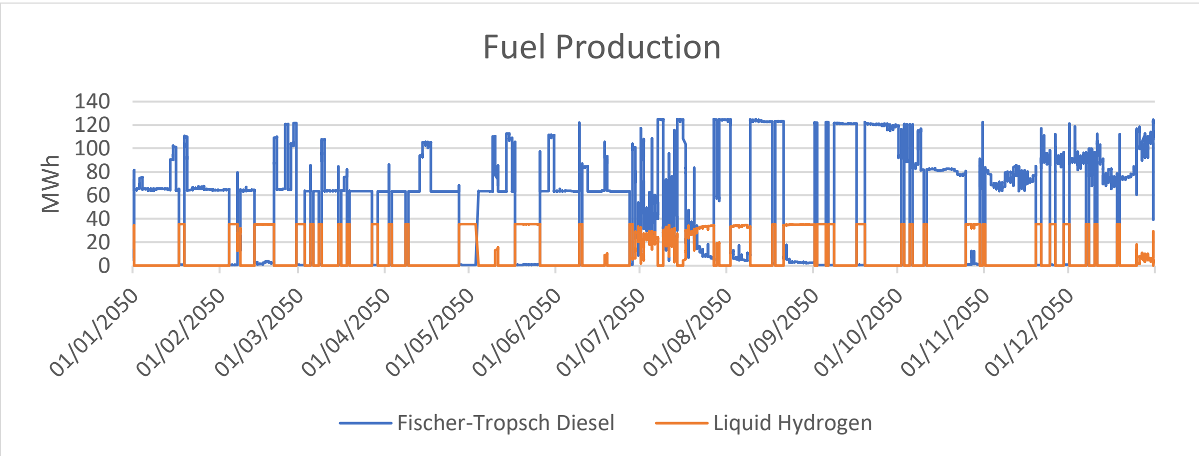

Figure 32: Fuel Production, Battery-Electric Ships Scenario

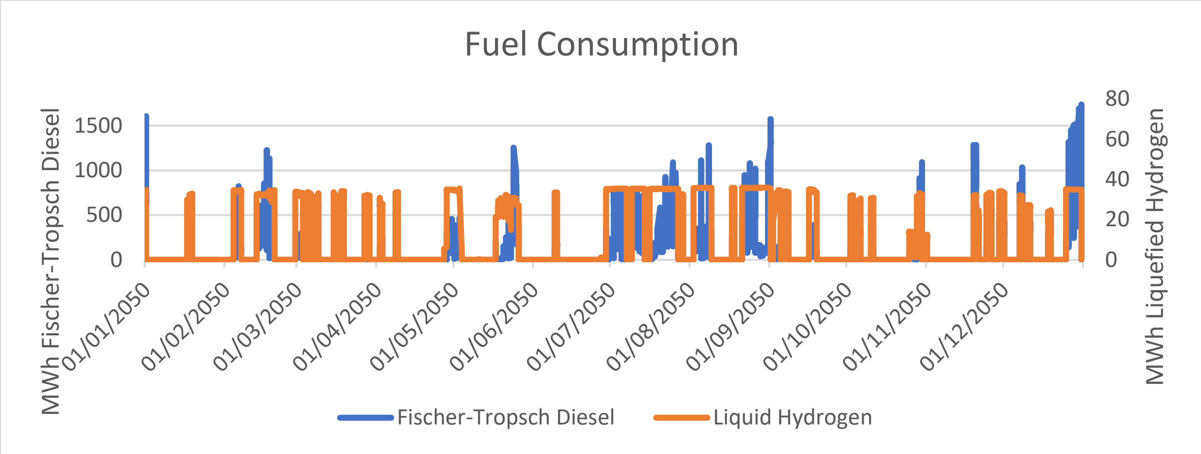

Figure 33: Fuel Consumption, Battery-Electric Ships Scenario

Figures 34 and *35* show the trend for electricity use and supply, including storage variations to account for all the electricity moving inside the system. As can be seen, the curves of use and supply are equal throughout the whole year. It is important to note the effect of storage to deal with the variable generation of RES. This is in fact constantly in use, with higher variations during the summer period. This is mostly caused by the higher solar availability, together with lower wind speeds. As solar irradiation is only present during the day, and winds are stronger as these generally peak in the afternoon, the system tends to store more energy during the day to have it available at night. Therefore, this causes a higher charge variation in this period. Furthermore, this also explains the drops in electricity usage for battery-electric ships during summer months.

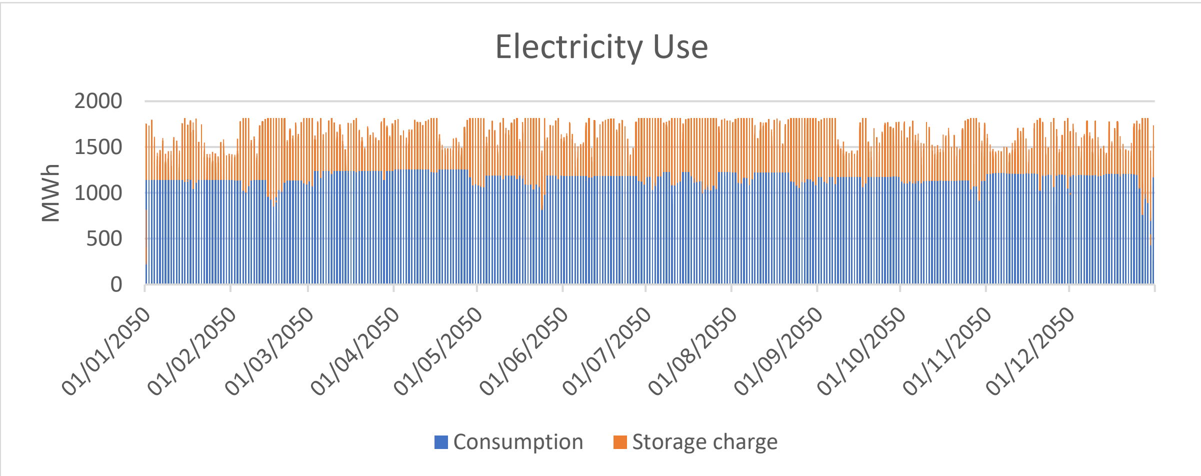

Figure 34: Electricity Use, Battery-Electric Ships Scenario

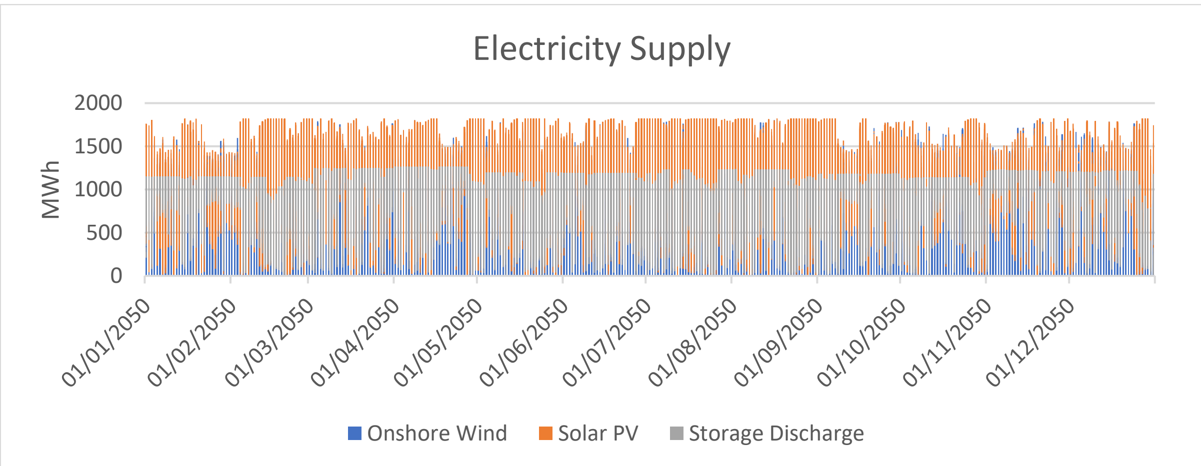

Figure 35: Electricity Supply, Battery-Electric Ships Scenario

Lastly, *Figure 36* shows battery storage levels throughout the year, to provide better clarity with respect to the figures presented above. As can be seen, 10.4 GW of storage capacity was installed in the system. The variations that can be seen throughout the year underline the impact of this technology in balancing variable generation.

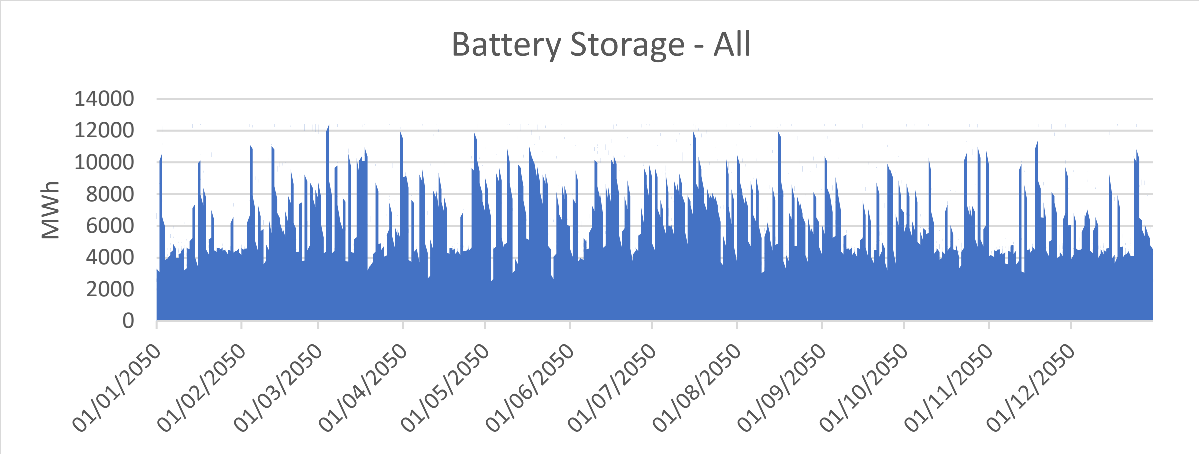

Figure 36: Battery Storage, Battery-Electric Ships Scenario

4.3. Sensitivity Analyses – Refined Model

Given the presented outcomes, sensitivity analyses were performed for the two scenarios, by changing the parameters characterizing the different technologies considered. This was done by considering the analyses presented in the previous chapter, as well as including the new technologies which were successively added. These include the following: onshore wind, solar PV, battery storage, and hydrogen import prices. This section deals with the analyses performed on the base scenario, while the following considers the one with battery-electric ships allowed.

4.3.1. Base Scenario

An overview of the obtained results for the base scenario is presented in *Table 11*. This reflects the impact on the previous set of results, as mentioned in the Ex-Post Correction in *Chapter 3*. It is expected that the changes made to the model would cause some variation to the reported numbers. For what concerns fuel production technologies, it is likely that the impact of DAC-SOEC and Fischer-Tropsch reaction plants is less significant due to the lower usage for this fuel. Contrarily, a higher impact would be expected when considering hydrogen liquefaction plants, given the importance that this technology assumed given the changes. Because of the higher hydrogen demand brought by the correction to the model, an increase in the impact of PEM electrolyzers on overall system costs is expected. Contrarily, given the null capacity installed for hydrogen import, its impact would be lower than the one reported below. Lastly, the impact of electric boilers on the overall system costs was left to show how, besides representing an additional cost in the system, its impact was limited.

Table 11: Sensitivity Analyses – Overview, Base Scenario

Technology	Base Value	Unit	Changed value	Reference	Variation	Objective Function	Variation	OF Base
						€ Billions		**€ Billions**
DAC+SOEC	3,762.00	€/kW	1,881.00	n.a.	-50.00%	27.763	-0.73%	**27.968**
			5,643.00	n.a.	50.00%	28.315	1.24%	
PEM Electrolysers	978.00	€/kW	591.00		-39.53%	27.679	-1.03%	

			1,365.00	Danish Energy Agency, 2023b	39.53%	28.656	2.46%
Hydrogen Liquefaction Plants	2,650.00	€/kW	1,417.00	IEA, 2020	-46.53%	27.656	-1.12%
			3,883.00	Connelly et al., 2019	46.53%	29.148	4.22%
Fischer-Tropsch Reaction Plants	*477.00*	€/kW	423.00	Decker et al., 2019; Danish Energy Agency, 2023a	-11.28%	27.623	-1.23%
			530.00		11.02%	28.722	2.70%
Electric Boilers	140.00	€/kW	100.00	Danish Energy Agency, 2023a	-28.57%	27.579	-1.39%
			150.00		7.14%	27.985	0.06%
Onshore Wind	978.00	€/kW	728.00	Danish Energy Agency, 2023a	-25.58%	27.686	-1.01%
			1,228.00		25.58%	29.186	4.35%
Solar PV	534.00	€/kW	309.00	Danish Energy Agency, 2023a	-42.08%	27.529	-1.57%
			759.00		42.08%	29.483	5.42%
Battery Storage	622.00	€/kW	394.00	Danish Energy Agency, 2020	-36.66%	27.209	-2.71%
			1,042.00		67.52%	28.367	1.43%
H_2 Transmission Infrastructure	0.094	€/km-kW	0.047	n.a.	-50.00%	19.638	-29.78%
			0.141	n.a.	50.00%	36.229	29.54%
Electricity Transmission Infrastructure	0.849	€/km-kW	0.425	n.a.	-50.00%	25.545	-8.66%
			1.274	n.a.	50.00%	30.414	8.75%
H_2 Price	1.40	€/kg	0.70	IRENA, 2022a	-50.00%	27.656	-1.12%
			2.10	n.a.	50.00%	28.208	0.86%
H_2 Refueling Infrastructure	2,518.00	€/kW	1,259.00	n.a.	-50.00%	27.793	-0.63%
			3,777.00	n.a.	50.00%	28.92	3.40%
e-Diesel Refueling Infrastructure	-	€/kW	364.00	n.a.	n.a.	33.794	20.83%
			1,259.00	n.a.	n.a.	34.181	22.21%

DAC+SOEC

As shown in *Table 11*, varying the required CAPEX for the DAC has a limited effect on the value of the objective function, with a maximum variation of +1.24% in the case of higher CAPEX. For what concerns the changes in the installed technologies, the main change is reflected in the DAC+SOEC system itself. In fact, the capacity grows 3.8% with a lower CAPEX, and diminishes 1.5% in the case of higher CAPEX. Furthermore, there is a slight increase in all technologies involved in the production of fuels by lowering the CAPEX, also causing a minor decrease in the amount of installed generation capacities.

PEM Electrolyzers

For what concerns PEM electrolyzers, the change in the objective function is a bit more significant with respect to the previously considered parameter, with a maximum variation of 2.46% in case of higher CAPEX. For what concerns capacities, the behavior of the system is opposite when comparing the two alternative values. When considering a lower CAPEX, the capacity of electrolyzers grows, as well as that of Fischer-Tropsch production. With a higher CAPEX, the opposite effect is observed.

Hydrogen Liquefaction Plant

For what concerns hydrogen liquefaction, the maximum difference can be seen for the higher CAPEX value, causing a +4.22% variation in the objective function. The variation is significantly lower in the case of lower value, being equal to -1.12%. In terms of installed capacities, the main difference can clearly be seen in the capacities for liquefaction plants, that are inversely proportional to the cost for installing these. On the other hand, installed capacities for PEM electrolyzers see an opposite trend, with lower installed capacities for lower CAPEX values for liquefaction.

Fischer-Tropsch Reaction Plants

For what concerns Fischer-Tropsch Diesel production, the impact of changing CAPEX is like that observed with PEM electrolyzers, ranging from -1.23% to +2.70%. The installed capacities in the two opposites vary similarly, especially for what concerns the production of Fischer-Tropsch itself. The range of this goes in fact from -2.5% to +2.3%, showing similar behavior in both directions. Additionally, a significant change can also be seen in hydrogen liquefaction capacities. In fact, with higher Diesel production capacity, liquefaction is reduced by -4.3%. On the other hand, this grows by 17.7% when considering a higher CAPEX for Fischer-Tropsch production.

RES Generation

By changing the capital investments required for RES generation, it is interesting to see the impact of these two technologies. For what concerns the objective function, solar PV CAPEX seems more significant with respect to onshore wind. Nevertheless, it is also important to note that the range of values for this is smaller, reflecting less uncertainty in the future cost projections. By comparing the installed capacities for the different technologies in the two alternatives, the main observation is that by raising one technology's CAPEX, its installed capacity is lowered. Subsequently, the installed capacity for the other alternative grows accordingly. The same reasoning works for lower CAPEX values. Another interesting effect of these changes is observed in battery storage capacities. In fact, this increases when the installed capacity for solar PV is higher.

Battery Storage

The following parameter to be analyzed is battery storage. *Table 11* shows how this is potentially more impactful considering a cost reduction, rather than considering a higher estimate. Considering the installed capacities for the two values, it can be seen that, other than varying the amount of installed storage, the proportions between RES technologies vary. In fact, with lower storage costs, and thus higher storage capacities, solar PV capacity is 7.9% higher, compared to a 3,9% reduction in onshore wind plants.

Energy Transmission

Given the inclusion of generation technologies, energy transmission was included in the model, considering both electricity and hydrogen. For both parameters, the base value was varied by 50% in both directions, showcasing the impact of these two on the final objective function. This underlines the impact of the hydrogen transmission system with respect to the overall value, as a 50% reduction of this cost implies a 29.78% reduction in the objective function value. Differently, the reduction decreases to -8.66% for electricity transmission's lower CAPEX. For what concerns hydrogen transmission, results show how an increased cost implies a lower transmission capacity, which requires an increase in PEM electrolyzers capacity to satisfy the overall hydrogen demand. The impact of changing the CAPEX for electricity transmission, instead, primarily causes the proportions between solar and wind to vary. With a higher CAPEX, more wind is installed, as this is more evenly distributed throughout the year, while solar PV would require higher capacity to make up for the production levels concentrated in summer.

Hydrogen Price

As shown in *Table 11*, the impact of varying hydrogen prices is limited with respect to the overall cost of the system. In fact, even considering a quite optimistic estimate equal to €0.7 per kg, only a -1.12% reduction is achieved. Similarly, this change barely impacts the installed capacities of the system, with only minor variations observed for all technologies. This underlines the magnitude of the capital expenditure required to install the transmission infrastructure.

Refueling Infrastructure

Lastly, the impact of varying the CAPEX of refueling infrastructure is analyzed. For what concerns hydrogen refueling infrastructure, a higher impact on the objective function value can be seen in the case of a higher CAPEX, with a 3.4% increase in response of a +50% increase in the parameter. The main difference in the installed capacities is related to Fischer-Tropsch production, with a slight reduction in the capacities with a lower CAPEX for liquefied hydrogen refueling infrastructure.

For what concerns e-Diesel refueling infrastructure, a significant increase in system costs happens by including this parameter. Nevertheless, it is interesting how the objective function increases by 20.83% by shifting from €0.00 to €364.00 per kW, and only by 22.21% when considering a value of €1,259.00. In the second case, liquefaction capacity is higher, with Fischer-Tropsch production levels that start decreasing.

4.3.2. Battery-Electric Ships Scenario

Shifting the attention to the scenario with battery-electric ships, *Table 12* provides an overview of the sensitivity analyses that were performed. In addition to the ones presented in the previous section, two additional analyses were included: first, changing the cost parameters for the recharging infrastructure for battery-electric ships; and second, by implementing a factor potentially reflecting a capacity reduction caused by the inclusion of batteries to power ships, which are heavier and more voluminous and might therefore require lower transported tonnage to avoid potential issues.

Table 12: Sensitivity Analyses - Overview, Battery-Electric Ships Scenario

Technology	Base Value	Unit	Changed value	Reference	Variation	Objective Function	Variation	OF Base
						€ Billions		***€ Billions***
DAC+SOEC	3,762.00	€/kW	1,881.00	n.a.	-50.00%	7.457	-0.23%	**7.474**
			5,643.00	n.a.	50.00%	7.486	0.16%	
PEM Electrolyzers	978.00	€/kW	591.00	Danish Energy Agency, 2023b	-39.53%	7.472	-0.03%	
			1,365.00		39.53%	7.476	0.03%	
H_2 Liquefaction Plant	2,650.00	€/kW	1,417.00	IEA, 2020	-46.53%	7.472	-0.03%	
			3,883.00	Connelly et al., 2019	46.53%	7.476	0.03%	
Fischer-Tropsch Reaction Plant	*477.00*	€/kW	423.00	Decker et al., 2019; Danish Energy Agency, 2023a	-11.28%	7.471	-0.04%	
			530.00		11.02%	7.475	0.01%	
Onshore Wind	978.00	€/kW	728.00	Danish Energy Agency, 2023a	-25.58%	6.88	-7.95%	
			1,228.00		25.58%	7.943	6.28%	
Solar PV	534.00	€/kW	309.00	Danish Energy Agency, 2023a	-42.08%	7.148	-4.36%	
			759.00		42.08%	7.718	3.26%	
Battery Storage	622.00	€/kW	394.00	Danish Energy Agency, 2020	-36.66%	7.11	-4.87%	
			1,042.00		67.52%	7.975	6.70%	
H_2 Transmission Infrastructure	0.094	€/km-kW	0.047	n.a.	-50.00%	6.985	-6.54%	
			0.141	n.a.	50.00%	7.791	4.24%	
Electricity Transmission Infrastructure	0.849	€/km-kW	0.425	n.a.	-50.00%	5.802	-22.37%	
			1.274	n.a.	50.00%	15.555	108.12%	
H_2 Price	1.40	€/kg	0.70	IRENA, 2022a	-50.00%	7.465	-0.12%	
			2.10	n.a.	50.00%	7.485	0.15%	
H_2 Refueling Infrastructure	2,518.00	€/kW	1,259.00	n.a.	-50.00%	7.469	-0.07%	
			3,777.00	n.a.	50.00%	7.476	0.03%	
e-Diesel Refueling Infrastructure	-	€/kW	364.00	n.a.	n.a.	7.506	0.43%	
			1,259.00	n.a.	n.a.	7.544	0.94%	
Battery-Electric Recharging Infrastructure	728.00	€/kW	364.00	n.a.	-50.00%	7.436	-0.51%	
			1,092.00	n.a.	50.00%	7.511	0.50%	
Battery-Electric Spatial Factor	1	-	0.75	n.a.	-25.00%	9.369	25.35%	
			0.5	n.a.	-50.00%	12.751	70.60%	

Conversion Technologies

The first parameters to be considered in this analysis are conversion technologies, including the following: DAC+SOEC and PEM Electrolyzers. *Table 12* shows how, among these, DAC-SOEC is more impactful towards total system costs. Nevertheless, the variations with respect to the objective function are limited, ranging from -0.23% to +0.16%. This reflects the low importance of those technologies supporting fuel production in this scenario, characterized by the dominance of battery-electric ships.

Fuel Production

For what concerns fuel production capacities, it can be observed that changing the parameters barely impacts the costs incurred by the system. This is mostly due to the relatively low importance of fuels in this scenario, given the presence of battery-electric ships representing a cheaper option. Similarly, almost no difference can be seen in the installed capacities, as these serve the role of compensating for periods in which electricity production is lower and are therefore adopted no matter the conditions.

RES Generation

Differently, the impact of changing the cost of RES generation is way more evident. The variations from these are higher for wind CAPEX with respect to solar, as the former makes the final objective function vary in a range from -7.95% to +6.28%, despite the lower cost estimates range. As was observed in the previous phase, raising the cost for one technology implies a higher installed capacity for the other one, and vice versa. Additionally, it is again observed that, when more solar PV is installed, a higher capacity for battery storage is required to satisfy the system's requirements.

Battery Storage

Another parameter that showed to be impactful is battery storage. The range of values for the objective function given the cost predictions range from a -4.87% to a +6.70% with respect to the original value. In terms of installed capacities, clearly a lower storage CAPEX implies a higher installed capacity for this technology. Furthermore, in this case a higher solar PV capacity is observed as well. Contrarily, with higher CAPEX for battery storage, the proportion between RES generation capacities tends more towards onshore wind.

Energy Transmission

As seen in the previous phase, energy transmission is significantly impacting the overall objective function value. In this phase the impact of electricity transmission costs is evidently more significant, as this ranges from -22.37% to +108.12% with respect to the original value, representing the most significant change amongst all analyses. This underlines the importance of RES generation if battery-electric ships were to be largely deployed. The lower impact of hydrogen transmission showcases the lower usage of hydrogen in this system, mostly due to the inclusion of battery-electric ships. By focusing on the installed capacities given by the changed parameters, several observations can be made. First, when hydrogen importation is in more favorable conditions, be this for a higher CAPEX for electricity or lower for hydrogen transmission, the capacities for fuel production significantly grow, even though battery-electric ships remain the main alternative to generate propulsion energy. Second, when electricity transmission is in unfavorable conditions, the system tends to install more wind at scape of solar capacity, given the higher consistency of production. Similarly, the model tends to import hydrogen whenever electricity production is more expensive.

Hydrogen Price

For what concerns hydrogen import price, *Table 12* shows how this has almost no impact on the overall value of the objective function. This is mostly due to two reasons: first, including battery-electric ships significantly reduced the importance of hydrogen in the system; and second, hydrogen transmission CAPEX is significantly more impactful than its price, also considering the distances that need to be covered by infrastructure. Due to the relative unimportance of this parameter, only minor changes can be observed in the installed capacities.

Refueling Infrastructure

By modifying the parameters related to refueling infrastructure CAPEX, it can be observed how these have a limited impact on the overall costs for the system. In fact, the highest increase can be seen for the higher estimate for e-Diesel, with a variation equal to 0.94%. In the case of e-Diesel and hydrogen, the main change that can be observed is related to the proportions between fuel storage technologies. In fact, with lower costs for hydrogen, or higher for Fischer-Tropsch Diesel, hydrogen storage slightly rises. Similarly, the same can be observed when considering lower costs for Diesel. For what concerns battery-electric recharging infrastructure, only minor variations can be observed.

Battery-Electric Spatial Factor

Lastly, it was chosen to apply a reduction factor to battery-electric ships, due to the properties of battery storage, considered to be used in the form of $LiFePO_4$ as the reference that was selected relies on these. On one hand, these are characterized by a specific energy ranging from 90 to 160 Wh/kg (Lithium Storage, n.d.), corresponding to a weight of 6.25 to 11.11 tons for each MWh of energy transported. Additionally, these are characterized by a volumetric energy density of 325 Wh/L (Lithium Storage, n.d.), translating into 1.17 MJ/L. Compared to HFO, this would entail an occupied volume being 3,173.5% higher for storing the same quantity of energy. On one side, this might represent a huge barrier to the adoption of this technology. On the other hand, some ships cover short routes, or make multiple stops throughout their journeys, and thus the quantity of fuel that they require to carry is lower. Considering the energy savings that a direct use of electricity would entail multiple solutions are being studied to address these challenges. Fleetzero, for example, aims at developing a network of users for their battery packs, composed of vessels as well as physical locations acting as checkpoints (Coldewey, 2022). This would allow vessels for a continuous interchange of battery packs, aimed at minimizing the overall quantity of these charged into each vessel. This underlines how, in view of a possible large-scale adoption of this technology, significant changes might characterize the shipping sector, presenting many uncertainties in the development of possible analyses. Additionally, the wide variety of ship types makes it complex to define a single factor. Lastly, the model does not consider the opportunity provided by storing these ships' battery packs, as these could possibly lower the requirements for battery storage capacities in port. Therefore, two arbitrary values were considered to define the potential implications of these in the future PoB. These were selected to provide an idea of the variation caused by lower spatial efficiencies.

Table 12 shows the changes of the objective function when applying the battery-electric spatial factor. By reducing the spatial efficiency to 0.75, a 25.35% increase to the objective function can be observed. If the factor is changed to 0.50, the increase of the objective function with respect to the base value equals 70.60%. This also impacts the production capacities for alternative fuels, as this increases by more than 500.00% when considering a 0.75 factor, and by more than 700.00% by applying a 0.5 factor. Liquefaction capacity remains nearly identical in both cases.

5. Discussions

In this chapter, the results as previously shown are analyzed and discussed. This involves a comparison of the outcomes from the different model phases and scenarios, inspiring the overall reflection on the meaning of the obtained results. This is followed by reflections on the feasibility of the obtained outcomes, and finally an analysis of the limitations of the model.

5.1. Interpretation and Discussions of Results

Firstly, the focus is posed on the differences between the demand model and the refined model, specifically the base scenario in which the difference is given by the consideration of RES generation. A comparison is made between these, to assess the effects of implementing variable generation into the system. Successively, a comparison between the base scenario and the one with battery-electric ships is presented. Because of the corrections to the model, which were made only in the base scenario of the refined model, determinate aspects are impossible to compare. Therefore, the focus of these comparisons is posed on the main differences that can be observed, such as the implementation of variable generation between the demand model and the refined model, or the impact of including battery-electric ships in general terms.

5.1.1. Demand Model – Refined Model

The first difference that can be noticed is represented by the higher production capacity in the refined model. As seen in Chapter 3, the constant conditions in which electricity is supplied to the system make the optimization converge towards production capacity minimization. By implementing RES generation, the conditions of energy supply are changed, making it necessary to increase production capacity to satisfy the same demand. This is because, if a period has scarce RES availability, the electricity supply is not sufficient to maintain production at almost constant levels, as happened in the demand model. As battery storage was included as technology, the amount of required production capacity is reduced, mitigating the effect of variability on fuel production patterns, and thus limiting the required production capacities. Keeping into account the changes that were made to the base scenario to the refined model, it is worth noting that despite implementing a second option to procure the required hydrogen to the system, PEM electrolyzers' capacity grows in the refined model. This is mostly caused by the corrections, in which the amount of required hydrogen to produce Fischer-Tropsch diesel grew, favoring liquefied hydrogen as a fuel.

The impact of variable generation can also be observed in the higher degree of adoption for what concerns liquefied hydrogen as a fuel. Besides representing the main fuel option after the corrections to the model, also in the previous set of results this saw an increase in importance, with Fischer-Tropsch diesel remaining the main fuel option. The uncertainties regarding resource availability make it necessary to not stick to a single fuel alternative, as a combination of events, such as high demand in a RES-poor period, might drain storage reserves, making it safer to consider multiple alternatives for generating propulsion. This is especially evident when observing the trend for fuel consumption throughout the year in the base scenario of the refined model. This is in fact characterized by the tendency of using liquefied hydrogen to satisfy the overall propulsion energy demand throughout the year. On the other hand, drops with respect to the average consumption are almost constantly present throughout the year. During these drops, the system compensates by shifting to Fischer-Tropsch diesel, so that the demand is satisfied.

In summary, the introduction of variability into the system has several implications. Firstly, additional importance is placed on adopting a mix of fuel alternatives rather than a single option. In fact, while in the demand model an almost constant production level can be observed, this is not the case for the refined model. Due to this, there are certain moments during the year in which the production for the main fuel is lower, and this causes storage levels to decrease, reaching the point of being completely depleted. Whenever this happens, the system compensates by shifting to secondary fuel alternatives, increasing the importance of the alternative. Another significant implication is the importance of battery storage, as a measure to mitigate the variability of RES generation. If this was not considered, this would impact production capacities, as all produced electricity should instead be used to produce alternative fuels, causing a significant increase in production capacity requirements. This highlights the double role of fuel production, which clearly serves as a measure to satisfy propulsion demand, as well as representing a form of energy storage for the system, as electricity is transformed into a more storable form of energy.

5.1.2. Refined Model: Base Scenario – Battery-Electric Ships Scenario

By shifting the focus on the refined model phase, a comparison can be made between the base scenario and the one with battery-electric ships allowed. While the previous comparison was aimed at analyzing the impact of implementing variable generation to the system, this is instead focused on the possibility of deploying battery-electric ships to generate marine propulsion, and the subsequent impact on the PoB system.

The first difference that can be underlined is represented by RES generation capacity. It can be observed that this is significantly lower in the battery-electric ships scenario, showcasing the effect of directly using electricity to generate marine propulsion. In fact, the fewer conversion steps that energy needs to face in the case of direct utilization, the lower overall energy demand from the system is, making it possible to reduce generation capacity.

Despite the evidently lower utilization rates of alternative fuels with respect to battery-electric ships, it is important to note that fuel production capacity is still present. The presence of these technologies underlines how, even if battery-electric ships were to be successfully implemented, a small portion of the overall demand for generating propulsion might still need to be covered with other options. This is mostly due to the variability of RES, as in periods of resource scarcity the system shifts to alternative options, which are more storable with respect to electricity, and this makes it possible to produce them while RES are abundant, to then use these when the case is the opposite.

For the same reason stated above, higher overall capacity for refueling (and recharging) infrastructure can be seen in the battery-electric ships scenario. Considering Fischer-Tropsch Diesel infrastructure and Liquefied Hydrogen's, the capacity is higher for the base scenario, as these need to fully satisfy the demand for refueling. On the other hand, if recharging infrastructure for battery-electric ships is considered, a higher capacity can be observed for the alternative scenario, including the capacity for alternative fuels, for a total of 1.9 GW (1 GW of which for battery-electric ships), against the total capacity of 1.65 GW for the base scenario. This again shows how, despite the dominance of battery-electric ships, a significant capacity is installed for alternative fuels refueling. This underlines the magnitude of the consumption of alternative fuels during determinate periods in which RES is lower, such as February, or when variability is more significant, such as July and August.

Lastly, another fundamental difference between the two scenarios is represented by the installed capacities for battery storage. In the scenario with battery-electric ships, the overall installed capacities are in fact equal to 10,400.00 MWh, equivalent to 4,642.9% of the capacity installed in the base scenario. This reflects the increased importance of this technology in the case of a large-scale deployment of battery-electric ships. As happened in the base scenario, the main objective of this technology is that of balancing RES generation. In fact, storage is charged whenever electricity generation is higher than the demand in the same timeslots, to then be discharged whenever RES availability is lower. On the other hand, as electricity is in the battery-ships scenario the main option as alternative fuel, it also takes on the role of fuel storage. In the previous phase, whenever electricity generation exceeded the required energy to produce fuel, this was either used to produce alternative fuels or stored to make up for RES-poor moments. In the alternative scenario this is also the case, but with a significant change of proportions, as the preferred option becomes storing electricity to satisfy propulsion demand in a second moment, rather than converting this energy into fuels. Therefore, it can be said that there is a fundamental change in the priorities to be followed by the system.

5.2. Model Limitations and Underlying Assumptions

To achieve a comprehensive understanding of the outcomes obtained with this project, it is essential to acknowledge its limitations. On one hand, several assumptions were necessarily taken to make up for knowledge gaps, be this for estimating the demand or to set values for parameters. On the other hand, as this project was based on the development of a model, it was inevitable to simplify reality to represent it within Calliope. The main limitations are analyzed and expressed below.

One of the primary limitations is related to the representation of propulsion energy demand. The total quantity of fuel consumed on a yearly basis was used to estimate the overall demand for the model. Nevertheless, the allocation of this quantity throughout the year was differentiated monthly, as this was the most granular representation of traffic flows in PoB being publicly available. Therefore, this is represented as an equivalent demand for every hour of each month. While in general terms this effectively represents the total numbers, this does not achieve to capture daily patterns of fuel consumption, setting a boundary for the representation of the complexity of the system. In doing so, it is likely that refueling infrastructure capacity will need to be proportionally higher than what was estimated in this project.

Secondly, an additional limitation regarding the demand is related to the electricity required to handle goods arriving at the port. Due to the wide range of goods arriving at the port, an elevated number of operating companies is present. Among these companies, there are multiple examples of unavailable information or outdated websites. For this reason, it was inevitable to take assumptions to make up for information gaps, possibly lowering the accuracy of the estimations which were made.

A significant aspect of the model that needs to be reflected upon is represented by the technologies that were not considered in its realization. For this project, two alternatives were considered as alternative fuels, with the inclusion of battery-electric ships in a separate scenario. On the other hand, several potential alternatives for decarbonizing the shipping sector are being studied. The same rationale can be applied to other aspects of the model. For example, RES generation can be achieved with different technologies other than solar PV and onshore wind, or energy can be imported from other countries, or in different forms, and so on. Nevertheless, this richness of possibilities made it necessary to make choices to develop the model, and thus these were not considered. This clearly represents a limitation towards the analysis of the possible future situation of PoB. At the same time, this wide range of alternatives makes the shipping sector characterized by high uncertainty, and making predictions is therefore out of scope of the project. For this reason, the technologies included in this project were selected as representative of the multitude of alternatives that might be characterizing the future.

Lastly, it is important to note how RES availability was considered. To represent yearly patterns for energy generation, historical data was considered, which may not accurately reflect future conditions. To enhance the precision of the predictions, an option could be to incorporate forecasts of RES availability rather than using datasets based on the past, especially in view of climate change and the impacts to this respect.

5.3. Reflection on Feasibility of Implementing Results

Additional reflections that were developed to assess the validity of the results with respect to reality are presented below.

Firstly, the focus is posed on the maximum installed capacities for a selection of technologies, as shown in *Table 13*. These include PEM Electrolyzers, onshore wind, solar PV, and battery storage. These technologies were selected for this comparison because these are already part of the plans for Spain's 2030 targets, and thus a reflection can be made by confronting what should represent reality in 2030 with the model results. By comparing the maximum resulting capacities in the model with the planned installed capacities of Spain by 2030, it can be noticed that none of these exceeds the projections. Nevertheless, these still represent a significant portion of the overall capacity, underlining the magnitude of the energy requirements of the port.

To this end, multiple considerations need to be made. Firstly, the target capacities refer to 2030, which is twenty years prior to the year in which the port has set its decarbonization objective. In this period, the process of energy transition is set to accelerate its speed, due to higher maturity of technologies and stricter sustainability targets. Therefore, the fraction of PoB's energy requirements with respect to the overall national capacity is set to decrease. Secondly, the model was developed by considering total self-sufficiency, as this considers both alternative fuel production and energy generation. While this was chosen to fully represent the energy consumption aimed at satisfying the overall energy demand of future ports, this results in a drastically different landscape than the current consumption of the port. This needs to be acknowledged when comparing the resulting capacities with current projections, as such a system would necessarily imply higher energy volumes involved. Keeping these considerations in mind, it could be argued that Spain's targets might be too low for what concerns RES generation, and this might be even more significant regarding battery storage. If ports were to be developed with self-sufficiency as an objective, current targets would need to be raised, especially considering the presence of other similar systems around the country. This might not be the case for what concerns electrolyzers capacity, as 2030 targets are already significantly higher than the required capacities according to the model results.

Table 13: Resulting Capacities vs 2030 Target Capacities (Spain)

Technology	**Maximum Resulting Capacity**	**Model Phase**	**Installed Capacity**	**Target 2030 Spain**	**References**
PEM Electrolyzers	3.69 GW	Demand Model	9.2 GW (Europe, 2023)	11.00 GW	IEA, n.d.-a; Reve, 2023
Onshore Wind	48.1 GW	Refined Model – Base Scenario	30.30 GW (Spain, 2023)	59.00 GW	Reve, 2023
Solar PV	29.87 GW	Refined Model – Base Scenario	26.20 GW (Spain, 2023)	76.00 GW	Reve, 2023
Battery Storage	10.40 GW	Refined Model – Battery-Electric Ships Scenario	4.5 GW (Europe, 2023)	17.20 GW	Murray, 2023; Reve, 2023

Another aspect of interest in the definition of the feasibility of the resulting systems is represented by water utilization. According to the stoichiometric values of the process of electrolysis, hydrogen production requires a minimum of 9 liters of water for each kg of hydrogen produced (Saulnier et al., 2020). Considering this value, the volumes of water for hydrogen production in the model can be calculated. *Table 14* summarizes the quantities of hydrogen flowing through the system in the different model phases. Intuitively, the maximum value can be found in the refined model, given the changes that were made to the model and the non-installation of hydrogen import infrastructure. In this case, 655.47 ktons of hydrogen are produced in a year, resulting in 5.90 billion liters of water consumption. As ultrapure water is required for electrolysis, the water source that is considered shapes the energy requirements to treat this. Intuitively, groundwater represents the best option in this respect, with an energy consumption of 2 kWh for each cubic meter of purified water. Electricity consumption increases to 2.2 kWh in the case of treated wastewater, and to 7 kWh in the case of seawater, as a desalination process needs to be performed (Madsen, 2022). On the other hand, the energy that is required for the electrolysis process for the same quantity equals to 5,000.00 kWh, underlining the low energetic requirements for water purification with respect to electrolysis (Madsen, 2022).

Considering the current numbers, wastewater treatment in the Catalan autonomous community is equal to 1.94 million cubic meters per day (Statista, 2023). This means that the water demand for electrolysis would be equal to 0.82% of the total treated wastewater in the region on a yearly basis. This underlines how, besides the quantity of used water would be significant, this could be possibly sustained by the treatment of wastewater. On the other hand, in case seawater is chosen to not affect the equilibrium on water availability on a regional level, higher costs should instead be considered. According to the capacity that would be required to satisfy the production levels of 5.90 billion litres of water consumption annually, a minimum capacity of 16,183 cubic meters per day of desalinated water should be installed. Given the capacity, the price of water desalination would equal around €0.728 per cubic metre (Shokri & Fard, 2023). As 9 litres of water are consumed for each kg of hydrogen, this can be translated into a cost of €0.007 per kg of hydrogen as desalination cost. Additionally, this reasoning did not include water resulting from other considered processes in the system, such as the Fischer-Tropsch reaction plants, which could lower the pressure on water treatment systems. In conclusion, despite water costs and availability not being implemented into the model, it was determined that this does not represent a significant neglection, due to the low impact on the overall outcomes.

Table 14: Hydrogen Production and Import, Total Yearly Values

	Units	**Demand Model**	**Refined Model – Base Scenario**	**Refined Model – Battery-Electric Ships Scenario**
Total H_2 Production	kilotons	349.83	655.47	3.05
	GWh	11,659.96	21,847.00	101.70
H_2 Import	Kilotons	-	0	11.40
	GWh	-	0	380.07

Lastly, a reflection needs to be made for what concerns the resulting capacities for hydrogen transport. This was considered to be imported from Morocco via pipelines, which present a significant capital investment. For this reason, it might be inefficient to consider such a system unless a minimum capacity is installed. As this project was developed based on a linear optimization model, this considers the capital expenditure for transmission under the form of €/km-kW. For this reason, the model sees no difference in installing a higher or lower capacity, as the CAPEX is a linear function depending on the installed capacity. Nevertheless, cost projections for transmission systems show how low-capacity pipelines are proportionally more expensive than bigger ones (Van Rossum et al., 2022).

Considering the capacities as presented in *Table 15*, it could be argued that, given the installed capacity for this system in the model, it might not be worth building an own transmission system. While hydrogen would be crucial in the considered system, given its characteristics as feedstock for both considered fuels, the costs relative to the transmission system should be higher given the magnitude of the capacity. Because of this, it could be more economically convenient to import the fuels, produce hydrogen locally, or make use of shared transmission pipelines, in case other systems join PoB in the development of such a project.

Table 15: Hydrogen Transmission Capacity

	Units	**Base Scenario**	**Battery-Electric Ships Scenario**
H_2 Transmission Capacity	MW	0	43.40
	Kg per hour	0	1,302.13

6. Conclusions

The development of this project was inspired by the attempt to find an answer to the research questions as presented in *Chapter 1*. The main considerations that can be taken from this research are summarized below.

Sub-Question 1: ***What could be the total energy demand of a carbon-neutral Port of Barcelona, by considering the production of alternative fuels and other changes the port may undergo?***

As previously discussed, the main demand of energy happening in the ports is represented by marine fuels. Currently, these are generally fossil-based, and almost completely imported from third countries. This therefore translates into a variable cost, as fuels need to be purchased to satisfy fuel demand in the port. On the other hand, a transition to alternative and sustainable methods is necessary, given the decarbonization objectives of PoB. Alternative fuels, such as synthetic diesel or hydrogen, can clearly be imported from third countries, maintaining the current structure. On the other hand, these present the opportunity of being produced locally, potentially lowering costs as transportation from other ports would not be necessary. This is the case that was considered for what concerns this project, showcasing the elevated electricity and feedstock requirements to satisfy this demand stream. Electricity is required to power up the different technologies used to produce fuels, as well as to those providing the necessary feedstock for fuel production. In this project, this is represented by hydrogen and carbon dioxide. The former is required to produce both considered fuel options, and can be produced by means of electrolysis, which translates into an additional electricity demand, or by importing it from third countries, translating instead into a variable cost for the system. CO_2 is required to produce synthetic fuels, specifically for Fischer-Tropsch Diesel in this project. This was considered to be provided exclusively with DAC plants, translating into an additional electricity demand. Nevertheless, this might be purchased from third parties, translating instead into a variable cost.

Other than the changes brought by marine fuel production, the infrastructural side is also set to vary. The main change in this respect is likely to be represented by OPS, providing electricity to vessels to perform in-port operations, by substituting auxiliary engines running on fossil fuels. This will represent an additional electricity demand stream, increasing the overall electrical requirements of the port. Another change might be caused by a general electrification of those processes being still (partially) based on fossil-fuels, such as certain cranes, vehicles used to transport individuals within port premises, or heating systems of buildings. Similarly to OPS, these changes are aimed at transforming a demand for fossil fuels into a demand of electricity, thus increasing the overall electricity demand. On the other hand, there are also systems that are set to reduce their overall demand for electricity. This is generally due to the improvements achieved with determinate technologies, which allow for higher efficiencies and, subsequently, lower electricity consumption. An example of this is represented by the lighting system present in the port, which is being switched to LEDs for higher performance.

In summary, the general trends that characterize the future energy consumption of PoB suggest that this will significantly increase. The magnitude of this variation is strongly dependent on the choices that are taken for what concerns alternative fuels, as local production would imply a significantly higher energy demand. It is not clear whether alternative fuels production will happen locally, as the current situation sees fossil fuel importation from third countries. On the other hand, it is safe to state that electricity demand will be higher either way, as many subsystems will likely be electricity-based in a decarbonized PoB.

*Sub-Question 2****: What could be needed in terms of energy storage, transmission, and RES generation capacities to sustain the total energy demand of the Port of Barcelona, by achieving carbon neutrality?***

For this project, two options were considered to provide energy to the system: RES generation, in the form of solar PV and onshore wind, and hydrogen import from Morocco. Results from the two scenarios presented in Chapter 4 show how the strategy that is taken by the model to satisfy the overall energy demand of the port strongly depends on the propulsion systems that are considered. Regarding the import of hydrogen, the corrections made to the model show that self-production is more economical, given the high costs for installing the transmission system. This poses further pressure on finding the proper combination of RES generation technologies to minimize the impact of variability into the system. A technology that instead proved to be crucial is electricity storage. Generally, this serves as a way to balance RES variable generation, being charged whenever RES are abundant, and discharged whenever electricity demand is higher than its production. It is noteworthy that, comparing the installed capacities in the two systems, this is significantly more important if battery-electric ships are deployed. In this case, other than balancing RES, this also substantially substitutes fuel storage, increasing its importance for the system. When considering the results from the base scenario, it is clear that electricity storage assumes a lower importance. This is mostly caused by the fact that electricity cannot be directly used as fuel and is therefore more convenient to use it to produce alternative fuels and store energy in different forms. This is caused by the fact that electricity storage is more expensive with respect to storing fuels, and subsequently fuel production assumes the role of energy storage, as the plants for production are deployed in RES-rich periods.

In conclusion, to satisfy the future energy demand, it is necessary for the system to change to accommodate the increased requirements. Depending on the fuel mix characterizing the port, the chosen strategy might differ, as alternative fuels generally require significant amounts of hydrogen as feedstock, requiring higher capacities for electrolyzers. Contrarily, battery-electric ships would increase the required capacity for electricity storage. Either way, this would require new RES generation capacity, as well as transmission infrastructure to transport energy to the system.

Which energy vectors could constitute Port of Barcelona's carbon-neutral energy supply, what could be their relative importance, and how could they be produced?

As shown throughout the project, the main changes characterizing the energy vectors of a decarbonized PoB will be caused by the necessity of switching to sustainable propulsion methods. Depending on the alternative fuels that are adopted, overall energy requirements for producing the required amount might vary significantly. In this project, three different alternatives were considered: Fischer-Tropsch diesel, liquefied hydrogen, and battery-electric ships. For the first two options, a higher amount of energy would be required, due to the several conversion steps that these would entail, as well as the necessity of producing feedstock. On the other hand, battery-electric ships would require a lower amount of energy to satisfy the same demand, as electricity would not need to be transformed into other carriers, thus presenting a higher overall energy efficiency from production to consumption. Nevertheless, this would require a higher capacity for electricity storage, as this would assume the double role of balancing RES generation and providing fuel storage for battery-electric ships. Furthermore, the significant barriers in large-scale deployment of battery-electric ships would possibly require significant changes to the shipping sector, such as shorter shipping routes or a higher number of stops when travelling from origin to destination, due to the energy density of this technology.

In response to the possible changes in the shipping sector, it is necessary to strengthen the current energy generation system, as it is unlikely that the national grid as it is would be able to sustain such a growth. On the other hand, in case fuel production is taken care of by the port, it might be more cost efficient to install an own RES generation system, as shown by the cost differences between the demand model presented in Chapter 3 and the scenarios from the following chapter. In this case, electricity storage would assume a crucial role, as it would be aimed at balancing energy generation.

In conclusion, the evolutions that might take place in the shipping sector will imply higher energy flows characterizing ports. These are mostly caused by the transition to alternative fuels, especially in case these are self-produced, but also other systems, such as OPS, will likely cause a significant increase in consumption patterns. Depending on the selected propulsion systems, energy demand might vary significantly, and the fuel mix will determine the necessary technologies to support the shift, such as hydrogen import or electricity storage.

6.1. Scientific and Societal Relevance

As introduced in Chapter 1, the nature of the shipping sector requires a comprehensive view, considering all of the subsystems composing ports. Ports are complex systems, in which multiple energy resources are involved, and the transition towards sustainable shipping will inevitably increase the degree of complexity of these interactions. State-of-the-art literature is currently characterized by projects which generally focus on specific subsystems of ports, without considering the bigger picture. This research represents an attempt to shift towards more comprehensive analyses, trying to capture the possible changes that might characterize the future PoB in a net-zero scenario.

The objective of achieving decarbonization of the shipping sector inevitably involves transitioning towards more sustainable ways of powering it. As previously mentioned, multiple potential alternatives are currently in study to achieve this. On the other hand, the richness of alternatives represents both a strength and a weakness. While this allows for a multitude of opportunities to achieve the final objective of decarbonizing shipping, this creates additional uncertainty regarding the future landscape of shipping. This intensifies the difficulties for what concerns planning ahead of what the future could be like. This shaped the choice of the considered alternatives of this project, which were chosen for their favorable characteristics, as well as for being representative of a determinate category of fuels.

6.2. Future Work Recommendations

As previously mentioned, this project represents the first attempt to represent a port within the Calliope framework. In doing so, the representation was developed by considering PoB as reference. Nevertheless, the method that was applied can be easily replicated to represent other systems. Possible ways to give continuity to this research are expressed below.

Firstly, the system that was considered could be enlarged. In this project, the port was considered in isolation, only considering the traffic of the port and its demand streams. On the other hand, the shipping sector is composed of a multitude of ports. For this reason, the model of PoB could be replicated for other port systems, with the objective of representing a network of these. In doing so, the scope of the system would inevitably change, as the analysis would shift from considering the energy vectors of a single port to considering the interactions between ports and their energy vectors. In view of the adoption of alternative fuels, this approach could be used to study the future market for these, possibly providing information about the optimal locations to produce determinate fuels. Another possibility of enlarging the system could involve implementing nearby systems into the model, to capture possible opportunities regarding interconnecting these with PoB. An example could be to consider the port paired to the city of Barcelona, or the nearby airport, to define possible energy exchanges between these aimed at minimizing overall consumption. Lastly, in order to define the possible magnitude of producing locally all of the fuels consumed in Spanish ports, an enlargement could be made to represent all of the national ports and their fuel demands, to define whether producing fuel for all of these could be feasible.

Alternatively, another option to carry on this work could involve enriching the current system. This would involve improving the level of detail of the model, which can be achieved in different ways. A first example could be considering other ways to supply energy to the system. For this project, three alternatives were considered in this respect, but more options are present to generate energy. For what concerns RES generation, other technologies could be implemented into the system, to explore whether other resources might be more suitable for powering ports. On the other hand, energy can be imported in different forms, and from different countries or parties, and is not limited to the selected option. This rationale can also be applied to other parts of the system, as several alternative fuel options were not considered, or as other technologies might take the role of the ones that were selected. By considering variants of the represented technologies, an additional level of detail can be reached with the analysis.

Lastly, improvements can be made with respect to the granularity in which propulsion energy demand is defined. As this is constant throughout each month, this does not represent possible daily patterns of refueling. The current representation depicts an optimal refueling pattern, with the demand being equal throughout the 24 hours of each day. On the other hand, by making a more granular representation, the focus can be placed on optimizing the refueling pattern, thus verifying the actual feasibility of this.

Appendixes:

A1: Other Measures

To achieve decarbonization objectives, that will require a global transition to alternative fuels and energy sources, the focus needs to be posed on the intermediate objectives set at 2030. For these, transitional and operational measures will likely need to be put in place, such as using data analytics to improve operational efficiency (Soone, 2023). In addition to OPS, many technologies or measures are cited in literature. In this subsection these are presented and analyzed, and it is pointed out whether these were considered or not when dealing with the realization of the Calliope model of PoB.

The first option when it comes to decarbonize port environments is that of powering these with RES. On a EU-level, this is already a partial requirement towards 2030, in which a minimum of 40% of the total required energy needs to come from RES (Soone, 2023). In the case of PoB, all of the electricity that is currently provided to the port comes from renewable sources, given the nature of their contract with electricity companies. Nevertheless, fossil-based consumption is still present, and new systems in the port will cause an increase in electricity demand, as is shown in Chapter 3. Depending on the magnitude of this increase, different pathways could be taken to support it. In case of limited growth, additional generation could be installed directly in the port, i.e., by placing photovoltaic panels in the roofs of the buildings. Contrarily, in case the additional demand cannot be satisfied by directly installing RES in the port, alternatives need to be found. These can be generalized into two different ways: firstly, identify one or multiple locations in which enough capacity can be installed, or secondly, import the required energy from a third party, i.e., a foreign country. For the former, the ideal would be to find a location near the considered system, to minimize transmission losses, and therefore lower costs (Terwel & Kerkhoven, 2018). Clearly, this would be bound to RES availability, such as wind speeds or solar irradiation. Therefore, analyses need to be done on the surrounding territory to evaluate which area would suit best to satisfy the requirements. On the other hand, in the case of importing energy from a third party, both transmission distance and energy/feedstock costs need to be considered, to minimize unitary costs of purchase. Simultaneously, as the objective of this study is to define possible setups for a decarbonized PoB, it is required that imported energy, in whichever form it is, comes from "green" sources. As the first part of the model is focused on energy demand, this was initially not considered. Although, in the second part this represented the core of the model, as the focus is on the ways to support the increase of energy demand. Therefore, further explanation is provided in Chapter 4.

Another option that is often mentioned in literature is that of adopting digital technologies to improve the efficiency of the different operations happening around shipping. These include both measures aimed at the infrastructure and at the vessels. Literature shows that there are many inefficient subsystems in port environments. A demonstration for this is the percentual time that ports spend in the port (Johnson & Styhre, 2015), that depends on the necessary times to perform operations, as well as on the proper management of ship arrivals to terminals. By minimizing waiting times, and thus increasing the time in which vessels are effectively used, these can theoretically increase the quantity of transported goods on a yearly basis. This would increase the overall efficiency, as boats would still consume energy while stalling in port otherwise. This inefficiency can be partially explained by the possibility of human error, which could lead to delays and prolonged waits for other vessels calling in the port. To respond to this, a combination of automation and data analytics could increase the overall efficiency of the system (Grosche & Haid, 2022). In fact, if ports were able to predict ship arrivals as accurately as possible by analyzing available data, planning precision would increase, also thanks to automation which would take care of operations to perform. In an ideal situation in which these are properly implemented, the port could be seen as a smart grid, in which the system is constantly monitored to manage overall energy allocation with the aim of meeting the varying energy demand of involved parties (IEA, 2022b). PoB itself is already planning to implement a smart grid in the *Moll de Pescadors* as a small pilot, by installing PV panels on the available area in the terminal and applying a smart grid to allocate the generated energy (PoB, n.d.-b). For what concerns the model, this option was not directly considered, because of the complexity to properly represent it. Although, as smart grids are characterized by a constant pairing of energy generation and demand, it could be argued that this was implicitly considered in the model. This is because the aim of the model is that of optimizing the overall energy system, by pairing demand and supply of energy throughout the whole year.

Measures aiming at increasing energy efficiency do not stop at digitalizing and automating operations. In fact, almost every subsystem in a port can at some degree be optimized to reduce overall energy consumption. For instance, by replacing lighting systems with newer technologies with higher efficiencies, lower energy consumption to this respect can be achieved. The same rationale can be applied to heating systems, that can be switched to electric heat pumps.

Another technology that is trending among scholars to decarbonize port environments is represented by EVs and hybrid vehicles. Inside ports there is usually a fleet of vehicles, used to move workers around the structure. Given the current automotive market, it is likely that these are still running on fossil fuels. By substituting these with EVs or hybrid vehicles, a small portion of emissions from the port would be avoided. By focusing on PoB, it can be seen how this road has already been paved, with 41% of vehicles being currently electric, and with a total of 47 charging points for these installed throughout the area. This process started because of the participation of PoB to the Voluntary GHG Reduction Agreements, encouraged by the Catalan Government Office of Climate Change (PoB, 2021b).

In literature multiple other options are theorized and presented for port decarbonization, underlining the degree of uncertainty that is still present when dealing with the evolution of complex systems such as ports. Because of the difficulties in abating emissions, some scholars proposed carbon offsetting as one of the options for ports. By doing this, emissions caused by the port would be offset in a different location, for instance by projects of reforestation. Besides being a valid option in terms of global efficacy, it was chosen not to consider this option for the model, because of the complexity in representing this, as well as potential ethical problems related to this (Anderson, 2012; Hyams & Fawcett, 2013). In fact, this would theoretically solve the problem, but on the other hand it takes longer for trees to absorb CO_2 when compared to the rhythm of generating it. Other technologies that are worth mentioning include the following: ship hydrodynamics optimization, autonomous shipping, wave and tidal energy, algae-based fuels, and waste management. Besides representing potentially viable options, the high uncertainties and barriers related to these, together with their novelty and consequent lack of maturity, brought to the decision of not consider them.

A2: Liquefied Hydrogen Spatial Factor

It was deemed necessary to identify a spatial factor to apply to vessels for liquefied hydrogen usage, due to the low volumetric density of hydrogen with respect to other fuels is that of a potential spatial factor to apply to vessels powered with liquid hydrogen. This is due to the low volumetric density of hydrogen when compared to other fuels. Liquid hydrogen has a volumetric density of 8 MJ/l, which means that in a cubic meter approximately 2,222.22 kWh can be stored. In view of the possibility of deploying liquid hydrogen as marine fuel, this aspect needs to be considered. In literature this issue is often mentioned, but there are still uncertainties on the actual quantification of the changes brought by on-board hydrogen storage systems. Therefore, it was necessary to make estimations based on the actual size of the vessels and their fuel consumption. In the report from PoB (2021a), other than a breakdown of the traffic to represent the different types of goods moved in the system, a breakdown of the traffic per destination is provided. This was used as a base to define the average distance to be covered by ships. By combining this with average speed and average daily fuel consumption per type of vessel, the average refuel per call was calculated. These energy requirements, expressed in GWh as shown in *Table A1*, were then transformed into spatial requirements. The necessary volume for storing these quantities of liquid hydrogen was then compared with one of the main types of goods as showed in the traffic reports, to define a spatial capacity factor. This is calculated with a ratio between the available space after installing the hydrogen storage on board, and the total capacity of the vessel without this installed. For this analysis, passengers' traffic was not considered, as travel distances are shorter and thus less liquid hydrogen would be needed. Furthermore, the first examples of hydrogen-powered ferries are already being deployed (Klevstrand, 2023), as well as the first cruises (Bahtić, 2022).

Therefore, it was assumed that these would be feasible and scalable by the time decarbonization will be a requirement for PoB.

Table A1: Liquid Hydrogen Spatial Factor

Vessel Type	Call Time	Required Refuel	Required Volume	Vessel Length	Vessel Width	Reference Good	Capacity	Spatial Factor
Unit	*Hours*	*GWh*	*m^3*	*m*	*m*			
Container Ships	16	202.24	85,462	366	49	2,217 TEUs	14,500 TEUs	0.85
Oil Tankers	49	375.60	158,720	415	63	134,912 t crude oil	500,000 tons	0.73
LNG	38	378.73	160,042	300	43	72,019 t LNG	267,000 m^3	0.4
Bulk Carriers	38	413.16	174,592	300	40	251,412 t cement	100k to 200k tons	*Non feasible*
Chemical Carriers	42	313.43	132,448	285	45	90,409 t ammonia	180k tons	0.39

As shown by the data above, where possible a spatial factor was determined, by considering the dead weight tonnage (DWT) or the available volume of the boats, and by taking as reference the mainly transported goods per each type of ship. As can be seen, the lowest space diminishment is that of container ships, in which the space for liquid hydrogen storage would take out 2,217.00 TEUs out of a reference value of 14,500.00 relatable to the New-Panamax generation (Rodrigue et al., 2020). This is followed by oil tankers, which can transport 500,000.00 tons of crude oil (Notteboom et al., 2022), but 27% of this space would be needed for storing liquid hydrogen. The other two factors that were calculated and proved to be feasible are LNG ships and chemical carriers, which resulted in similar factors, given by the reference values that were taken, equal to 267,000.00 m^3 for LNG ships (Bai & Jin, 2016) and 180 kilotons for chemical tankers (Notteboom et al., 2022). The last value that was calculated is that of bulk carriers. By considering the high energy requirements of these vessels, that resulted the highest when compared to other ship types, and comparing this volume with the amount of cement that would be transported otherwise, this results in 251,412.00 tons of cement, compared to a capacity of 100 to 200 kilotons (HandyBulk, n.d.). On the other hand, as previously mentioned, the terminals have been modelled as locations in which different types of ships are grouped. This means that bulk carriers are grouped under the same location with other vessel types that are instead feasible with liquid hydrogen. As bulk carriers account for 33.93% of the total traffic happening in the terminal, and for 8.79% with respect to the total, it was chosen to ignore this issue, and consider a joint spatial factor to be applied to the terminal as it is modelled. This was done by merging the values that were instead found to be feasible, proportionally to their relative weight, calculated by comparing the tonnage of goods assigned to the different vessels. This resulted in a spatial factor of 0.603, applied to all categories of ships that were initially considered under the "Bulk Terminal". Lastly, as it was not possible to calculate spatial factor for the "General Cargo Terminal", mostly because of the diversity of goods to be compared (PoB, 2021a), it was chosen to make an average between the factors considered for the other two terminals, resulting in a 0.7265 factor. Once these were defined, it was necessary to decide how to represent this in the model. As the spatial factor will have the effect of increasing the necessary number of boats to transport the same quantity of goods, given the lower spatial availability, it was decided to combine this with the engine efficiency that was considered for hydrogen. By doing this, the result should imply a higher liquid hydrogen requirement, representing the higher number of port calls happening on a yearly basis, assuming the same quantity of goods to be moved. As energy efficiency of liquid hydrogen-based engines was found to be equal to 0.65 (Stark et al., 2022), the resulting factors are the following: 0.55250 for the "Container Terminal"; 0.47223 for the "General Cargo Terminal"; and finally, 0.39195 for the "Bulk Terminal".

A3: Calliope

Calliope is a framework that was developed to analyze energy systems with high shares of renewables. Therefore, this was created with the main objective of dealing with generation variability, in order to explore scenarios in which RES are implemented. Thanks to its formulation, this system is suitable for analyzing energy systems of any type, ranging from a local to an intercontinental scale (Pfenninger & Pickering, 2018). Calliope is being openly developed on GitHub, and it uses different Python packages to compose the different parts of the framework, as shown in *Figure A1*. In synthesis, a Calliope model is composed of *YAML* and *CSV* files, defining technologies, locations, links, resource potentials, constraints and other factors influencing the system to be studied. These inputs are first analyzed, with packages such as *pandas* and *ruamel*, and then restructured with *xarray*. The optimization problem is formulated using *Pyomo* with the restructured inputs, and this is sent to the solver, that can be chosen from a list of possibilities. For this research, *Gurobi* was chosen, as this is faster when compared to other solvers, and therefore more suitable for analyzing complex systems such as PoB (Pfenninger & Pickering, n.d.). Once the solver completes the simulation(s), this is sent back to *pandas* and *xarray* to restructure the results. This allows both to visualize the results in an interactive manner, via *Plotly*, and to save the results as *NetCDFs* and figures, with *xarray* and *plotly*.

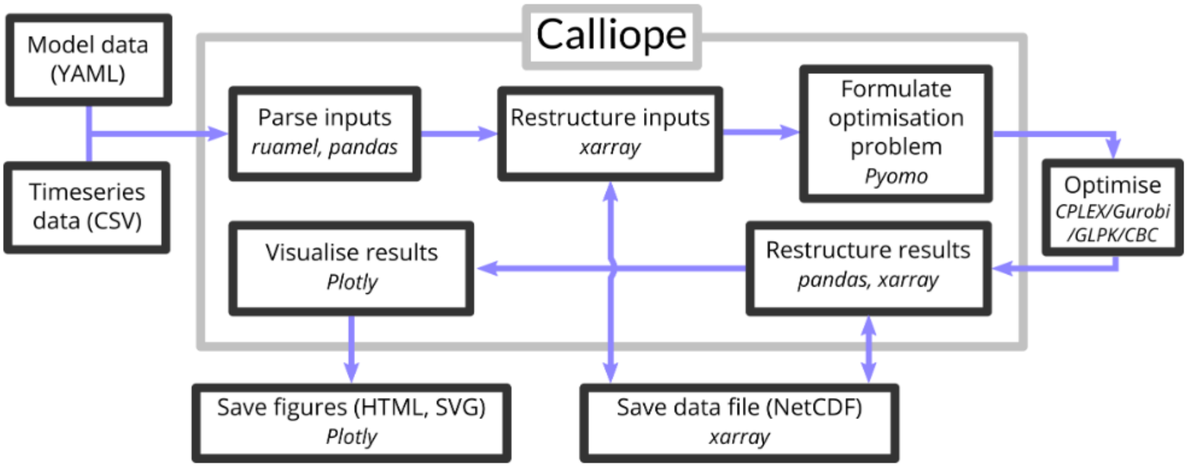

Figure A1: Calliope Framework Composition
Source: Pfenninger & Pickering, n.d.

As mentioned, different projects have been developed using Calliope, each focusing on certain aspects in a particular area. The example of Euro-Calliope is one of the most important and known, as this was developed to explore ways to reach a carbon-neutral European power system (Tröndle et al., 2020). This study was developed by considering weather data from 2010 to 2018, and after computing the cost-optimal combination of technologies for each year, the SPORES mode, allowing for multi-scenario simulation, was used to relax the optimality objective by 5, 10 and 15 percent, to explore alternative combinations under these slacks. This resulted in a total of 441 possible scenarios in which the objective of decarbonizing the European energy system is reached (Pickering et al., 2022). Another model that was developed with Calliope is Bangalore-Calliope. Here the size of the system is closer to that of this research, and the objective was to consider the energy system at a district-level to optimize decision-making while minimizing risks for the end-users. Results of this study suggest that, considering the assumptions taken to model the district, single-building energy systems might prove to be safer than district-level ones, because of the many outages in the Bangalore energy system ("Mitigating Risk in District-level Energy Investment Decisions by Scenario Optimization," 2018). The number of projects that were developed via Calliope does not stop at these two. Nevertheless, there are currently no publicly available projects for which this framework has been used to represent a port environment, despite the large availability of tools that could be used to perform this task.

The choice of using Calliope for developing this model is mainly justified by the nature of the framework itself. Because of Calliope being a framework developed to analyze energy systems with high uncertainty and high shares of renewables, this represents a perfect fit to study a complex energy system such as PoB. In fact, the large increase in energy requirements, mostly caused by local renewable fuel production, needs to be supported with an adequate increase in energy supply. To achieve decarbonization of the energy system, it is necessary for this additional supply to be renewable-based, and so fuel production will be planned according to the renewable energy generation.

For better clarity, some terminology regarding Calliope is provided. As previously mentioned in this section, a Calliope model basically consists of *YAML* and *CSV* files. These latter exclusively represent data timeseries, that can either represent resource potential for a determinate area (i.e., capacity factors for solar PV given irradiation levels), or the demand for an energy carrier in a given location (i.e., electricity). On the other hand, *YAML* files represent user-made code in which most aspects of the model are defined. There are three required files for a model to exist: *model.yaml*, *techs.yaml*, and *locations.yaml*. The first one represents the model specifications and can be divided in three main parts: the paths in which all model data is saved, including other *YAML* files; general information of the model, such as the standard formats and subset times; and the run specifications, in which aspects such as the solver, the run mode and the objective options are indicated. In *techs.yaml*, as the name suggests, the different possible technologies are modelled. In Calliope, any subsystem that somehow deals with energy can be considered a technology. These are categorized depending on the manipulation these cause to energy and are grouped in seven different categories. These are further explained in the following subsection. Lastly, *locations.yaml* includes the geographical side of the model, meaning both the different locations composing the system, and the links connecting these. For each location, available technologies are specified, as well as potential additional constraints to apply to these, while for each link, applicable transmission technologies are indicated. At the same time, technologies make use of resources, that are then transformed into carriers that flow throughout the system to satisfy each locations' demand.

As mentioned, technologies are grouped under seven different categories in the Calliope framework, which are the following: *supply*, *supply_plus*, *demand*, *storage*, *transmission*, *conversion*, and *conversion_plus*.

Supply technologies are those supplying energy to a carrier, yielding therefore positive resources, meaning that these increase the overall amount of energy in the system. These may therefore represent means of supplying energy, such as energy import.

Supply_plus technologies are quite similar to *supply* technologies, with the difference that additional constraints can be applied. These include, for instance, efficiencies or storage options. Examples of *supply_plus* technologies include power generation such as solar photovoltaic or wind farms.

Demand technologies, contrarily to *supply*, are those technologies whose impact causes the overall amount of energy in the system to decrease, by demanding this from a specific carrier. Therefore, any "energy sink" in the system needs to be modelled as *demand*. In the model, this is represented by the demands of electricity, and of propulsion energy.

Storage technologies are used to store carriers in determinate locations. As other technologies, different constraints might be applied to these, such as discharge rate or roundtrip efficiency.

Transmission technologies are different with respect to other types, as these are the only technologies that are assigned to links and not to locations. These are used to transport specific carriers between locations, such as electricity or fuels.

Conversion technologies include those that transform one carrier into another with a certain efficiency. These, together with *conversion_plus*, are necessary to make it possible to account for transformation losses, or required capacity for transforming one carrier into another.

Conversion_plus technologies differ with *conversion* ones for being able to transform one or more carriers into one or more carriers. Therefore, these allow representing more complex transformations including multiple inputs and/or outputs.

The definition of the technologies that can be installed in each location, as well as the links transporting energy throughout the system, compose the base of the system, together with all of the characteristics that are specified for each of these.

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