



MSc Thesis

Developing an Energy System Model for Ports

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*“Eu o engenheiro, eu o civilizado, eu o educado no estrangeiro,
Gostaria de ter outra vez ao pé da minha vista só veleiros e barcos de madeira,
De não saber doutra vida marítima que a antiga vida dos mares!
Porque os mares antigos são a Distância Absoluta,
O Puro Longe, liberto do peso do Atual...
E ah, como aqui tudo me lembra essa vida melhor,
Esses mares, maiores, porque se navegava mais devagar.
Esses mares, misteriosos, porque se sabia menos deles.”*

Álvaro de Campos, Ode Marítima

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Abstract

Maritime trade plays a pivotal role in the global economy, with over 80% of goods and services transported by sea. The emissions from the world's maritime fleet have been rising, having increased by over 20%, in the last decade alone. This upward trend in emissions poses a significant threat, especially considering established climate goals - such as the Paris Agreement, PNEC2030 and RNC2050. Ports, today, extend beyond mere trading hubs for goods and energy, evolving into future low-carbon vector hubs, also considering the goal of achieving carbon neutrality in ports by 2050, aligning with global climate goals.

This thesis aims to develop an open-source, transparent tool to help identify optimal energy transition pathways for maritime ports, following last year's other project of the research group. An energy model of a generic port is created and various decarbonization scenarios are simulated, to identify opportunities for improving energy efficiency and promoting sustainable port operations in a container terminal.

The development of a port energy model encompasses an extensive characterization of the energy use in a port. Furthermore, comprehensive techno-economic data pertaining to each conceivable technology is compiled. The Reference Energy System (REF) is created, including the entire energy chain of the operations area in a container terminal, from primary energy sources to end-uses. The end-uses are disaggregated into various technologies in the model to provide a more comprehensive understanding of the system. Additionally, an accessible and reliable simulation model is created using the OSeMOSYS platform.

A case study of Port of Sines is implemented, having 2020 as a reference year, defining the demand and certain restrictions, alongside five distinct scenarios, which enable a comparative analysis of the emissions and energy consumption.

The findings highlight that the electrification of Port of Sines is a possible and likely scenario. However, by 2050, carbon intensity is still expected to be around 13 g/kWh and, hence, pursuing a total greenhouse gas emissions reduction entails a more rapid electrification trend and changes in ocean-going vessels' fleets, which leads to a significant investment in local energy generation and import capacity.

Keywords: Container Terminal, Decarbonization, Energy Modeling, Energy Transition, Energy Systems, Maritime Port, OSeMOSYS, Techno-economic Analysis, Port of Sines.

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Resumo

O comércio marítimo tem um papel fundamental na economia global, com mais de 80% dos bens e serviços a serem transportados pelo mar. As emissões mundiais da frota marítima têm aumentado, tendo tido um acréscimo de mais de 20%, apenas na última década. Esta tendência de crescimento representa um desafio, especialmente tendo em conta os objetivos climáticos existentes - como o Acordo de Paris, o PNEC2030 e o RNC2050. Na atualidade, os portos representam mais do que meros locais de troca de bens e de energia, sendo também futuros locais de armazenamento e ou produção de vetores energéticos de baixo carbono, tendo em conta o objetivo de atingir a neutralidade carbónica nos portos até 2050.

Esta tese procura desenvolver uma ferramenta transparente e de livre acesso para ajudar a identificar as melhores trajetórias de transição energética para portos marítimos, no seguimento de outro projeto deste grupo de investigação, onde as emissões de um porto foram alvo de estudo.

Um modelo energético de um porto genérico é criado e vários cenários de descarbonização são simulados, no sentido de identificar oportunidades de melhoria no consumo energético e promover operações portuárias mais sustentáveis, num terminal de contentores. O desenvolvimento de um modelo energético aplicado a portos marítimos envolve uma extensa caracterização do uso de energia num porto. Além disso, são compilados dados técnico-económicos abrangentes, referentes a cada tecnologia existente no modelo. O Sistema de Referência Energético (REF) é criado, incluindo toda a cadeia energética da área de operações de um terminal de contentores, desde as fontes primárias de energia até aos usos finais. Estes são ainda desagregados em várias tecnologias de conversão de energia, no sentido de termos a energia útil, para proporcionar uma compreensão mais abrangente do sistema. Para além disso, um modelo de simulação robusto e de fácil acesso é criado, usando a estrutura do OSeMOSYS.

Um caso de estudo do Porto de Sines é implementado, tendo o ano de 2020 como ano de referência, introduzindo a procura e certas restrições, juntamente com cinco cenários distintos, que permitem uma análise comparativa das emissões e do consumo de energia.

Os resultados evidenciam que a eletrificação do Porto de Sines é um cenário possível e provável. Apesar disso, em 2050, ainda se espera um fator de intensidade carbónica de aproximadamente 13 g/kWh, ficando evidente que uma redução total das emissões dos gases com efeito estufa implica uma eletrificação mais rápida e mudanças na frota dos navios que atracam no porto, o que leva a um investimento significativo em tecnologias de geração local de energia e em capacidade de importação.

Palavras-Chave: Análise Técnico-Económica; Descarbonização, Modelação Energética, OSeMOSYS, Porto de Sines, Portos Marítimos, Sistemas Energéticos, Terminal de Contentores, Transição Energética

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List of Symbols

Acronyms and abbreviations

ADENE	Agência para a Energia
EC	European Comission
EN-H2	National Hydrogen Strategy
ETS	Emissions Trading System
EU	European Union
FE	Final Energy
FEU	Forty-foot Equivalent Unit
GHG	Greenhouse Gas
HC	Harbour Craft
HFO	Heavy Fuel Oil
ICE	Internal Combustion Engine
IEA	International Energy Agency
IMO	International Maritime Organization
IRENA	International Renewable Energy Agency
LNG	Liquified Natural Gas
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
OGV	Ocean-Going Vessels
PA	Port Authority
PE	Primary Energy
PNEC2030	Plano Nacional para Energia e Clima 2030
QC	Quay Crane
REF	Reference Energy System

RNC2050	Roteiro para a Neutralidade Carbónica 2050
TEU	Twenty-foot Equivalent Unit
UNCATD	United Nations Conference on Trade and Development

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Chapter 1

Introduction

1.1 Background and Context: Importance of Ports

Maritime trade plays a pivotal role in the global economy, with over 80% of goods and services transported by sea. Driven by the forces of globalization, this sector is projected to experience continued growth in volume. Consequently, greenhouse gas (GHG) emissions from the world's maritime fleet have been rising. In the last decade alone, emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have increased by over 20% in the maritime transport sector.

This upward trend in emissions poses a significant threat, especially considering established climate goals. Following the Paris Agreement, the European Union (EU) has set a target of achieving carbon neutrality by 2050. Portugal echoes this goal with its "Roteiro para a Neutralidade Carbónica 2050" (RNC2050) and the "Plano Nacional Energia e Clima 2030" (PNEC2030), which mandates a 55% reduction in emissions compared to 2005 levels by 2030 and increased integration of renewable energy sources.

Similar measures are being taken to directly address maritime transport emissions. The EU aims for a 40% (or even 50%, if feasible) reduction in CO_2 emissions by 2050, compared to 2005 levels. Staying below the 2-degree Celsius global warming target requires collective efforts from ship owners, ports, and the energy sector. The International Maritime Organization (IMO) plays a key role in addressing climate change and its impact from maritime transportation.

Moreover, ports themselves are crucial for achieving sustainability in the maritime sector. Ports serve as a crucial link between maritime routes and land-based transportation networks, such as trains and trucks. Today, they extend beyond mere trading hubs for goods and energy, evolving into potential centres for technological advancements in both industry and logistics. Additionally, ports can become future low-carbon vector hubs, holding growing significance in the global economy.

While emissions are significantly higher during a vessel's cruising phase compared to manoeuvring or anchoring in port, ports can indirectly influence the fleet and encourage the adoption of greener fuels. Alternative fuels hold promise and may be a viable option for the future.

1.2 Relevance of Energy System Modelling in Ports

Energy management and efficiency are increasingly central concerns for regulators and various sectors, including maritime transport. Consequently, recent years have seen numerous studies focused on achieving higher energy efficiency across all processes and services, with ports being a key target. These studies often recommend specific measures to promote green and sustainable port

operations. Others focus on calculating energy emissions using different methodologies.

However, a significant gap exists in the availability of simulation models that comprehensively map energy consumption within a port. While port authorities or regulatory bodies might possess their models, these are often not open-source, limiting wider accessibility.

Energy system models offer valuable tools not only to characterize a port's energy flow but also to simulate various scenarios. This capability allows for the development of strategies to achieve national and European emissions reduction targets, potentially leading to the adoption of greener technologies and energy sources.

1.3 Research Questions and Objectives

This thesis is built upon a previous work from the research group [1]. It aims to address the lack of readily available simulation models by creating an open-source and transparent model of energy consumption in a generic port, while addressing the critical need to achieve carbon neutrality in ports by 2050, aligning with global climate goals. Thus, the model will be used to assess energy use trends between 2020 (the reference year) and 2050, enabling the study of different decarbonization strategies in different scenarios. To achieve this goal, the research will address the following questions:

- How can an energy system model be created to accurately represent current and future energy flow within a port, encompassing the entire chain from primary energy sources to end uses, with a focus on the Operations area (encompassing both sea and landside operations)?
- What are the various decarbonization pathways available for a port within the 2020-2050 timeframe, considering energy consumption needs and associated GHG emissions?
- How can this model contribute to the development of low-carbon shipping and identify opportunities to facilitate the transition towards more sustainable, energy-efficient, and low-carbon port operations?

To address these research questions, the following specific objectives have been defined:

- Characterize energy use within a port, focusing on the technologies and fuels involved and associated carbon emissions.
- Develop an energy flow model for a port using the OSeMOSYS platform. This model should be adaptable to different scales, accessible, reliable, and transparent.
- Implement a case study, defining the demand and certain restrictions, and simulate different scenarios to understand how the system evolves from 2020 until 2050.
- Identify the best energy transition pathway that allows the specific port of our case study to achieve emissions reduction goals. This will inform the development of a global decarbonization framework for regulatory bodies.
- Analyze the model's results to identify opportunities for improving energy efficiency and promoting sustainable port operations, as well as the adoption of low-carbon shipping green technologies.

1.4 Structure of the Thesis

The organization of this master's thesis work is as follows:

- Chapter 1 serves as an introduction to the project. It provides context about ports and energy models and defines the research questions and objectives.
- Chapter 2 describes the literature review, which is a comprehensive analysis of existing scholarly sources on ports, their operations, energy models (particularly the OSeMOSYS model), and existing models in the field. This analysis allows for the identification of research gaps and establishes how this research will address them in answering the proposed questions.
- Chapter 3 describes the model creation process, starting with the Reference Energy System (RES). It details the disaggregation of demand into end uses and the sets and parameters definition. Technologies characterization is also explained. Through this base system, it is possible to generate the simulation model using OSeMOSYS, implement a case study and simulate several scenarios.
- Chapter 4 presents the results obtained by simulating the model, focusing on emissions and energy consumption of a port. Several scenarios are compared to simulate different evolutions until 2050. This chapter also includes a discussion of these results.
- Chapter 5 refers to the main conclusions and findings of this project work and suggests any other future works.

Chapter 2

Literature Review

This chapter presents a literature review that explores various topics relevant to the work developed in this thesis. The literature review aims to provide a deeper understanding of the role of ports from both economic and energy perspectives, emphasizing the key contribution of ports as energy and trade hubs. The current energy use in ports and the supporting technologies and energy carriers that facilitate their operation are explained. Additionally, the chapter introduces the concept of energy modelling and the OSeMOSYS energy model. This is the basis for designing port-specific energy and decarbonisation policy measures.

Thus, a comprehensive literature review was carried out on the topics associated with maritime transportation, ports energy use, potential decarbonisation measures and energy models. In order to ensure that the research is comprehensive, several databases were consulted, such as scopus, google scholar and science direct. Reports from different institutions were also analysed to better understand the general picture of maritime ports.

2.1 Maritime Transportation and Ports

2.1.1 Maritime Transportation

Maritime transportation, also known as seaborne transportation [2], involves transporting large volumes of cargo by ship overseas. The total international seaborne trade has been steadily rising, registering a 67% increase in terms of weight since 1980 [2]. Maritime trade currently represents more than 80% of global trade [3], making the world economy directly dependent on seaborne transportation [2]. Additionally, shipping costs are susceptible to fluctuations in market forces and behaviour trends [4]. Ship transportation encompasses various types, reflecting the diversity of ships and the wide range of goods they carry [2]. This includes consumer goods, food, livestock, industrial equipment, and raw materials. To cater to this variety of goods, numerous vessel types exist with distinct characteristics and classifications. These include tankers, bulk carriers, container ships, and refrigerated vessels, among others [2]. Considering the sector's size, the impact of maritime transportation on the environment is significant, with greenhouse gas emissions being a major concern. In recent years, emissions from the world's maritime fleet have been heading in the wrong direction [4]. Even though they only account for 3% of the global total emissions, they have increased by 20% over the last decade [5]. Figure 2.3 illustrates this trend in CO_2 emissions over the past few years.

Without corrective action, emissions could reach 130% of their 2008 levels by 2050 [5]. Expanding the scope to include all shipping emissions (carbon dioxide, methane, and nitrous oxide expressed in CO_{2e}), encompassing international, domestic, and fishing activities, reveals an increase from 977

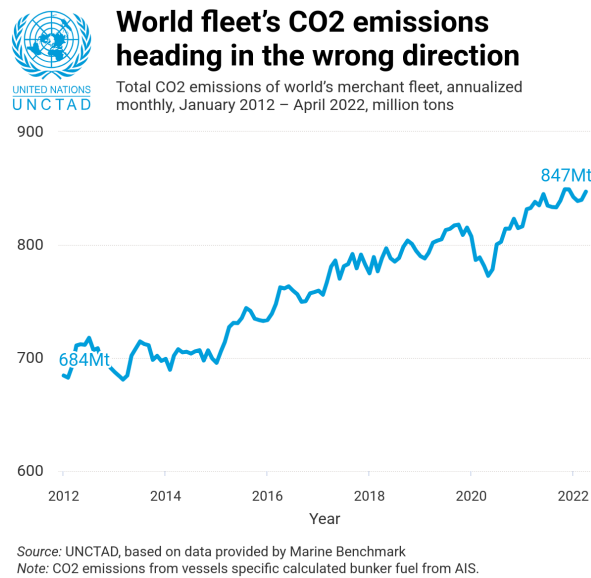


Figure 2.1: Evolution of CO₂ emissions from global merchant fleet [5].

million tonnes in 2012 to 1,076 million tonnes in 2018, representing a 9.6% rise [6]. These emissions are larger in international shipping than in domestic services [6]. Container ships, oil tankers, and bulk carriers, the most numerous ship categories, are responsible for the majority of CO₂ emissions, as expected [7]. Different fuels contribute to various levels of emissions, with heavy fuel oil being the most commonly used fuel among reporting ships [7] [6].

Another pressing challenge in ship transportation is the rising average fleet age [4]. Older ships contribute more to environmental pollution. According to the United Nations Conference on Trade and Development (UNCTAD), the average ship's age reached 22.2 years in 2023, with the fleet operating almost exclusively on fossil fuels [5].

At the EU level, maritime transport represents 3 to 4% of the EU's total CO₂ emissions [8]. This has led to the implementation of measures to monitor and control CO₂ emissions from vessels. The slow pace of decision-making at the IMO prompted the European Commission (EC) to establish its regulations and adopt a CO₂ emissions reduction target [9]. By 2050, it aims to achieve a 40% (or potentially even 50%) reduction compared to 2005 levels [10]. To achieve this goal, maritime emissions have been incorporated into the EU Emissions Trading System (ETS), which defines the maximum amount of greenhouse gases that can be emitted under the system [9]. Additionally, several legislative packages have been proposed, such as the 'Fit for 55' package [9].

Furthermore, the decarbonization process and the achievement of the Paris Agreement objectives are challenging because maritime transportation operates mainly in international waters, leaving this activity largely outside the scope of many international treaties [2].

Alternative fuels, which will be explained later, hold significant potential, even though their adoption remains in the early stages [5]. The IMO GHG Study 2020 estimates that alternative fuels could contribute to around 64% of the total CO₂ reduction by 2050 [6].

On a more optimistic note, there have been improvements in carbon intensity for international shipping between 2012 and 2018. This is largely attributed to significant advancements in overall design efficiency [6].

In addition to alternative fuels, several other approaches can enhance energy efficiency or reduce the carbon intensity of shipping. These include utilizing energy-saving technologies, modernizing the vessel fleet, and reducing vessel speeds [6] [11]. Operating speeds have a direct influence on

emissions and are not fixed by technical specifications. Instead, these are influenced more by fluctuating market forces.

Achieving full decarbonization of maritime transportation by 2050 presents a significant challenge and will necessitate substantial investments. Estimates suggest that decarbonizing the global fleet by 2050 could require annual investments ranging from 8 to 28 billion dollars [5]. These costs may lead to higher shipping prices, potentially impacting nations heavily reliant on maritime transport, such as small island developing states [5].

2.1.2 Importance of Ports

Ships operate between ports, which function as hubs for loading and unloading cargo, fuel, water, and other supplies [2]. These vital links connect maritime routes to land-based transportation networks like trains and trucks. However, in today's world, ports go beyond their role as mere trading hubs for goods. They can potentially become technological advancement centres, both in industry and logistics. Additionally, ports can emerge as future hubs for low-carbon vectors, potentially producing and storing green energy carriers like hydrogen or synthetic fuels, further amplifying their significance in the global economy [10] [12].

There are numerous types of vessels [13]. A port's capacity to accommodate a particular vessel depends on its dimensions, with fees varying accordingly [2]. These various vessel types will be introduced in a dedicated section, chapter 2.1.3. Different cargo types necessitate different kinds of terminals within a port [14]. For instance, a container terminal serves distinct purposes from a natural gas terminal, as their names imply.

Other crucial operations accompany loading and unloading activities. Upon arrival and departure, vessels receive assistance with manoeuvring and berthing from patrolling, piloting, and towing boats [14]. Landside logistics also play a vital role. As Figure 2.2 illustrates [15], transport routes move cargo across different areas of the port. Once unloaded at the quayside by a quay crane (QC), the goods are transported to the yard, by a truck, for storage purposes. From there, they embark on their final journey, either delivered by train or truck to their inland destination or loaded onto other maritime vessels [16].

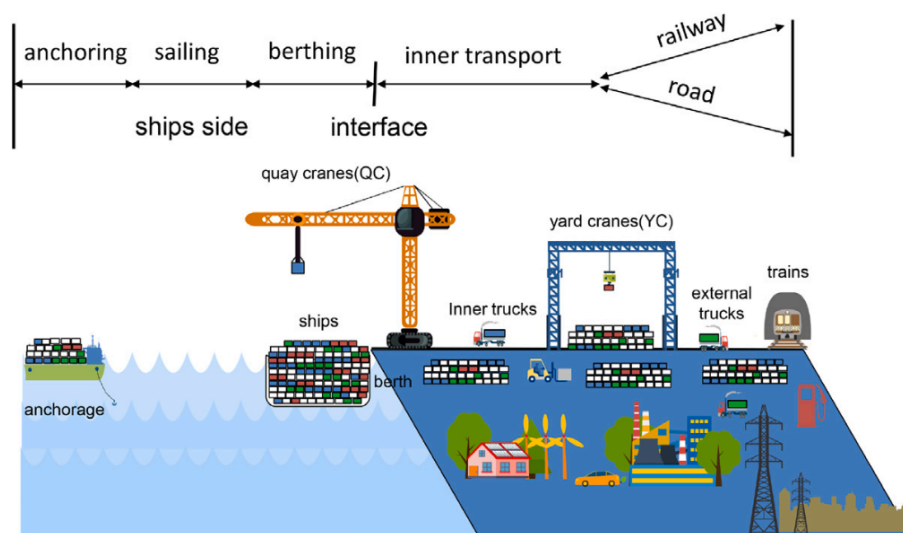


Figure 2.2: Simplified representation of the different areas and operations of a port [15].

Emissions are significantly higher when a vessel is cruising compared to manoeuvring, anchor-

ing, or berthing [6]. In fact, port emissions only accounted for 7% of the total reported maritime transport emissions in 2019 [7]. Figure 2.3 shows the total reported emissions at berth, with passenger ships contributing over 30%, while container ships and oil and chemical tankers combined were responsible for 46%. [7].

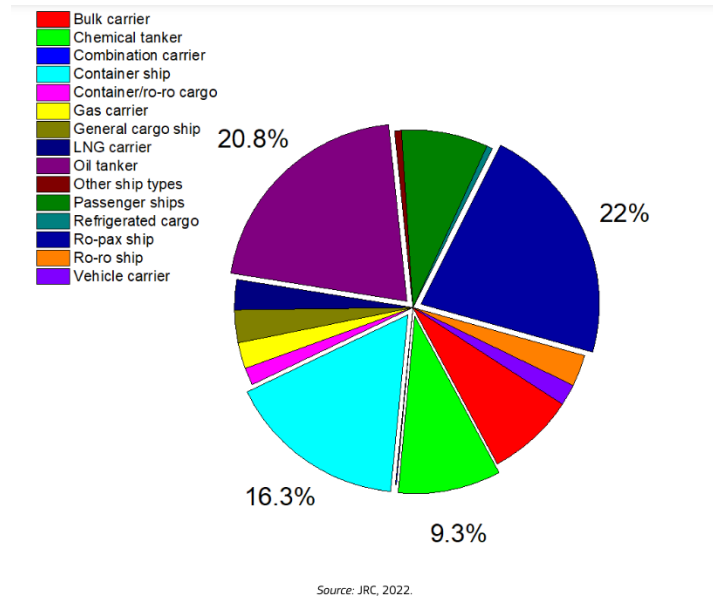


Figure 2.3: Total reported emissions at berth, by vessel type [7].

Despite these challenges, ports can play a critical role in the transition to a greener sector and towards emissions reduction. Optimizing container movement within a port is one way to improve port efficiency, directly impacting emissions [5]. Regulations, tariffs, or similar incentives can also boost the demand for marine renewable and low-carbon fuels. For example, the European Union's new FuelEU maritime regulation establishes a maximum limit on the greenhouse gas content of energy used by ships calling at European ports [9]. This policy encourages zero-emission technology at berth and can influence maritime transportation fleets.

Green ports further contribute to the transition of communities, cities, and even entire countries, acting as catalysts for this crucial shift [17].

2.1.3 Energy Use in Ports

A comprehensive energy analysis of a port requires a breakdown of all energy services and their associated emissions, originating from both ships and land-based systems.

This report focuses primarily on the operational area of a container terminal. While a wide variety of technologies might be involved in port operations, not all are included in the model for the sake of simplicity. Additionally, energy storage systems are excluded to maintain a manageable model complexity. The following sections detail the shipping and land-based activities which served as guides to the simulation model.

Shipping Activities

A diverse range of ships operate within a port. For this analysis, we will categorize them into two main groups: Ocean-Going Vessels (OGV) and Harbor Crafts (HC) [1]. OGV travel beyond the port

perimeter, while HC operate solely within the port area.

Table 2.1 lists the different OGV types.

Table 2.1: Types of Ocean-Going Vessels [1].

Ocean-Going Vessels

Chemical Tankers
 Container Ships
 Dry Bulk Carrier
 Ferry RoPax
 General Cargo
 Liquefied Gas Tanker
 Miscellaneous - Fishing
 Miscellaneous Vessels
 Oil Tanker
 Other Liquids Tankers
 Passenger Cruise Ships
 Passenger Ferries
 Refrigerated Vessels (Reefer)
 Roll-On Roll-Off Vessels (RoRos)
 Service - Other
 Yatch

Dry bulk carriers transport raw, dry materials like iron ore, coal and even products like rice and sugar [18]. In contrast, tankers, which can be further divided into subcategories, carry bulk liquid cargoes like oil products, liquefied natural gas, and other chemical or liquid goods [19]. Both these vessel types play a critical role in global trade by supporting the movement of raw materials and ensuring energy supply chains [19].

Container ships, which can be visualized in Figure 2.4, as their name implies, transport standardized shipping containers in two sizes: 20-foot (TEU) and 40-foot (FEU) equivalent units [20]. These vessels handle the vast majority of manufactured goods and products and correspond to the second-highest number of port calls after liquid bulk carriers [20] [5]. Out of curiosity, the largest container ships can carry over 24,000 (!) containers. This number might even continue to grow considering the size increase observed over the past decade, even though this trend has slowed due to the pandemic [21] [5]. This size increase also contributes to two significant challenges: a high number of containers lost at sea and port congestion, leading to longer waiting times before berthing, despite the faster cargo handling compared to bulk carriers [21] [5]. The longer a vessel has to wait, the more energy it consumes and the more pollutants are emitted.

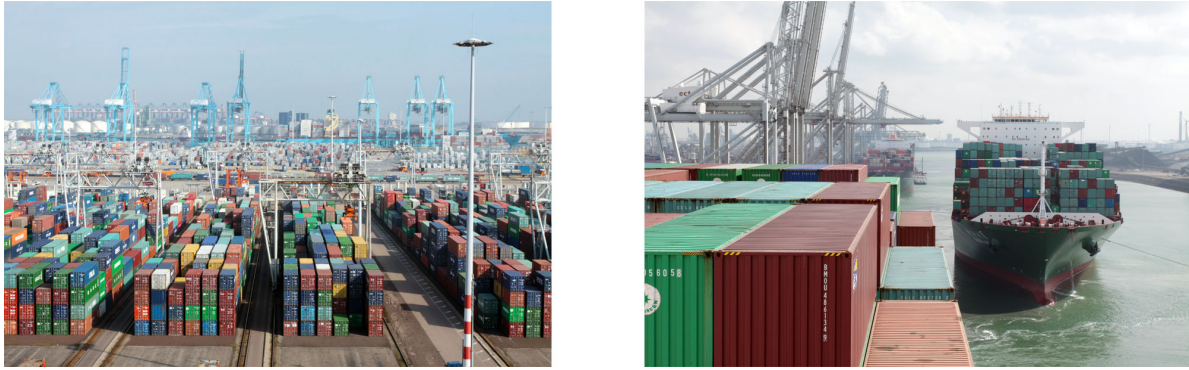


Figure 2.4: Images of a real port [21].

The rest of the vessels have different uses. Refrigerated vessels ensure the cold supply of chains, which is useful for transporting perishable goods. An alternative is using refrigerated containers in container ships, and these are called reefers. These insulated containers have special energy needs, to keep the goods refrigerated, whether they are located inside the containership or in the storage area of the port and, hence, influence the energy consumption of the ship and the port [22] [23].

To transport different types of cargo and passengers there are various other ships. RoRos allow quick loading and unloading, which is useful for vehicles' transportation, for example. These can also be used for passengers, just like cruise ships [24] [25] [26].

Harbour crafts, presented in Table 2.2, have different characteristics and purposes.

Table 2.2: Types of Harbour Crafts [27].

Harbour Crafts

Bunker Barge Boats
Dredger Boats
Ferry Boats
Pilot Boats
Tugboats

The most relevant crafts are presented in the table, though it should be mentioned that there is a wide variety of vessels within this category, such as other work boats or even government vessels [1]. While most port emissions come from OGV, harbour crafts contribute to, roughly, 23% of those, according to some studies [28]. This, however, depends on the port in question. Despite being outnumbered by OGV, their sheer number significantly impacts the port and surrounding community [29].

Looking at each craft's function, bunker barge boats supply fuel to docked ships at the port [30]. However, other methods exist, such as stationary refuelling stations or tanker trucks. Dredger boats remove sediment from the seabed for maintenance or construction purposes [31]. Ferry boats transport passengers within the port area.

Pilot boats, smaller but faster vessels, guide ships when entering or leaving the port. Their purpose is to allocate a pilot to the ocean-going vessel, as soon as this is in the port's surroundings and allowed to enter. They may also perform search and rescue or towing operations [32]. Tugboats' main function, on the other hand, is to assist larger vessels with manoeuvring within or near the port [33] [34]. Their disproportionately large power, relative to their size, allows for short bursts of

power for towing or pushing other heavier vessels [35].

Pilot boats, tugboats, and bunker barge boats are the most frequently used harbour crafts in everyday port operations. Patrol boats, which are also common to find, act as a security force within the port [14]. However, their duties may extend beyond the port, excluding them from the harbour craft category [1].

Land Based Activities

A variety of operations and technologies are involved in loading and unloading cargo at the port quay, as it was shown in Figure 2.2. Table 2.3 lists the most relevant technologies used in a container terminal. This list excludes numerous other types of equipment found in other terminals, designed to handle liquids or bulk materials.

Table 2.3: Types of Cargo Handling Equipment in a Container Terminal, According to the Operation Area [1].

Areas of Operation	Cargo Handling Equipment [REF]
Quay	Quay Cranes
Quay to Storage	Internal Trucks (Yard Trucks)
	Empty Container Handler
	External Trucks
	Forklifts
Storage and Receipt-Delivery	Reachstacker
	Stacker Reclaimer
	Shunt Locomotives
	Yard Cranes (Stack Cranes)

The list of equipment is, essentially, divided into different types of cranes and transport vehicles [1].

Starting by the quayside area, where berthing occurs, quay cranes (QC) are responsible for the loading/unloading operations with containers from/to vessels [1]. There are different types of QC, with a single or a double-trolley, which allows it to lift two containers simultaneously.

Moving beyond the quayside, internal trucks play a valuable role in cargo transportation within the different container terminal areas [1].

In storage and receipt-delivery areas, heavy-duty stack cranes take centre stage. Unlike their mobile counterparts, quay cranes, stack cranes are designed for a more stationary role. These overhead crane systems, which move containers within the storage area, are remotely operated for safety reasons, allowing operators to control them from a safe distance. Stack cranes can travel on either rails or rubber tyres, and depending on the specific type, are known as rail mounted gantry cranes or rubber tired gantry cranes [36] [37].

Once containers are emptied, a different type of equipment comes into play: empty container handlers and reach stackers. These similar technologies excel at efficiently transporting empty containers within the terminal, boasting fast lifting cycles for optimal handling speed. However, container handlers offer greater versatility compared to reach stackers. Their design allows them to lift and transport a wider range of containers and cargo types, making them a more adaptable solution [38] [39]. Forklifts are another common sight within ports, used for various short-distance material handling tasks.

Cargo is then transported to or from the hinterland (the area outside the port) by trucks or trains. It should be mentioned that, depending on the port, a higher or lower share of the containers is transshipped, this is the transportation of a container from one vessel to another [14]. When this occurs, containers go from the storage area to the quayside and then to another vessel.

Shunt locomotives, a specialized type of railway equipment, are used to manoeuvre railcars within the port. Their high power allows them to attach and move various wagons. Compared to long-haul locomotives, shunt locomotives have a different load profile and energy demand, as they spend only 30% of their time actively pulling. The extensive use of diesel shunt locomotives in ports is due to the challenges of implementing overhead catenary systems for electrification [40].

As already mentioned, when in the storage area, after or before being loaded/unloaded to or from the vessel, reefers also require energy, for refrigeration purposes, which also contributes to the port's overall energy consumption.

Energy Generation

To assess a port's energy use and emissions, energy generation processes cannot be ignored.

Ports are key infrastructure for energy carrier trade. Products like crude oil, coal, and natural gas are primarily imported and exported through ports. In the future, ports are expected to support the trade of renewable energy carriers like hydrogen or synthetic fuels, which are discussed in the following section, chapter 2.1.4. Beyond simply acting as hubs, ports are also starting to generate their own energy. Cogeneration plants, which can utilize oil products or even residues [41], are one method for on-site electricity production. However, renewable energy sources like solar, wind, or wave energy can also be harnessed [42] [43]. Additionally, the generated heat can be distributed through district heating networks to meet the heating needs of docked vessels [44] [45]. Ports can also transform imported energy carriers and generate their energy in a decentralized manner, increasing their independence.

The types of energy carriers used in ports vary considerably, with marine fuels being a prominent category. Coal is no longer used as a marine fuel; instead, refined products derived from crude oil are the norm. These refined products include Marine Gas Oil (MGO), Marine Diesel Oil (MDO), and Heavy Fuel Oil (HFO) [46]. The global demand for bunker fuel (fuel for ships) is around 370 million tons annually [46].

Despite their shared origin in crude oil, these fuels have significant differences.

- Heavy Fuel Oil is the most common fuel for marine engines due to its low cost. Its high viscosity and energy content makes it suitable for large vessels. However, it also has a high sulfur content and contains impurities like metals [47] [48].
- Marine Diesel Oil is a middle distillate fuel, whereas Marine Gas Oil is a lighter distillate. MDO offers a lower viscosity and density compared to HFO. It also has a lower sulfur content, making it a cleaner alternative [47]. Both MDO and MGO are used in smaller vessels and auxiliary engines [47].

The CO_2 emissions associated with these fuels depend on the total fuel consumption and the carbon concentration in the fuel molecule itself [46].

New regulations have spurred the introduction of biofuels like methanol and biodiesel for shipping in recent years. Electric vessels are also emerging, although their range is currently limited [46]. As a short-term option, Liquefied Natural Gas (LNG) can be a fuel alternative with lower CO_2 emissions compared to other marine fuels. However, concerns remain regarding methane (CH_4) emissions [6].

2.1.4 Measures to Achieve Decarbonization in Ports

Climate change is already a consensual threat to humanity and efforts are being taken globally. The United Nations Climate Change Conference 2021 (COP21) established a collective goal of decarbonizing all sectors by 2050 [49]. Even before, driven by the Paris Agreement, the European Union (EU) has set this ambitious target of achieving carbon neutrality by 2050 [50]. Portugal echoes this goal with its "Roteiro para a Neutralidade Carbónica 2050" (RNC2050) [51], while the "Plano Nacional Energia e Clima 2030" (PNEC2030) [52] outlines a roadmap for emission reduction (55% compared to 2005 levels) and increased renewable energy integration (49% of energy needs by 2030).

There are also specific emissions reduction targets for the transport sector. PNEC 2030 mentions an emissions reduction target of 40%, with a renewable energy integration of 23%. International Maritime Organisation has also defined several greenhouse gas emission reduction targets for the upcoming decades [6] - 20% until 2030, 70% until 2040 and 100% in 2050, in comparison to 2005 levels. Still applied to maritime transportation, EU is less ambitious and has set the goal to achieve a reduction in CO_2 emissions by 40% in 2050 [50], having also included maritime shipping in its EU Emissions Trading Scheme, which consists of a carbon tax on vessels entering European ports [9].

This section explores strategies for achieving full port decarbonization by 2050. With most port emissions coming from berthed ships' engine operations [43], this is the primary challenge to address.

Several measures can be implemented to achieve this goal:

- **Onshore Power Supply (OPS):** Also known as cold ironing, OPS involves electrifying the dock to provide power to berthed ships. This allows vessels to switch off their auxiliary engines, significantly reducing emissions, air pollution, and noise [43]. However, the effectiveness of OPS depends on the grid's energy mix, which should not have emissions associated with it. Additionally, challenges exist in defining the correct voltage and grid capacity [53] [54].
- **Electrification of Harbour Crafts and Cargo Handling Equipment:** Utilizing electric-powered ships, cranes, trucks, trains, and other equipment reduces a port's dependence on fossil fuels. However, this again hinges on the electricity mix. Emissions only decrease if the specific emission factor (CO_2eq grams per kilowatt-hour) is low, signifying the need for green electricity with guaranteed origin [53] [54] [55]. Electrification also increases demand, necessitating a corresponding rise in local electricity production.

Local renewable energy production using solar, wind, wave, or tidal energy offers independence from the grid and promotes sustainability. Ports can install photovoltaic plants (floating or fixed), on and offshore wind farms, and wave, tide, and ocean thermal technologies within their perimeters or nearby areas, leveraging their proximity to the ocean [56] [54] [42].

- **Alternative Fuels:** Utilizing alternative energy carriers to produce mechanical energy (through thermal or electrical processes) offers another viable approach. Currently, heavy fuel oil, a major source of environmental and health hazards, is the dominant fuel for ships [57]. While not a zero-emission solution, liquefied natural gas (LNG) offers a short-term option by reducing emissions of pollutants like sulfur oxides compared to heavy fuel oil [58]. E-fuels, biofuels, and green hydrogen represent further alternatives [56] [54] [42] [59].

Biogas, a potential biofuel option, can be generated using organic waste, sewage, or biomass materials from ships, serving as a sustainable energy source that reduces fossil fuel reliance and lowers emissions [44]. Biomethane, for instance, can be used in the natural gas network and even engines.

Used directly in fuel cells, green hydrogen - produced through electrolysis or steam methane reforming with carbon capture and storage - also offers a zero-emission option [60]. This green hydrogen, along with captured CO_2 , can be used to produce e-fuels like e-ammonia, e-methane, e-methanol, and e-diesel, which possess the same properties as their conventional counterparts but are produced using renewable electricity sources [61] [62]. While e-ammonia synthesis requires nitrogen in addition to hydrogen, other e-fuels utilize carbon dioxide and hydrogen [63]. It should be mentioned that methane can also be produced through gasification of organic materials. Table 2.4 lists the different synthetic fuel production processes and the respective feedstock.

Table 2.4: Different Synthetic Fuels Production Method.

Fuel	Synthesis Process	Inputs
E-Ammonia	Haber-Bosch	$H_2 + N_2$
E-Methane	Methanation	$H_2 + CO_2$
E-Methanol	Methanol Synthesis	$H_2 + CO_2$
E-Diesel	Fischer-Tropsch	$H_2 + CO_2$

Incorporating energy storage systems using batteries or hydrogen storage tanks can improve the reliability and robustness of the port's energy system, even though this is not explored in detail within this report [64]. Other measures such as replacing older vessels with more efficient ones and optimizing cargo movement processes and shipping schedules can also contribute to reducing emissions. A lower cruising speed can lead to lower fuel consumption and emissions, suggesting the potential effectiveness of reduced speed zones [65]. Optimizing container movement and scheduling to minimize wait times for berthing, loading, and unloading would also contribute to lower energy consumption [56].

Decarbonizing ports by 2050 is an ambitious yet achievable goal. Implementing a combination of the strategies outlined in this chapter, along with ongoing research and development in clean technologies, can pave the way for a sustainable future for the maritime industry.

2.2 Modelling of the Ports Energy System

2.2.1 Energy System Models

Mathematical models have become indispensable tools to understand and analyze complex systems. This corresponds to the description of any real-world system by using mathematical formulas, equations, and inequalities [66]. A model helps to quantify the correlation between different parameters in a system, revealing previously unrecognized relationships that might not be evident through simple observation [67].

An Energy System Model describes the various linkages and effects between different phenomena that influence energy supply and demand. It allows us to understand how these factors interact and predict their impact on the overall system [66]. These models can be classified in numerous ways to understand their needs, roles and specificity concerning the system under consideration [67]. An incorrect application of the model may result in significant misinterpretations.

The classification of energy models can be approached from various perspectives and can be classified in several ways, such as purpose, analytical approach or methodology [67]. The purpose can be either more general or more specific to a certain aspect, such as energy demand. Concerning the analytical approach, models can be categorized in two ways: top-down and bottom-up [67].

In a top-down model, economic indicators such as energy prices are used as the basis to model the energy demand and supply, whereas the bottom-up model uses the technology costs, efficiencies and impacts on the environment to drive the model choices. The bottom-up model focuses, therefore, on the physical system itself, instead of focusing on the costs. Lastly, methodology classification highlights the underlying method of the model, whether its focus is economic equilibrium, optimization, simulation of the model or other [67].

Energy models facilitate the quantification of the impacts of policies and measures [66]. They can also be used to run different scenarios and sensitivity assessments, to assess how a certain change in the model will affect it. These models are, hence, useful to simulate decarbonization strategies, such as the transition towards renewable energy sources, considering the time horizons of 2030 and 2050. Some of the drawbacks of these models are related to their transparency [68]. Usually, the assumptions made and the data sources used, also including the detailed algorithms, are not provided, which creates difficulties in the use of these models.

A distinction between software tools and author-developed models should be made when addressing different energy planning models. While software tools are dedicated software packages for this purpose, models developed by authors have their principles described in research papers or books [69].

This thesis project adopts a software tool and, hence, more attention to the detail of these is given. There are several software tools, such as OSeMOSYS, TIMES, LEAP, PowerPlan and EnergyPlan, to name a few [67]. These differ in terms of the level of detail, the considered timeframe and model flexibility.

Open Source Energy Modeling System (OSeMOSYS), an energy equilibrium model which focuses on the long-run energy planning term and the entire economy of the system, is used in this thesis project. It is considered an optimization model, due to its goal of obtaining the least-cost solution under given constraints, such as emissions cap, using a bottom-up analytical approach [70]. With a steep learning curve and an easily accessible code, OSeMOSYS tool is often used within the energy research community and energy planners.

2.2.2 Overview of Existing Energy System Models for Ports

This thesis is built upon a previous work from the research group [1]. That project involved a literature review on port operations and the development of a tool for calculating emissions within a specific port. This research takes things a step further by creating an energy model for the port itself. This model allows us to simulate various scenarios and analyze potential outcomes.

A comprehensive search for existing port energy system models was conducted to create these energy planning tools. Several models were discovered, encompassing ship emissions, combined ship and port emissions, land-based emissions, and even models that consider all port emissions collectively. However, a crucial limitation emerged - none of these models are publicly available online. This restricts users from creating their scenarios and exploring alternative strategies. While further research was conducted this past year, the situation regarding public accessibility of port energy system models remains unchanged. No significant advancements have been made in making these models readily available to users. In these last few months, several studies were carried out on emissions, energy consumption and also decarbonization strategies in ports. These studies often take the form of specific case studies. Smaller ports, for example, might rely on simpler energy types, leading to a more limited energy demand. On the other hand, large seaports often require a diverse mix of fuels, resulting in a more complex assessment of both energy demand and emissions. As the scale and energy requirements of ports increase, so too do the challenges associated with evaluating and managing energy consumption and emissions [71].

Table 2.5 provides examples of these different model categories.

Table 2.5: Models for Different Types of Ports' Analysis.

Sector of the Model	Year	Reference
Emissions Analysis	2023	[15]
	2023	[72]
Energy Consumption	2023	[15]
	2024	[43]
Decarbonization Strategies	2024	[58]
	2023	[42]
	2023	[44]
	2023	[73]

Studies like those referenced in [15] and [72] dig into emissions analysis using two key methods: top-down and activity-based bottom-up. As previously explained, the top-down method relies on total fuel consumption and specific fuel emission factors. In contrast, the bottom-up method focuses on the activities of ships within the system, in this case, the maritime port. The first case study also analyzes energy consumption.

Other studies, such as those referenced in [43], [58], [42], [44], and [73], focus on strategies to reduce vessel emissions.

In sum, there is a gap in publicly available energy models applied to maritime ports. This is explored in chapter 2.4.

2.3 OSeMOSYS Energy System Model

The OSeMOSYS model is an open-source modelling system for long-run integrated assessment and energy planning and is used in this report [70]. Its flexibility and modular structure allow students and researchers to create models from the scale of continents down to the scale of countries, regions or villages. It is also free and accessible, time-consuming but with a fast learning curve, unlike other long-established energy systems. The fact that it is an open-source modelling tool makes it more transparent than others.

The original code is written in GNU MathProg and it can be used with the open-source solver GLPK, use to translate the models in matrices, find the optimal solution and print the numerical outputs [74]. Otoole, or OSeMOSYS tools for energy work, which is a Python package that allows the user to convert between data formats, process solutions, and visualise the reference energy system can be also used [75].

In short, OSeMOSYS balances the energy supply and energy services demand, every year and in every time step of the case under study. The model computes the energy supply mix and it minimizes the total discounted costs of the energy system. To do this, in mathematical terms, it is used a deterministic, linear optimisation and long-term modelling framework [74].

One of the main characteristics of this model is the wide and flexible definition of technology and energy vector [70]. Any asset that involves energy conversion processes is a technology, from resource extraction and processing to electricity supply, transmission and distribution and end-use appliances.

A legitimate model will always depend on the input data. Using accurate data and making con-

sistent assumptions will turn into a better and more representative system. Data requirements for these models are [76]:

- Energy demand for the activities that are considered in the model and a time variation (annual or hourly) for the relevant demands;
- Technology techno-economic characteristics - specific efficiencies, electricity generation capacity, technology-specific factors (capacity/availability), construction time, lifetime and capital, fixed and variable O&M costs;
- Fuel costs (both local and imported costs);
- Resource potential (e.g. renewable energy potential);
- Emissions (specific emission factors of each fuel).

To study different scenarios and policies, constraints may be applied to the models [74]. These may be technological, but may also be economical or related to environmental targets. For instance, we may impose an emissions cap on our time interval.

An energy system model is only fully defined when the sets and parameters are introduced [77]. Sets define the physical structure of the model, such as the time domain, time split, spatial coverage and the technologies and energy carriers considered. These do not vary within different scenarios that are run. The table below, table 2.6, presents the sets of OSeMOSYS. Parameters, on the other hand, are defined by the user and they can be changed when running different scenarios or sensitivity analyses. Each parameter is a function of one or more sets. For example, the demand may depend on the fuel, the year considered and also the region and timeslice.

The outputs of the model are our variables. These are related to the demand, storage, capacity, activity, costing and to reserve margin.

The most relevant parameters and variables, considering the model created for this report, can be found in Appendix A, with a brief description of each one attached.

Another aspect worth mentioning is the modular structure of the OSeMOSYS code [70]. The division in several blocks of equations, which comprise one objective function and several constraints, is what guarantees the flexibility of these models.

Table 2.6: List of OSeMOSYS Sets and a brief description of each [77].

Set Name	Description	Index
YEAR	It represents the time frame of the model, it contains all the years to be considered in the study.	y
TECHNOLOGY	It includes any element of the energy system that changes a commodity from one form to another, uses it or supplies it. As the model is an abstraction, the modeller is free to interpret the role of a technology at will, where relevant.	t
TIMESLICE	It represents the time split of each modelled year, therefore the time resolution of the model. The annual demand is sliced into representative fractions of the year. In order to reduce the computation time, these slices are often grouped. Thus, the annual demand may be split into aggregate seasons where demand levels are similar. Those seasons may be subdivided into aggregate day types, and the day further sub divided depending on the level of demand.	l
FUEL	It includes any energy vector, energy service or proxies entering or exiting technologies. These can be aggregate groups, individual flows or artificially separated, depending on the requirements of the analysis.	f
EMISSION	It includes any kind of emission potentially deriving from the operation of the defined technologies. Typical examples would include atmospheric emissions of greenhouse gasses, such as CO ₂ .	e
MODE OF OPERATION	It defines the number of modes of operation that the technologies can have. If a technology can have various input or output fuels and it can choose the mix (i.e. any linear combination) of these input or output fuels, each mix can be accounted as a separate mode of operation. For example, a CHP plant may produce heat in one mode of operation and electricity in another.	m
REGION	It sets the regions to be modelled, e.g. different countries. For each of them, the supply-demand balances for all the energy vectors are ensured, including trades with other regions.	r
SEASON	It gives indication (by successive numerical values) of how many seasons (e.g. winter, intermediate, summer) are accounted for and in which order. This set is needed if storage facilities are included in the model.	ls
DAYTYPE	It gives indication (by successive numerical values) of how many day types (e.g. workday, weekend) are accounted for and in which order. This set is needed if storage facilities are included in the model.	ld
DAILYTIMEBRACKET	It gives indication (by successive numerical values) of how many parts the day is split into (e.g. night, morning, afternoon, evening) and in which order these parts are sorted. This set is needed if storage facilities are included in the model.	lh
STORAGE	It includes storage facilities in the model.	s

2.3.1 Structure of an Energy System

Each type of model has its own structure. An OSeMOSYS model considers different levels of energy to describe the flow of energy along all stages of energy conversion and the balancing act between energy supply and demand [67].

The approach usually taken when modelling the energy demand is by looking at the level of useful energy (or final energy, in some cases) and by considering the different technologies that convert different types of energy.

Figure 2.5 represents the approach followed in this work to represent the energy system in terms of energy conversion technologies and processes, and energy flows between these. The arrows represent the direction of the energy flow [78]. The Reference Energy System (REF) in this project adopts this structure.

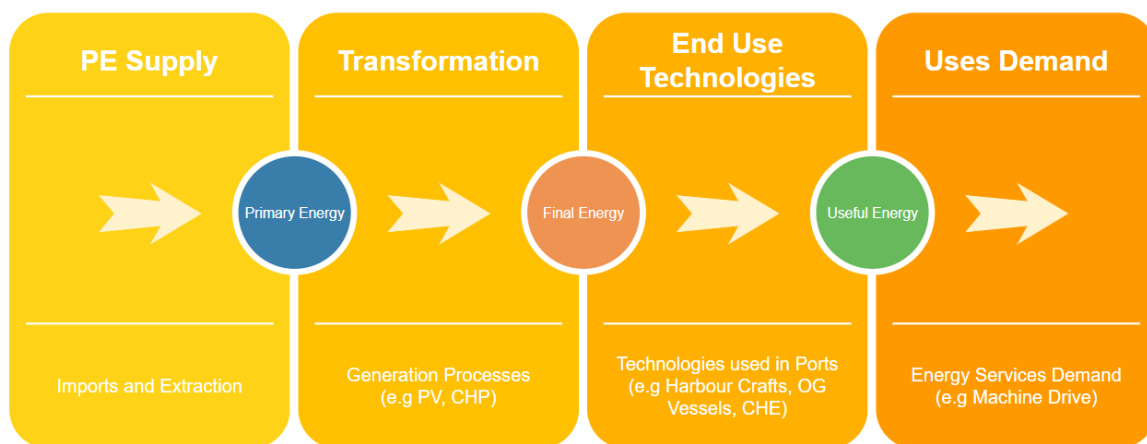


Figure 2.5: Energy flows from primary energy supply to useful energy use and end uses, with examples of technologies and activities related to maritime ports.

The REF is read from the left to the right. On the left-hand side, the primary energy resources, which can be extracted domestically or imported, are represented. The energy chain always starts with a technology and it goes from the left side to the right. Alongside this line, as Figure 2.5 illustrates, the energy carriers are transformed by different technologies to finally meet the final demand and the end-use energy services demand [66].

Energy flows are traditionally classified into three levels of energy use [78]. It may be useful to clarify these three levels of energy, going from primary to final and useful energy, with two stages of energy conversion. There is a separate debate around whether these two stages are or are not enough to represent the actual energy flow and whether actual delivered energy services should be included. However, that is not relevant to this report.

Primary energy (PE) is the energy directly recovered from the natural environment, i.e. natural resources such as biomass or crude oil. This PE can be transformed and processed, which will originate the final or secondary energy (FE), the amount of energy that is available for direct use by the consumers. Useful energy (which can be heat, motion or light, for example) is the last form of energy flow and is directly used to cover the energy services demand [78]. The two energy conversion stages are, therefore: primary-to-final and final-to-useful conversions. The first energy transformation occurs from primary to final energy, where the energy taken from natural resources is upgraded into more useful forms of energy, through conversion processes. The second transformation is also the last energy conversion stage and is where final energy carriers are converted into useful energy. This transformation usually occurs where the energy services demand is, such as a factory

or household, using end-use conversion devices [78]. There are energy losses in every conversion stage.

Our REF hence includes all energy carriers involved with primary supplies, conversion and processing and the end-use demand for energy services. This demand can be disaggregated by sector (e.g., operations in a port) and by specific functions within a sector (e.g., machine drive) [78].

2.4 Research Gaps and Basis for the Proposed Research Questions

This report describes the development of a tool to assess port emissions and energy consumption. The tool considers both the port's perimeter and the port authority's direct area of responsibility. Ocean-going vessels, for instance, while influencing port emissions, fall outside the port's direct control. However, when a vessel is berthed and receives fuel from the port, this contributes to the port's overall emissions.

The model focuses on operational emissions, specifically those arising from nautical and terminal activities. Container terminals are a primary area of focus in this study. Only the technologies and energy sources used in these operations are considered within the model's scope.

Several existing studies on port emissions and energy consumption have been identified, although their approaches vary. For example, a previous work from the research group [1] examined emissions within the port perimeter regardless of the source, even though it did not involve a simulation model. Other studies explore different emission calculation methods, while some solely focus on berthed vessels. Compared to the emphasis placed on vessel emissions, there has been generally less attention paid to port efforts to reduce their footprint [15].

The key limitations identified in existing models are their lack of accessibility and flexibility. Most publicly available models are either restricted by cost or require permission to use. Additionally, some models utilize outdated versions incompatible with OSeMOSYS models. Furthermore, the majority of articles discussing models lack transparency regarding the technologies and fuels considered in their analyses.

Therefore, this thesis addresses these shortcomings by presenting an OSeMOSYS-based model. This model will allow users to not only assess a port's current energy usage but also simulate various scenarios for future decades, a capability not readily available in existing literature. The model's ability to incorporate diverse energy types facilitates the evaluation of emissions and energy consumption in larger seaports, demonstrating its flexibility and adaptability.

A comprehensive yet concise model like this allows for the gathering of valuable information for future work. This includes not only present technologies and fuels but also potential options that could emerge to support the decarbonization process.

The following chapter delves into the methodology behind the construction of this simulation model.

Chapter 3

Methodology

3.1 Reference Energy System

A detailed energy model for a port was built from scratch to have a better comprehension of the energy flow from the primary energy to the end-use energy. For this purpose, a broad set of technologies and fuels were included in the diagram, since the goal is to be able to simulate the energy consumption patterns of a generic port, calculate the associated emissions and create several scenarios. The energy flow represented in the diagram is from the point of view of the Port Authority and it only considers the operations category, i.e., the nautical and terminal-oriented operations. Container terminals are relevant in every larger port and they are the focus of this dissertation.

The diagram that represents the model is quite large and, hence, Figure 3.1 shows how it is organised. On the left part of the diagram, the imported fuels are presented, followed by technologies where these fuels are transformed and energy is generated. From here, the transmission and distribution network transports the generated or imported energy, in various forms, to the seaside and landside operations area, where the end-use devices are.

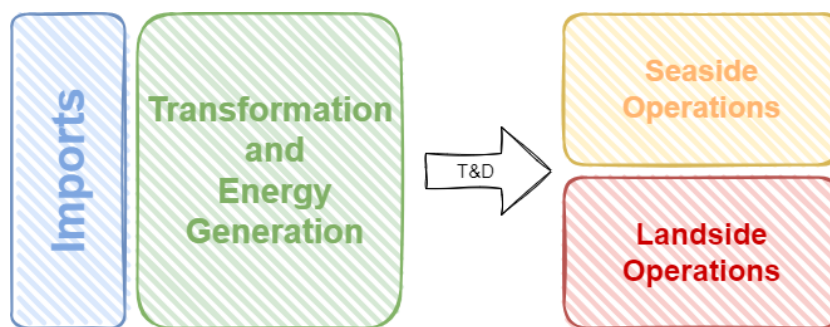


Figure 3.1: Simplified representation of the model diagram.

The elements included in the diagram are based on the literature review, from the technologies to the energy carriers used in a port, including greener technologies which may potentially be used in upcoming years. These technologies and fuels are introduced and explained in chapter 2.1.3. For now, only the energy chain from the primary to the final energy is presented and explained. The first part of the Reference Energy System (REF) is, hence, shown in Figure 3.2.

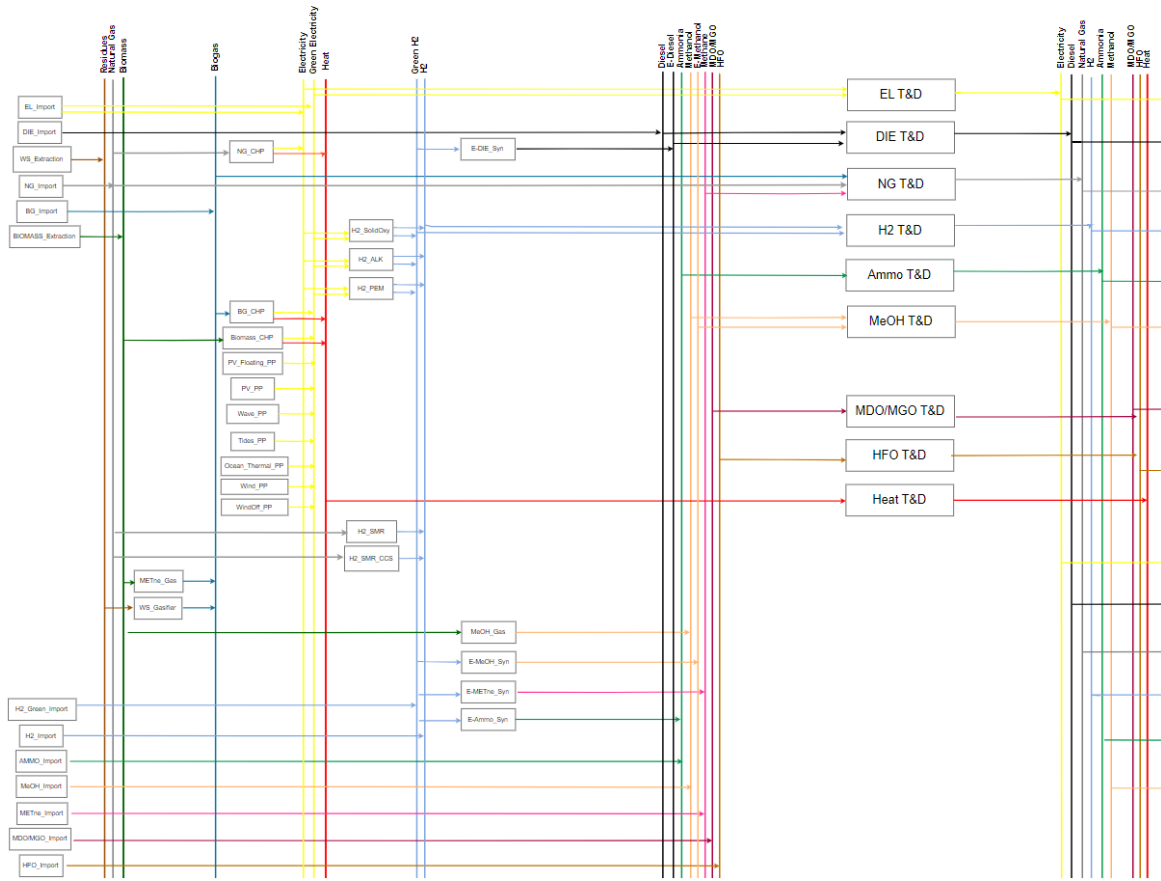


Figure 3.2: Reference Energy System (REF) - Import, Transformation and Local Energy Generation.

The lines on this diagram represent energy carriers (e.g., electricity, natural gas etc.), while the blocks represent transformation technologies (e.g., power plants, transmission and distribution stations etc.). Both are defined using code names, which can be found in the Appendix B.

In the initial phase, there is primary energy, which consists of imported and extracted fuels. Some of these fuels will be used in the second phase, on local energy generation. Others, once imported, are ready to be consumed, which justifies the direction of the energy flow into the final energy layer. The local energy is generated by combined heat and power plants and also by renewable energy technologies. In this model, the technologies considered are photovoltaic plants (floating plants included), wind plants (onshore and offshore) and devices that use water energy (tides, waves and ocean thermal energy).

There are also three intermediate steps related to the production of hydrogen, biogas and synthetic fuels. Biogas can be produced locally using the vessels and port residues as input and through gasifiers. Hydrogen can be produced through steam methane reforming, with or without carbon capture technologies, and electrolysis, which involves electricity. This electrical energy can be imported, generated through cogeneration or through green technologies, which means it is not necessarily green. Due to this, two electricities are used in this model, being one "green electricity", which represents electricity with a guarantee of origin. A guarantee of origin is an electronic document that proves to the end consumer that a given quantity of electricity was generated using renewable energy sources [79]. This electricity is also important in synthetic fuel production. The purpose of using e-fuels in a port is, as was already mentioned, to decarbonize the operations within its parameters. This implies that they should also use the electricity with zero emissions associated with, or the green hydrogen previously produced.

The layer corresponding to the final energy can be seen on the right part of Figure 3.2. These fuels are prepared to go into the transmission and distribution network. From here, the energy will flow into the end-use energy (i.e. vessels, cargo handling equipment).

A few relevant notes for a better comprehension of the system and to clarify some assumptions made:

- Even though biogas can represent several types of gases, it is assumed that it is biomethane, to be blended into the same network that transports natural gas. Therefore, this network may transport natural gas, e-methane and biogas. Diesel and e-diesel can also be transported in the same network, just like methanol and e-methanol, but they have to be distinguished due to the different emissions associated to them.
- Marine diesel oil and marine gas oil are considered together (as one energy carrier) to simplify the data gathering process and since heavy fuel oil is much more used than these.
- Green hydrogen, just like green electricity, is different from hydrogen. That is why there is a distinction between these two, right from the import technologies until to the hydrogen production technologies, where it is relevant to ensure the production of green hydrogen.
- The focus of this report is on the emissions, not on the energy efficiency. For that reason, in the hydrogen production process, the water origin is ignored, and the energy necessary for a possible desalination or purification process is neglected. The same happens in the CO₂ separation process, with carbon capture technologies, just as with nitrogen, useful for the production of e-ammonia, since air separation processes can obtain this.
- Transmission and distribution network is considered as a dummy technology, i.e. it does not influence the model since is not characterized in terms of costs or efficiency. This is for the sake of simplicity of the model.

3.1.1 Disaggregating Demand into Final End Uses

Until now, the structure of the REF model stopped at the final energy demand of all end-use sectors. A detailed characterization of the end-use sectors should be made to have a proper and realistic model.

In this model, the technologies that convert the final energy into useful are also considered, to disaggregate the demand to the level of end-uses, either in harbour crafts or in cargo handling equipment. The technologies involved in this disaggregation have been also introduced in section 2.1.3 and are listed in Appendix B.

In the case of OGV, whose diagram part is shown in Figure 3.3, this disaggregation is not made due to this model being based on the point of view of the Port Authority and, therefore, only the end-use sectors that may be directly affected by PA measures are considered. The energy consumption activities within these types of vessels are not within the range of the operator of a port. As a consequence of this, the port is only responsible for the fuel supply process, while the vessel is berthed. Depending on the vessel type, the engine and the respective fuel, different energy carriers may be needed. The fuel supply process can be done in several ways, either by using a tanker truck, a bunker barge or a fixed and stationary refuelling station. Here, to simplify the analysis, it is considered that bunker barge boats are in charge of the refuelling process. Only three types of bunker barge boats were considered - moved by diesel, hydrogen or natural gas. Each bunker barge, moved either by diesel, hydrogen or natural gas, may transport seven different fuels to the ocean-going vessels. This explains the two inputs of these technologies, since one energy carrier

is the one responsible for the bunker barge movement, whilst the other one will be transported to vessels at berth.

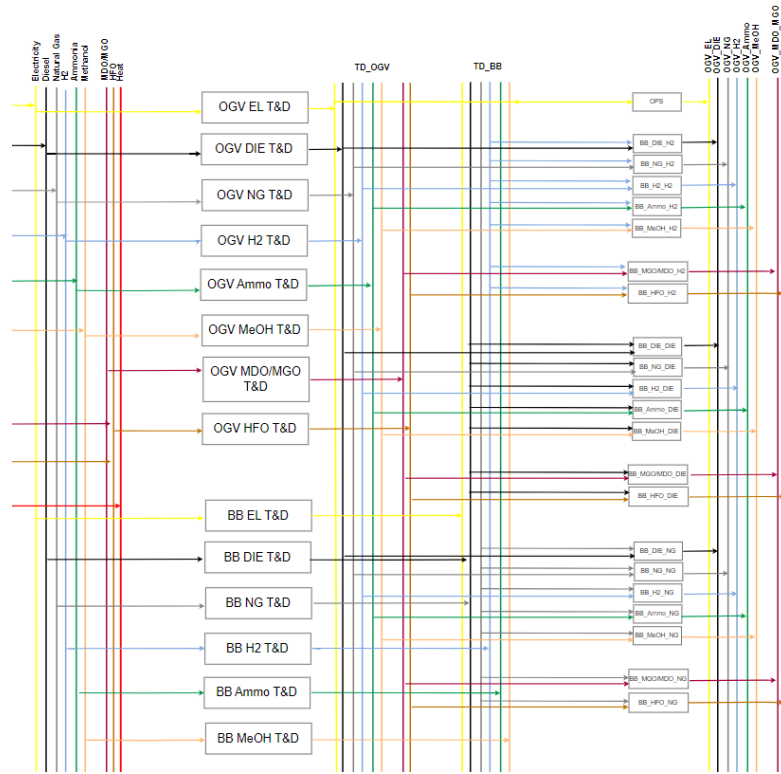


Figure 3.3: REF - Ocean-Going Vessels.

The other two types of harbour crafts - tugboats and pilot vessels - are also represented in the demand disaggregation. The main end-use of these technologies is the vessel's movement, being the end-use energy related to the machine drive. Figure 3.4 presents the disaggregation in the case of tugboats, being the end-use energy always in green. For pilot vessels, the process is similar.

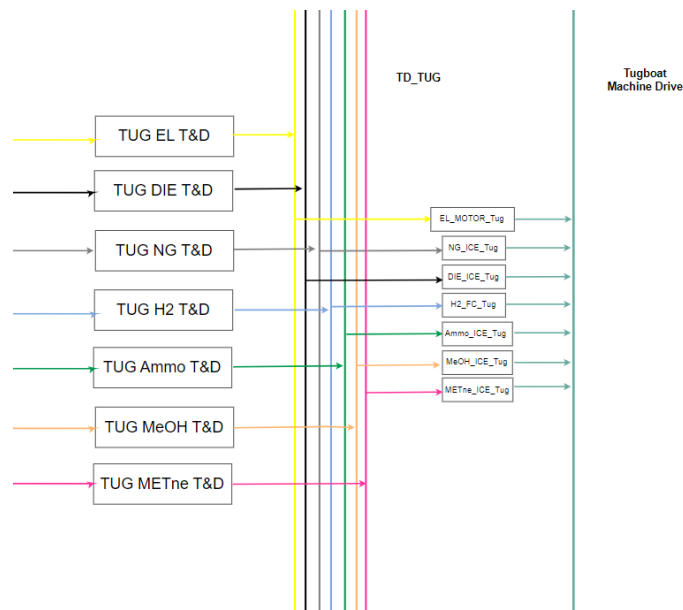


Figure 3.4: REF - Tugboats Disaggregation.

The same organisation process applies to the landside and cargo handling equipment. Figure 3.5 illustrates the example of Quay Cranes and Internal Trucks, which corresponds to the quay area and from there to the storage.

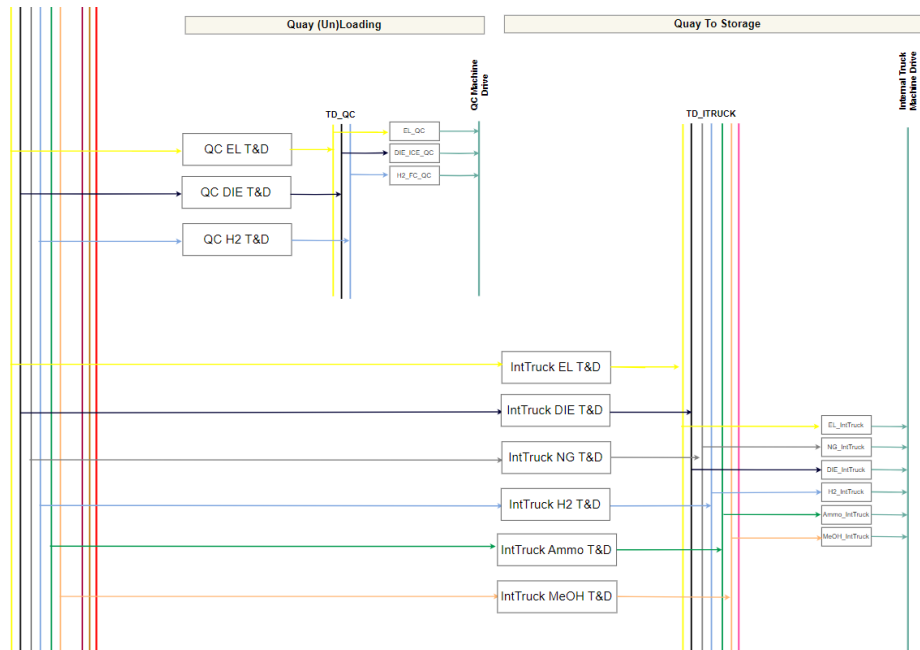


Figure 3.5: REF - Cargo Handling Equipment in the quay area and from there to the storage.

In all of these examples, it should be noticed that different energy conversion devices are used for the different energy carriers. For instance, a tugboat that works with a diesel internal combustion engine (ICE) is different from an electric engine tugboat. In this model, it is assumed that heavy fuel oil and marine diesel or gas oils are only used in ocean-going vessels due to their predominant use in these when compared to their use in harbour crafts, which commonly uses diesel fuels.

The demand associated with each ship or cargo handling equipment can be easily obtained by adding the demand associated with each fuel. The same occurs with the final energy layer, which allows the calculation of all the energy needs in a container terminal of a maritime port.

The remaining parts of our REF diagram can be found in Appendix C.

3.2 Implementation in OSeMOSYS

As already mentioned, this model analyses the overall energy system of a port, while focusing on the emissions. At the same time, there is a broader purpose of exploring future scenarios, with comparisons between “business as usual” reference scenarios and other possible paths. This model adopts a bottom-up analytical approach since it uses detailed information related to the technologies - engine power, operation time, travel distance, maximum speed, among others - to estimate the emissions.

The simulation model in OSeMOSYS has two phases: the first phase is building the system being studied, which is a maritime port, in this case. This involves the definition of the time domain and time split, the spatial coverage and the technologies and fuels considered but also the parameters that characterize these, such as costs and efficiencies. The second phase is creating a specific scenario of the case study, where other parameters related to the demand, to cost and others are defined.

This section describes this first phase, where the physical structure of the model is defined. The template file that is used to run the model contains the different sets and parameters, that should be filled first.

3.2.1 Sets and Parameters

The OSeMOSYS sets - technologies, fuels, day type, daily time bracket, emissions, modes of operations, region, season, time slices and year - are here introduced in the model.

The technologies and fuels presented in the Reference Energy System diagram, in section 3.1, are added here, using the code names listed in Appendix B. The links between fuels and technologies are also created, this is, the energy carriers that are the inputs and the outputs of a certain technology are connected in this first phase, just as the diagrams illustrates.

The region of our system is a Port and the time interval that pretends to be simulated is from 2020 to 2050. The model starts in 2020, and not 2024, to gather a more solid basis of information. This model is also prepared for seasonal and daily variations, along the four calendar seasons - autumn (AU), winter (WN), spring (Sp) and summer (Su) - and along the day, with differences between the day and night periods. This creates a model with 8 time slices. Even though the OSeMOSYS model operates on an annual basis, it utilizes time slices within each year to capture more granular details of energy flows and system behaviour.

The emissions emitted by any type of technology considered are added to the list (CO₂ and NO_x, in this case) and the different modes of operations are defined. These modes are useful to describe the electrolyzers use, guaranteeing the production of green hydrogen, using electricity with a guarantee of origin. By doing this, it is ensured that renewable energy is being used in this technology. Hence, mode 1 allows the use of electrolyzers with any type of electricity, whereas mode 2 guarantees that renewable energy is being used and, thus, assures the production of green hydrogen, with no emissions associated, which is particularly useful in the generation of e-fuels. These two modes have different inputs and outputs. Operation modes are also applied to the electricity import technology, to distinguish the import of green electricity, and to the transmission and distribution networks. Different modes within a certain technology correspond to the distribution of different fuels - for instance, in the natural gas network, depending on the mode, biogas or e-methane can also be transported.

The storage technologies in this model are not included, since that was not within the range of our report.

A few parameters were initially introduced too, namely the year split, the technologies' operational life and the output activity ratio. These are related to how each year should be split and to the technologies' lifetime and efficiency. Output activity ratio is typically set to be 1, due to the OSeMOSYS understanding of the 'activity' concept, simplifying the calculations within the model.

From now on, units considered are important. OSeMOSYS is unit-agnostic, i.e. it does not consider any units in its calculations. However, these are crucial to have consistent data and to interpret the outputs of the model. The consistency is relevant in terms of cost, power, energy and mass (in terms of emissions). The adequate units are introduced in section 3.2.2.

3.2.2 Technologies Characterization

Technologies techno-economical characterization is crucial to conclude the construction of the physical part of the model. This involves the description of the technologies' costs, efficiencies and capacity, emission and availability factors. This process consists of several steps, the first one being a literature review of existing technologies. Due to the complexity associated with a port, the

thorough description of this many technologies requires the use of proxy technologies for a realistic description. This consists of using similar technologies, assuming they have similar functions and, hence, similar characteristics. As a last resource, a few simplifications are also made.

Relevant techno-economic information is gathered through a comprehensive search across multiple databases and existing models. It is relevant to say that to have a coherent description of each technology, a few simple calculations are made, but not mentioned - for example, from dollars to euros, or from mass to energy, considering the fluid properties.

The complete techno-economic characterization, alongside each reference, can be found in Appendix D.

Most of the technologies involved in the local energy generation part are described based on the following datasets and reports: JRC-EU TIMES model [80], Techno-economic energy dataset in Colombia [81] and IEA (International Energy Agency) and IRENA (International Renewable Energy Agency) reports [82] [83]. Two previous projects from the research group - "Energy system modelling - Portugal 2050" [84] and "Characterizing the Hydrogen Chain: Efficiency, Costs, and Applications across Different Sectors" [60] - are also consulted. Tables 3.1 and 3.2 show some of the information gathered, concerning hydrogen and e-fuels production technologies.

Table 3.1: Hydrogen Production Technologies Characterization [80] [83].

Hydrogen Production Technologies	Costs							Efficiency			Availability Factor	Lifetime (years)
	CAPEX (€/kW)			OPEX (€/kW)		VARCOST (€/GJ)						
	2020	2030	2050	2020	2030	2020	2030	2020	2030	2050		
PEM	1200	950	186	36.0	29.0	-	-	70%	75%	80%	95%	3
ALK	626	377	186	40.0	10.0	0.15	-	67%	-	70%	90%	40
Solid Oxyde	785	450	280	66.0	14.0	-	-	75%	85%	85%	95%	10
SMR	201	158	-	10.0	7.65	0.08	0,05	75%	79%	-	90%	20
SMR w/ CCUS	273	191	-	14.2	11.5	0.53	0,07	64%	70%	-	90%	20

Table 3.2: E-Fuels Production Technologies Characterization [85].

E-Fuels Production Technologies	Costs									Efficiency			Availability Factor	Lifetime (years)
	CAPEX (€/kW)			OPEX (€/kW)			VARCOST (€/GJ)			2020	2030	2050		
Methanation	880	739	440	35.2	29.6	17.6	4.20	3.50	2.10	77%	77%	77%	95%	30
Fischer-Tropsch	2050	1557	880	103	77.9	44	5.20	4.10	2	73%	73%	73%	95%	30
Haber-Bosch	678 (€/ton/y)			19.7 (€/ton/y)			-			95%	95%	95%	95%	30
Methanol Production	705 (€/ton/y)	531 (€/ton/y)	339 (€/ton/y)	10.6 (€/ton/y)	7.97 (€/ton/y)	5.09 (€/ton/y)	-			95%	95%	95%	95%	25

Fuels import costs, which correspond to variable costs, also play an important role in the simulation model and are obtained through several different sources, listed in table 3.3. Due to the lack of data, a few simplifications are considered. The cost evolution of hydrogen and green hydrogen is assumed to be similar to the biogas and, even though their costs vary a lot with time, it is assumed that methanol and marine diesel and gas oil have the same cost in the time range considered, since that has been the trend in past years [86]. Looking at the past decade, heavy fuel oil has also been around 75% of the cost of other oil products [87]. It is expected that this trend continues.

A distinction between the different energy carriers' transportation costs nearby the port perimeter (and not within the port, since those are dummy technologies) is also considered. While liquid fuels are transported by tanker trucks or by ships, with much lower costs, electricity and gaseous fuels require appropriate infrastructure. Electrical transmission lines or pipelines investment cost is, hence, considered, due to the electrification trend that is expected in the upcoming years. These costs are presented in Appendix D, in Table D.1. The lifetime of these technologies is assumed to be 30 years and other costs and efficiency are neglected.

Table 3.3: Fuels Imports Variable Cost Characterization.

Technology Code	Variable Cost (M€/PJ)				REF
	2020	2030	2040	2050	
NG_Import	6.70	10.4	-	13.9	[88]
DIE_Import	8.50	20.5	-	26.6	[88]
EL_Import (Mode 1)	38.9	19.4	19.4	20.8	[89]
EL_Import (Mode 2)	44.4	22.2	22.2	22.2	[90]
Ammo_Import	30.9	30.9	30.9	30.9	-
MeOH_Import	1.48	1.48	1.78	2.13	[86]
METne_Import	72.2	72.2	72.2	72.2	[91]
MDO_MGO_Import	1.48	1.48	1.78	2.13	-
HFO_Import	6.05	6.04	7.41	8.92	-
GreenH2_Import	43.8	43.8	25.0	7.70	[92] [93]
H2_Import	7.70	7.70	7.70	7.70	[94]
BG_Import	14.0	11.1	8.37	4.65	[84]
Biomass_Extraction	4.65	8.37	8.37	9.30	[84]
WS_Extraction	1.86	1.86	1.86	1.86	[84]

Information relative to cargo handling equipment and harbour crafts, two fundamental categories of technologies in a port, was also found to be scarce and scattered. Different sources, listed in Appendix D, allow us to obtain the following characteristics of OPS technology, tugboats, cranes, forklifts, trains and locomotives (table 3.4). Truck characterization, due to their different units, is shown separately, in table 3.5.

Table 3.4: Harbour Crafts and Cargo Handling Equipment Technologic and Economic Characterization.

Technology	Costs			Efficiency (%)	Lifetime (years)
	CAPEX (€/kW)	OPEX (€/kW)	VARCOST (€/GJ)		
Tugboat Diesel	225	282	-	-	20
Tugboat Natural Gas	460	138	-	-	20
Tugboat H2 FC	1860	-	-	54	20
Tugboat Electrical	265	248	-	-	20
Crane	335	-	-	90	10
ReachStacker	3468	-	-	-	-
Forklift Electrical	1415	60	-	92	-
Locomotive Diesel	-	-	-	-	30
Locomotive Electrical	-	-	-	95	30
Train Electrical	-	-	-	95	-
Train H2 FC	1700	-	-	91	20
OPS	500	0.250	-	-	-

Table 3.5: Trucks Technologic and Economic Characterization [81].

Technology	Costs							Efficiency			Operational Lifetime (years)
	CAPEX (M€/Gtkm)			OPEX (M€/Gtkm)		VARCOST (M€/PJ)					
	2020	2030	2050	2020	2030	2020	2030	2020	2030	2050	
Truck Electric	287	287	75.4	1.86	1.86	-	-	9.70 Gtkm/PJ			25
Truck Natural Gas	272	272	272	5.45	5.45	-	-	0.809 Gtkm/PJ			25
Truck Diesel	93.0	93.0	93.0	5.74	5.75	-	-	1.15 Gtkm/PJ			25
Truck H2	370	370	76.9	7.41	7.41	-	-	9.26 Gtkm/PJ			15

The emission factors are mostly filled based on Agência Nacional de Energia (ADENE) manuals [95], on Los Angeles Port Air Emissions Data [96] and on a previous work carried out by the research group [84]. Port's technologies emissions are described based on the information on similar technologies from LA Port. However, it should be added that these technologies have different manufacturing years and, therefore, the emission factor is influenced by it. The emissions associated with fuels are CO₂ emissions, since these depend on their molecular structure, while NO_x emissions are associated with the conversion devices. Other types of pollutants, such as PM₁₀, are neglected in this model. Table 3.6 presents the technologies' emissions, with the respective code names.

Table 3.6: Emission Factors.

Technology Code	CO ₂ e Emissions (Mton/PJ)	NO _x Emissions (Mton/PJ)	REF
NG_Import	0.056	-	[84]
DIE_Import	0.043	-	[95]
EL_Import (Mode 1)(2020)	207 g/kWh	-	[97]
EL_Import (Mode 1)(2030)	96.5 g/kWh	-	-
EL_Import (Mode 2)	0	-	-
Ammo_Import	0	-	[98]
MeOH_Import	0.110	-	[99]
METne_Import	0.055	-	[95]
MDO_MGO_Import	0.074	-	-
HFO_Import	0.074	-	-
GreenH2_Import	0	-	-
H2_Import	0.067	-	[100]
BG_Import	0.550	-	[84]
Biomass_Extraction	0.002	-	[84]
WS_Extraction	0.092	-	[84]
WS_Gasifier	-	2.09×10^{-4}	[84]
NG_CHP	-	8.90×10^{-5}	[84]
BG_CHP	-	8.90×10^{-5}	[84]
Biomass_CHP	-	8.10×10^{-5}	[84]
TUG_ICE_DIE	-	4.33	[96]
PIL_ICE_DIE	-	4.33	[96]
ITRUCK_ICE_DIE	-	0.86	[81]
YC_ICE_DIE	-	1.68	[96]
FL_ICE_NG	-	0.38	[96]
FL_ICE_DIE	-	1.65	[96]
ECH_ICE_DIE	-	1.70	[96]

The import of electricity has two modes, as previously mentioned. Mode 2 corresponds to the import of electricity with a guarantee of origin. In mode 1, electricity emissions depend on the electricity mix used and, therefore, will vary with the location of the port. This emission factor concerns the Portuguese electricity mix.

As it is visible, a lot of techno-economic information is still missing. For certain technologies, such as OPS, a proxy technology had to be used. It was considered that onshore power supply consists in typical substations, associating its lifetime and efficiency to transformers'. The installation cost was based on an existing project. Since reefers work similarly, considering their electrical energy demand when stored, the investment is also assumed to be similar. The lack of data is not, however, the only problem faced. Technologies in the model have different levels of maturity, which contribute to uncertainty in literature values and to some missing data concerning certain more recent technologies, such as tidal energy or ocean thermal energy conversion devices. In both cases, available data is related to case studies, where different cost evolution scenarios are considered. In other cases, technologies share some similarities but do not correspond exactly to what we have in this model, as it occurs in retrofitted technologies or, for example, hybrid cranes.

All of this makes the use of proxy technologies or the simplification of the characterization process inevitable. To simplify the model, it was assumed that HC and several CHE had similar technical-economic characteristics themselves. Hence, when different information was not gathered, pilot vessels, tugboats and bunker barge boats have the same input for certain parameters. The same happens with the different types of trucks (internal and external trucks), cranes (assumed to be rubber tyres gantry cranes) - quay cranes, yard cranes and train terminal cranes - and even empty container handlers and forklifts.

Both in harbour crafts and in cargo handling equipment, one technology is conveniently used as a reference, the one with more data available in the literature. For HC, tugboats are used as the reference. This means that the same cost ratios (for capital and fixed costs) between the different tugboats (diesel, electric and hydrogen) are applied to barge boats and pilot vessels. The operational lifetime of these three crafts is the same and it should be pointed out that the electrical version of the tugboat is, in fact, a hybrid version, and hence the same assumption applies to the other HC.

The same train of thought is applied to CHE, with trucks' cost ratios being used as a reference. It is also assumed that empty container handlers and reachstackers have similar specifications and costs.

In the case of methanol internal combustion engines, costs are based on the vessels' retrofitting. It is, therefore, assumed that a diesel ICE vessel is adapted to include a methanol ICE. The trend in the evolution of costs was also set based on these reference technologies. Generally, diesel and natural gas engine prices will not vary a lot, whilst hydrogen technology costs are expected to decrease.

When it comes to technology efficiencies, isolated engines (diesel engines, electrical engines, among others) are used. For example, to characterize a vessel moved by a methanol engine, the specifications of a standard methanol engine were considered. Methane and natural gas engines are considered similar, due to the closeness of the fluid properties.

Considering the proximity of biogas, methanol and methane, all the gasifiers have the same technical and economical characterization. Floating photovoltaic panels are also viewed as similar to land panels, except for the cost.

A few other notes are worth mentioning. In the fuel transportation process, bunker barges have two inputs and, therefore, two different values in the parameter input activity ratio: one associated with the fuel transportation process, where no losses are considered, and another one related to the efficiency of the bunker barge movement. To calculate the input associated to the craft movement, a ratio is established between the energy needed for the movement of one bunker barge and the energy of fuel transported. For this calculation, it is necessary to know the bunker barge capacity and

consumption [101] [102], the distance of one trip (measured in Google Earth) and the properties of every single fuel involved - density and energy density. In this calculation, a few simplifications are also considered: the bunker barge is always either totally full or empty and its efficiency is considered constant, neglecting the effect of the transported fuel weight on the craft performance.

Also concerning harbour crafts, emissions factor only contemplates the emissions coming from the main engine and not when both the main and auxiliary engines are working.

Despite all of these assumptions, results are still expected to be different and coherent due to the differences in the demand of each type of harbour craft or cargo handling equipment. The demand is, essentially, what drives an OSeMOSYS model.

Considering the conducted research, the units that better suit the model are the following ones, Table 3.7.

Table 3.7: Input Variables Units.

Input Variable	Unit
Energy	PJ
Power	GW
Cost	Million Euro
Emission	Mton

These are, therefore, the model units from now on. However, there is one exception: trucks have different units and, hence efficiency and demand are expressed in terms of Gt_{km} (gigatons multiplied by kilometres).

Bearing in mind the power and energy units, GW and PJ, respectively, capacity to activity unit parameter can be introduced in the model. The conversion factor from GW to PJ is 31.536 and, hence, when the activity of a certain technology is presented in terms of power, this conversion factor is required.

3.3 Case Study

After the basic structure of our port simulation model is created, it can be populated with a particular case. The model is now ready to be applied to a case study to test and demonstrate its effectiveness. For this purpose, Port of Sines, in Portugal, already used in a previous work from the research group [1], is the target of this case study.

The model is thought to be applied to a container terminal and only considers that operations area which includes nautical and terminal operations. Thus, only these are considered in the Port of Sines.

The first step involves the use-case definition, which involves the set of actions considered in the calculation of the annual energy demand for the container terminal in the Port of Sines. A few assumptions have to be made and they are clearly stated. When there is no reference, the data in question comes directly from the Port Authority.

Once an ocean-going vessel reaches nearby the port perimeter, pilot vessels and tugboats are required. Pilot vessels will move next to the OGV and transfer a pilot and return to the port, while tugboats use their significant power to pull the containership. Already within the port area, the berthing of the vessel occurs and the cargo is unloaded in the quay area, assuming the ship has containers. Here, a quay crane and an internal truck move the container to the storage part of the

port, where a yard crane is used for the first time. Refrigerated containers have special needs and, when stored, must have electrical energy supplied to them.

A container that is unloaded in the Port of Sines can leave the port in three different ways: it can be transshipped to another vessel, or it can go to the hinterland, either by truck or train. Usually, 80% of the containers are transshipped, while the 20% other containers leave the port, either by truck (35%) or train (65%). There are, therefore, three use-cases that should be considered from the storage area. If a container goes to another vessel, the same equipment - yard crane, internal truck and quay crane - are again needed. If a container leaves the port in a truck, the yard crane moves the container back to the external truck, which then leaves the port perimeter. For cargo leaving by train, yard cranes move the containers back to the internal trucks, which will move them to the train terminal, where a train terminal crane is used.

During this process of unloading the ocean-going vessel, its energy needs are covered by the fuel supply process, performed by bunker barge boats. These refuel at a specific point of the port, located a few kilometres away from the berth, and then approach the ocean-going vessel and transfer the fuel in question. Currently, Port of Sines has no OPS points, even though there are plans to install them. Although the model is prepared to include technologies such as external trucks, empty container handlers and reachstackers, the scope of the case study was reduced, to get more realistic and useful results. This is due to the lack of data in the characterization process of certain technologies. For instance, in the yard area, some of the yard crane movements are actually performed by empty container handlers or reach stackers, but this would make the demand calculations more complex since these technologies' consumption is usually expressed in working hours. Thus, the demand for external trucks, empty container handlers or reachstackers is not considered. A few other assumptions are made, now listed:

- Containers are stored in piles, meaning that cranes have to do several moves to reach the pretended container. Due to the lack of data and complexity associated with this, the container is always assumed to be the first one on the pile - only one crane move is sufficient to load it and another one to unload it.
- The energy consumption of harbour crafts or cargo handling equipment in their waiting time is neglected.
- Yard cranes and train terminal cranes are assumed to be the same, with the same power. This is due to the lack of more reliable information concerning Port of Sines.

Figure 3.6 visually outlines the different areas of a port, helping to understand the distances involved in the cranes and trucks work.



Figure 3.6: Different Areas of Port of Sines Container Terminal (1 - Quay Area, 2 - Yard Area, 3 - Train Terminal).

From here, demand can be calculated, using Port of Sines available data, which refers to the year of 2022. In OSeMOSYS models, demand is associated to the fuels. However, for a better understanding, here the demand is going to be introduced as the technology demand. Thus, the energy conversion devices which will have a certain energy demand are:

- Bunker Barge Boats (for the fuel supply process)
- Tugboats
- Pilot Vessels
- Quay Cranes
- Yard Cranes
- Reefers
- Internal Trucks
- Train Terminal Cranes

3.3.1 Demand Calculations

The 2022 data does not differ significantly from the 2020 data and, hence, is used to characterize our base year. Demand is calculated, first, for our base year and then its evolution until 2050 is calculated.

Data from the Port of Sines, visible in Table 3.8, contains the number of calls, which is the number of stops vessels make for cargo operations, the maximum number of TEU containers in each containership, the onshore power supply demand, the berthing time and the number and total power of tugboats used in the operations. Even though the maximum number of TEU containers is not necessarily equal to the number of containers, the annual number of containers that entered the port is also known, corresponding to 1 824 059 TEU. The seasonality of the port activity is not here considered for the sake of simplicity.

Table 3.8: Brief version of the 2022 data available from Port of Sines.

Call	Berthing Time [hr]	Max Number of TEU's	Gross Tonnage (tons)	Number of Tugboats	Power of Tugboats [kW]	OPS [kW]
1	31	868	9981	1	1790	894
2	66	5550	61870	1	3879	4390
3	34	1835	23722	2	4177	1903
4	29	6627	73157	1	3879	5081
5	39	8819	96331	1	3879	6459
6	22	9411	95514	1	3879	6411
7	22	4870	50963	2	5968	3707
8	30	9411	95514	1	3879	6411
9	29	6402	73819	1	3879	5121
10	46	20568	214286	1	3879	12970

The ocean-going vessels' demand is related to the bunker barge boats' demand. Currently, the energy demand of ocean-going vessels, when at berth, is covered by fossil fuels, since Port of Sines has not installed OPS points yet. Thus, there is currently a demand for marine diesel oil and heavy fuel oil.

Knowing the berthing time of each vessel allows us to calculate the final energy demand in case the port had the onshore power supply. Since it does not, the efficiency of the conversion devices, either from the OPS technology and from the auxiliary engine that works with HFO, must be considered.

Table 3.9 summarizes this. The final energy from OPS is used to calculate useful energy which, in turn, is used to obtain the heavy fuel oil final energy.

Table 3.9: OGV Demand Calculation.

Energy Conversion Technology	Engine Efficiency	Final Energy Demand [PJ]	Useful Energy Demand [PJ]
OPS Technology	97%	82.0	79.5
HFO Auxiliary Engine	47%	169	

The fuel needs for the ocean-going vessel movement are also considered. For this, annual fuel consumption data from 2022 is used, in table 3.10. Knowing the fuel properties, such as lower heating value, it is possible to obtain the energy demand of both of these fuels and, hence, the final energy demand associated with ocean-going vessels, that affects bunker barge activity results.

Table 3.10: Fuel Consumption Energy Demand.

Fuel	LHV [MJ/kg]	2022 Consumption [kg]	Energy Demand [PJ]
MGO	44.0	5.53×10^7	2.43
HFO	40.9	5.19×10^8	21.2

When an OGV arrives at the port, tugboats initially approach the vessel and then start pulling it, which leads to two different phases, with different load factors. As table 3.11 suggests, these are two significantly distinct operation phases. Phase 1 is when the tugboat is not pulling the vessel,

while phase 2 is related to the pulling phase. This gives some context to the differences in velocity [103] and load factor [104]. It should be added that it is assumed that tugboats work at the same time and that the load factor is the same for the two boats. Considering the distances - the 3300-meter distance is an approximation and it was measured in Google Earth - the times of operation will also be different. The power specifications of each tugboat, available in the Port data, allow the final energy demand calculations. Since these are diesel tugboats, and taking into account the 31% engine efficiency that characterizes our diesel tugboats, this results in a lower useful energy.

Table 3.11: Tugboats Useful Energy Demand.

Operation Phase	Velocity (knots)	Distance (m)	Load Factor	Engine Efficiency	Useful Energy Demand (PJ)
Phase 1	15.0	6600	0.20	31%	0.0051
Phase 2	2.00	6600	0.8		

Pilot vessels also approach the ocean-going vessel, but do not have the pulling function and, hence, only one operation phase is considered. Fuel consumption data is again used. In 2022, almost 120 000 litres of diesel were consumed to cover the pilot vessels' demand. Once again, through the lower heating value, it is possible to obtain the final energy demand and, then, the useful energy, as table 3.12 shows.

Table 3.12: Pilot Vessels Useful Energy Demand.

Pilot Vessels	
2022 Fuel Consumption [liters]	1.20×10^5
Diesel Density [lg/L]	0.85
Diesel LHV [MJ/kg]	44.0
Engine Efficiency	31%
Useful Energy Demand [PJ]	0.00447

The three cranes' demand have already taken into account the destination of the container. As previously mentioned, 80% of the containers are transshipped, while the 20% other containers leave the port, either by truck (35%) or train (65%). This influences the number of moves done by cranes and, hence, results in three different cases, whether the container goes to another ship (transshipment, case 1) or if leaves the port by truck (case 2) or by train (case 3). This results in a different number of crane moves, a table 3.13 shows.

Table 3.13: Number of Moves per Type of Crane.

Type of Crane	Number of Moves		
	Case 1	Case 2	Case 3
Quay Crane	2	1	1
Yard Crane	2	2	2
Train Terminal Crane	0	0	1

Having this and the different cranes' energy consumption (it is assumed that the train terminal crane has the same consumption as the yard crane) in mind, assuming one move per container as

previously explained, it is possible to reach to the demand values in terms of useful energy, presented in table 3.14.

Table 3.14: Quay, Yard and Train Terminal Cranes Useful Energy Demand.

Type of Crane	Crane Consumption [kWh/move]	Crane Efficiency	Useful Energy Demand [PJ]
Quay Crane	6	31%	0.0275
Yard Crane	5		0.0127
Train Terminal Crane	5		0.000828

Refrigerated containers, once stored, also receive electricity from the grid and, therefore, influence demand numbers. Due to the lack of information concerning these special containers, a few assumptions had to be made. It is assumed that 5% of the containers in each vessel are refrigerated containers [105] and that each of these has a consumption of 3,6 kW [106]. The longer the stay in the storage part of a port, the more significant will be the fee to be paid. This results in an assumption that the average refrigerated container stay in a port is about one week, or 604 800 seconds. Once again, with this, it is possible to calculate the amount of energy needed to keep these containers refrigerated, as it is visible in Table 3.15.

Table 3.15: Refrigerated Containers Useful Energy Demand.

Refrigerated Containers	
2022 Number of Reefer Containers	9.12×10^4
Consumption [kW/TEU]	3.60
Average Storage Time [s]	6.04×10^5
Efficiency	92%
Useful Energy Demand [PJ]	0.183

The previously defined cases that distinguish the containers' destination also influence the action of internal trucks. In case 1, trucks are used to move the container from the quay area to the yard area and to do the return trip, back to a different vessel. In case 2, internal trucks are only used for the 500m (measured distance) between the quay and the yard area, while in case 3 the truck has to cover the same 500m but also an additional 800m (also measured) from the yard area to the train terminal area.

Nevertheless, the useful demand for trucks is more easily expressed in tons per kilometre. Through the available data concerning the number of containers, the distances covered by the internal trucks and assuming 16 tons as the average container weight [1], useful demand can then be calculated, Table 3.16. Due to the significant value, demand should be expressed in gigatonne-kilometre.

Table 3.16: Internal Trucks Useful Energy Demand.

Internal Trucks	
Case 1 Distance [m]	1000
Case 2 Distance [m]	500
Case 3 Distance [m]	1300
2020 Number of TEU Containers	1.82×10^6
Average Container Weight [ton]	16
Useful Energy Demand [Gtkm]	0.0293

All in all, the energy demand of Port of Sines in 2020, considering the container terminal and only the operations part, is around 193 PJ, without including internal trucks demand. The demand for the year of 2020 is listed in table 3.17.

Table 3.17: 2020 Demand by Technology.

2020 Energy Demand		
Final Energy	OGV MDO	2.40 PJ
	OGV HFO	190 PJ
Useful Energy	Tugboats	0.00510 PJ
	Pilot Vessels	0.00447 PJ
	Quay Cranes	0.0275 PJ
	Yard Cranes	0.0127 PJ
	Reefers	0.182 PJ
	Internal Trucks	0.0293 Gtkm
	Train Terminal Cranes	0.000823 PJ

The model considers a time interval of thirty years and, hence, it is important to know how this demand is expected to evolve. The evolution prediction is based on the TEUs prediction growth, obtained through the electricity demand growth predictions from the Port of Sines, excluding possible growth due to the electrification of certain technologies. This increase is justified by the new containers terminals that are expected to be built. By applying this growth indicator to the energy demand of our base year, for each technology, it was possible to characterize the evolution until 2050. Table 3.18 presents the demand values until 2030. From 2030 to 2050, Appendix E should be consulted.

Table 3.18: Demand Evolution from 2020 until 2030.

Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Demand Growth Indicator	1.00	1.16	1.32	1.48	1.64	1.80	2.00	2.20	2.40	2.60	2.80
Final Energy											
OGV MDO [PJ]	2.40	2.80	3.20	3.60	3.90	4.30	4.80	5.30	5.80	6.20	6.70
OGV HFO [PJ]	190	221	251	282	312	342	380	418	457	495	533
Tugboats [PJ]	0.00510	0.00595	0.00677	0.00759	0.00841	0.00923	0.0102	0.0112	0.0123	0.0133	0.0143
Useful Energy											
Pilot Vessels [PJ]	0.00447	0.00519	0.00590	0.00662	0.00734	0.00805	0.00895	0.00984	0.0107	0.0116	0.0125
Quay Cranes [PJ]	0.0275	0.0319	0.0363	0.0407	0.0451	0.0495	0.0550	0.0605	0.0660	0.0715	0.0770
Yard Cranes [PJ]	0.0127	0.0148	0.0168	0.0189	0.0209	0.0229	0.0255	0.0280	0.0306	0.0331	0.0357
Reefers [PJ]	0.183	0.212	0.241	0.270	0.300	0.329	0.365	0.402	0.438	0.475	0.512
Internal Trucks [Gt.km]		0.0293	0.0340	0.0387	0.0434	0.0481	0.0527	0.0586	0.0645	0.0703	0.0762
Train Terminal Cranes [PJ]	0.000828	0.000961	0.00109	0.00122	0.00135	0.00149	0.00165	0.00182	0.00198	0.00215	0.00231

Before testing the model, restrictions should be implemented to obtain more realistic results. The Port of Sines connection to the grid has a certain capacity, which should be reflected in the model, since it affects electricity imports. Thus, until 2030, this capacity is 10 MW and, from then until 2050, it is 64 MW.

The model should also have some residual capacity from before the modelling period, to ensure that in our year we have the same technologies that Port of Sines, currently, has. This requires a few conversions from energy to power, using the 2020 energy demand values. Thus, in 2020, the Port of Sines has diesel harbour crafts (tugboats, pilot vessels and bunker barge boats) and diesel trucks and train terminal cranes, whilst also having electric quay and yard cranes. This is a rough estimate of residual capacity since it is assumed every technology is operating at full capacity and was bought in 2020.

3.4 Scenarios

Once the model is created, it can be executed. As mentioned earlier, one of the advantages of simulation models is the possibility of creating different evolution scenarios, each imposing different constraints on the demand and emissions.

This is particularly useful in the scope of climate transition. As it stands, several legislative documents define reduction emissions goals to be achieved in the upcoming years and decades. Some are more broad, whereas others are towards the maritime transportation sector. Chapter 2.1.4 presents a few of the planned objectives to gradually achieve carbon neutrality. Scenarios pretend to study the implementation of these goals, set by maritime sector organisations or governmental institutions.

Based on the set of goals previously mentioned, five scenarios are created, as Table 3.19 presents.

Table 3.19: Summary List of the Scenarios.

Scenario	Description
SC 1	Business-As-Usual
SC 2	Emissions Reduction Trajectory
SC 3	Carbon Tax on Port Emissions
SC 4	OGV Decarbonization - Conservative Evolution
SC 5	OGV Decarbonization - Innovative Evolution

The initial scenario (SC1) is the BAU (business-as-usual) scenario, which refers to the model without any other restriction or different evolution path, rather than the ones which currently exist, such as the electrical grid connection capacity. It can be defined as the scenario where there is no adoption of new regulations that may impact emissions or energy consumption and, hence, serves as a baseline, to compare with other scenarios.

Scenario 2 (SC2) corresponds to the simulation of an emissions reduction trajectory. As previously mentioned, there are two primary ongoing initiatives at the national level, in Portugal, to achieve climate and energy objectives - PNEC2030 and RNC2050. According to these, there is a 40% emissions reduction target by 2030 for the transport sector, in comparison with 2005 emission levels, and the carbon neutrality goal by 2050, which means an almost total reduction of the emissions. To avoid redundancy it was decided to combine the two legislative documents and its targets, by 2030 and 2050. However, it should be noted that the scenario focuses only on the emissions which depend on the Port's Authority and, hence, does not consider the ocean-going vessels'

fuel emissions. By applying these restrictions, it is expected to have a penetration of renewable energies in the port energy chain. This scenario also accounts for some of the physical limitations in the Port of Sines. Currently, there are plans to have, by 2050, a capacity of 24 MW of wind energy, 17.5 MW of solar energy and 7 MW of wave energy. These projects are based on an ambition to have 100% of renewable energy by 2050 and consider the physical limitations of the port in terms of space. The idea behind this scenario is also to simulate how the port should overcome these physical limitations in the production of green energy, in case of a greater demand that requires more renewable energy production. It is assumed that all the electricity generated by these installations has the container terminal as its destination, which is close to reality since this terminal represents the highest share of energy consumption.

Scenario 3 (SC) evaluates the impact of a carbon tax applied to maritime transportation and ports. Recently, the EU Emissions Trading Scheme has been extended to cover emissions from large ships entering European ports and IMO also plans to implement a similar worldwide scheme in the upcoming years [107]. Assuming that a similar tax would be applied to ports, considering the current carbon cost - currently around 70 euros per tonne and, in 2030, it may be around 279 euros [107] - this scenario pretends to study the impact of a tax, as an incentive to opt for cleaner fuels. Even though there are plans to extend this tax to other greenhouse gas, such as NO_x and CH₄, for now this only applies to CO₂ emissions.

The last two scenarios, scenarios number 4 and 5 (SC 4 and SC 5, respectively), simulate different evolutions of the vessel's fleet. Port Authority does not directly influence or control the type of ships that berth in its perimeter. Nevertheless, in the upcoming decades, it is expected that ocean-going vessels will adopt renewable or less polluting fuels, which will affect the energy chain of a port, depending on the type of energy carrier that these vessels' engines will need. Based on a study applied to inland shipping [108], considering that a similar evolution will occur among ocean-going vessels, it is possible to define the demand evolution of the final energy carriers of these ships. However, a few assumptions had to be made for this: diesel demand corresponds to heavy fuel oil and biogas and biofuel demand corresponds to methanol, while hydrotreated vegetable oil is assumed to be ammonia. This simplification can be done due to the focus of the model on the emissions. Establishing parallelism with the existing synthetic fuels in the model is possible since synfuels have similar production processes to biofuels, with similar costs and zero emissions.

When defining the ocean-going vessels' final energy demand, two energy uses must be considered: bunker energy, whose purpose is the vessel locomotion, and the energy delivered to cover the needed operations at berth, mainly using the auxiliary engines.

What distinguishes these two scenarios is their more conservative (SC 4) or innovative (SC 5) character. Concerning the energy demand for the operations at berth, table 3.20 depicts the evolution considered. The legislation mandates that by 2050, every ocean-going vessel will be either electric or use renewable fuels. Here, to simplify, it is assumed that, independently from the fuel used in the ships' locomotion, every vessel will be adapted to receive electricity through onshore power supply or use green hydrogen in a fuel cell.

Table 3.20: OGV Operations Demand Distribution.

Fuel Demand	SC 4 CONS		SC 5 INNOV	
	2035	2050	2035	2050
OPS	30%	60%	50%	60%
H2	2%	40%	10%	40%
HFO	68%	0%	40%	0%

Table 3.21 presents how the bunker energy demand is expected to be distributed, in 2035 and 2050, in both of these scenarios. It is assumed that the final energy demand increases in the same proportions, maintaining this mix of fuel demand constant.

Table 3.21: OGV Bunker Energy Demand Distribution.

Fuel Demand	SC 4 CONS		SC 5 INNOV	
	2035	2050	2035	2050
Ammonia	25%	35%	10%	5%
Electricity	0%	5%	7%	20%
HFO	67%	15%	63%	15%
Hydrogen	0%	5%	2%	25%
Methanol	3%	40%	13%	35%
Natural Gas	5%	0%	5%	0%

To create these scenarios in the simulation model file, certain parameters had to be changed. Essentially, scenarios 2 and 3 affect emissions-related parameters (annual emission limit and emissions penalty), while scenarios 4 and 5 cause a change in OGV final energy demand. In scenario 2, to define the emissions cap of the port, the total emissions result from the BAU scenario is used, considering the CO₂ emissions coming from the import of HFO and MDO. Since emission reduction targets are in comparison to 2005 levels, the Port of Sines emissions of that year are estimated considering the volume of cargo handled, in comparison to 2020 data. In all of these scenarios, except for BAU, it is expected a higher penetration of electric technologies and, hence, a greater demand for electricity. As a consequence, it is assumed that the grid connection capacity will be expanded in 2025 and 2030, to 100 and 500 MW, respectively. This is also an external subject to the port's authority, but the decarbonization targets will lead, eventually, to this capacity reinforcement.

The model will optimize based on the current state without any additional limitations. OSeMOSYS will prioritize cost reduction as its primary objective.

Chapter 4 presents the results and discussion of these scenarios.

Chapter 4

Results and Discussion

After the model was generated and processed, results were obtained and analysed. OSeMOSYS prioritizes cost reduction and, hence, the energy pathways and the investment plan are influenced, mostly, by the cost factor. This chapter presents the model outcomes, through graphical representations, such as bar charts and diagrams. These are obtained through a Python script and using jupyter notebook, a helpful tool for data analysis and visualisation. There should be some caution in analysing the results plots, due to the lack of consistency in the bars colours.

The discussion focuses on the model's most relevant aspects - energy use, emissions and costs. As already mentioned, it should be noticed that results highlight energy use and not energy efficiency, otherwise, the energy involved in, for example, obtaining nitrogen or separating CO₂ from air, would have to be considered.

4.1 BAU Scenario

4.1.1 Energy Use

As the Port of Sines currently stands, it uses electric and diesel energy conversion technologies. The reference year, 2020, visible in the Figure 4.1, which is a Sankey Diagram, illustrates that. Electric - quay and yard cranes and reefers - and diesel technologies - tugboats, pilot vessels, bunker barge boats, train terminal cranes and internal trucks - demand the port to import diesel and electricity from the grid. Heavy fuel oil and marine diesel oil are also imported to cover the ocean-going vessel demand.

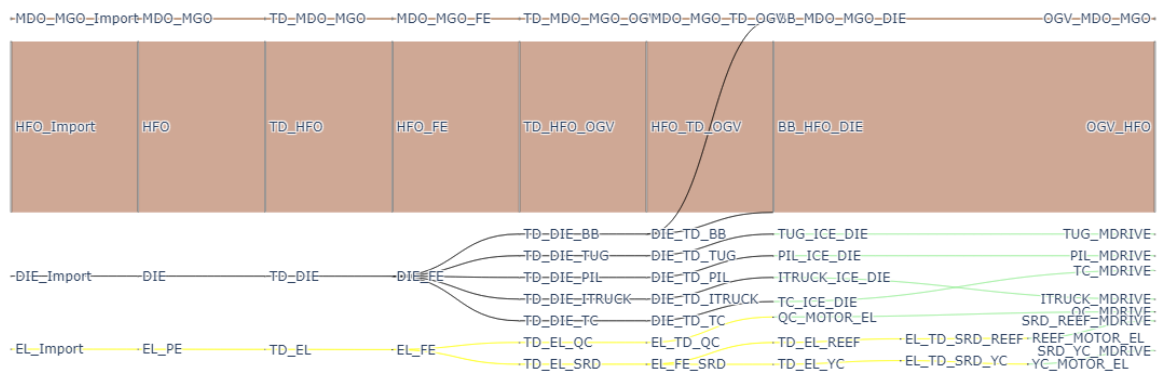


Figure 4.1: Sankey Diagram - BAU Scenario - 2020 (with OGV).

Sankey Diagrams show the energy system as a whole and, thus, act as a useful tool in the model energy flow visualisation, from primary to useful energy, except for the ocean-going vessels, where the demand disaggregation does not occur. Figure 4.1 helps to visualise the disproportional difference in energy demand between the ocean-going vessels and harbour crafts and cargo handling equipment combined. For this reason, the following diagrams hide the demand associated with OGV, allowing for a better visualization of the other energy demands.

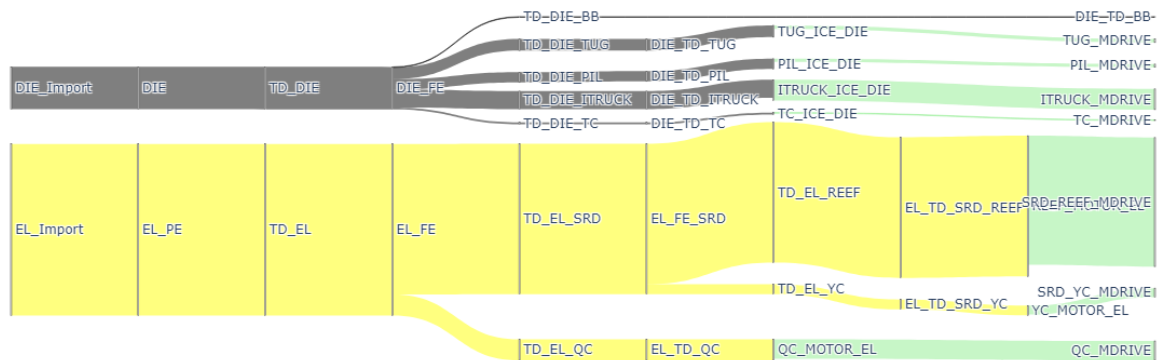


Figure 4.2: Sankey Diagram - BAU Scenario - 2020.

Just by visualising the energy flow, a few immediate conclusions can be taken immediately. Fossil fuels, mostly diesel and heavy fuel oil, represent the largest share of energy carriers' use. Also, within the electrical energy demand, refrigerated containers' energy consumption represents a significant portion of the energy demand.

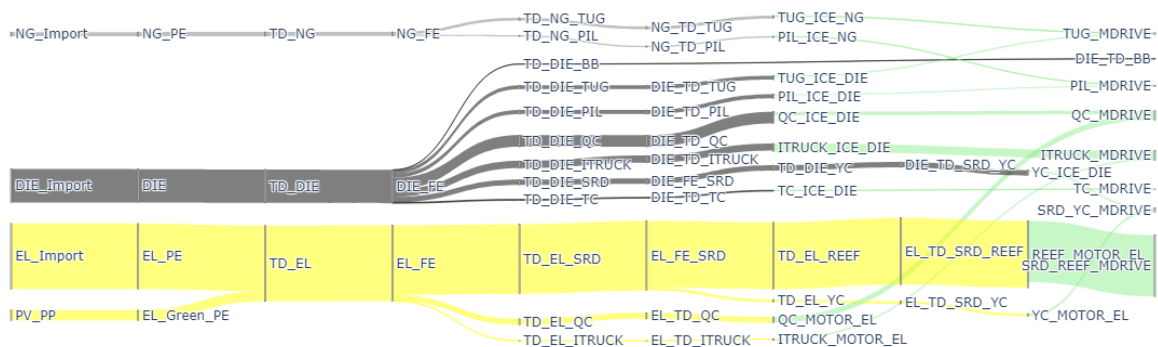


Figure 4.3: Sankey Diagram - BAU Scenario - 2022.

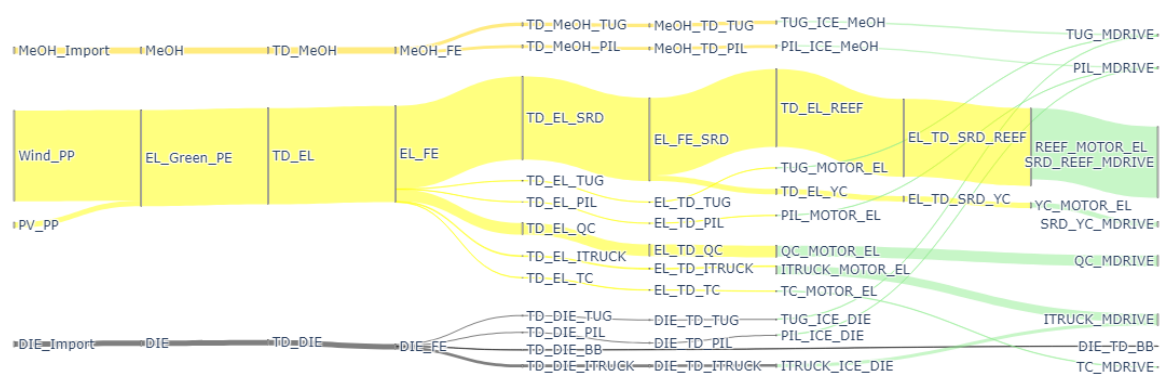


Figure 4.4: Sankey Diagram - BAU Scenario - 2030.

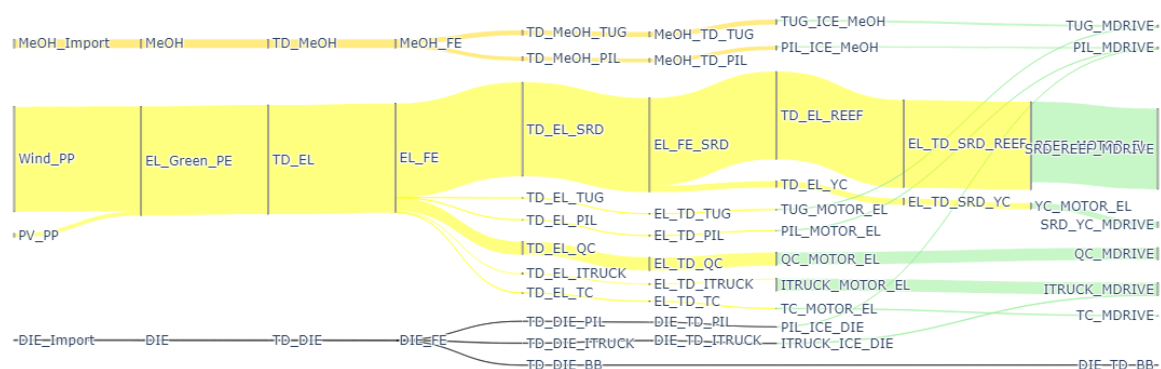


Figure 4.5: Sankey Diagram - BAU Scenario - 2040.

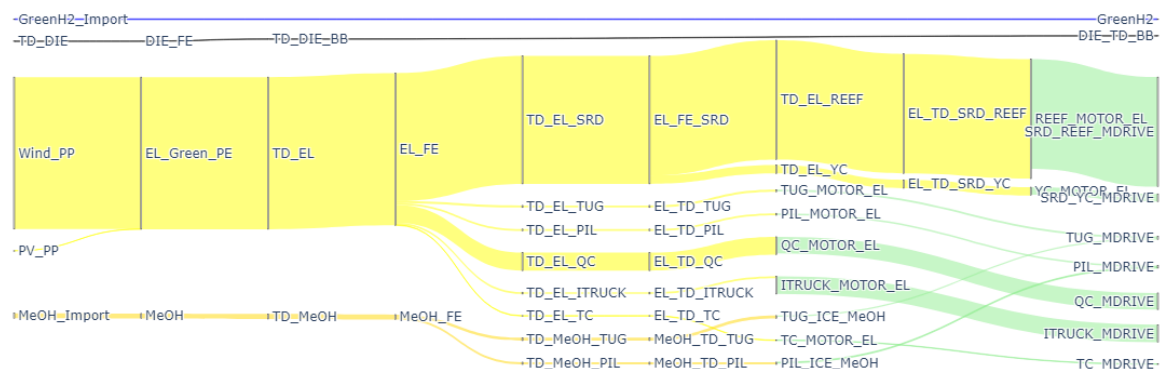


Figure 4.6: Sankey Diagram - BAU Scenario - 2050.

From 2020, until 2050, considering the increase in the number of containers handled by the port, an investment in local energy generation technologies and, simultaneously, in adapting the final energy conversion technologies, having cost as the main priority, is expected.

From 2022 (Figure 4.3), the port will start investing in natural gas technologies, such as tugboats and pilot vessels. Even though this does not correspond to reality, since, by 2024, Port of Sines has not yet invested in these technologies, this should eventually turn out to be the trend. This imprecision, which extends to every scenario simulation, happens due to the combination of an increase in the demand and the phase-out of the residual capacity parameter in the simulation model. The

residual capacity installed should also consider the evolution in container demand between 2020 and 2024. Since this does not occur, the growth in demand is followed by an investment in new technologies, such as diesel cranes, due to their lower cost. As also mentioned earlier, this is a result of the assumption that the existing electric cranes are operating at their full capacity, which is likely to not be true.

Still in 2022, to reproduce the Port of Sines reality, photovoltaic panels are installed. One decade later, onshore wind turbines are also expected to be installed, followed by a gradual electrification trend, visible in the energy flow in the years of 2030, 2040 and 2050 (Figures 4.4, 4.5 and 4.6, respectively).

By 2030, the investment in natural gas is replaced by methanol. Methanol usually has a similar cost to marine diesel oil and, unless the synthetic fuel e-methanol is used, the carbon footprint is also significant. Methanol can be produced using as feedstock natural gas, coal or biomass, for example, which indicates that the normal trend is for methanol to be more expensive than natural gas, which is not the case, leading to the choice of methanol technologies, over natural gas. This imprecision in the model may have happened due to the fluctuance of fuel prices over time, which resulted in a lower cost for methanol in comparison with, for example, natural gas, causing this discrepancy.

Despite this imprecision, certain key trends are still apparent - the electrification of the technologies is expected to happen and, by 2050, the demand is mostly for electrical energy. Although, there will still be a portion of energy demand coming from fossil fuels - which, in this case, corresponds to methanol.

Energy Imports and Electricity Generation

An assessment of the installed capacity of technologies that generate electricity and on the total annual amount of energy that is imported by the port is illustrated in Figures 4.7 and 4.8.

Electricity is initially imported, but later starts to be generated locally. A phase-out on the import of diesel can also be noticed (which corresponds to DIE_Import in the graph), even though another fossil fuel, in this case methanol, is still used. This replacement occurs due to the diesel cost being relatively higher than natural gas or grey methanol.

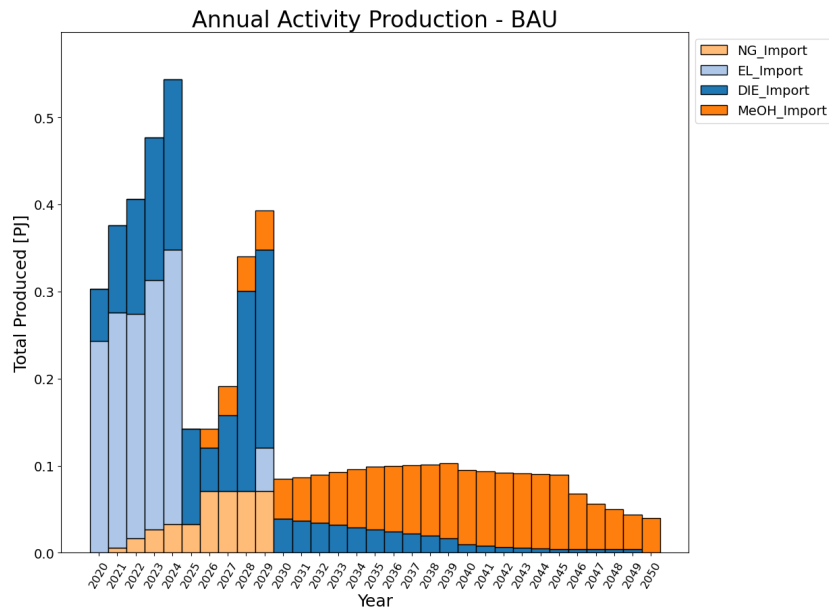


Figure 4.7: Total Annual Activity of Energy Import Technologies - BAU Scenario.

Importing electricity from the grid depends on the maximum capacity of the connections to the national electric grid, which justifies the constant values until 2030 and then until 2050. On another hand, a consistent increase in wind power plant capacity is possible to observe, increasing the energetic independence of the port. Thus, the model depicts a picture where local energy generation will be cheaper than importation, in the upcoming years.

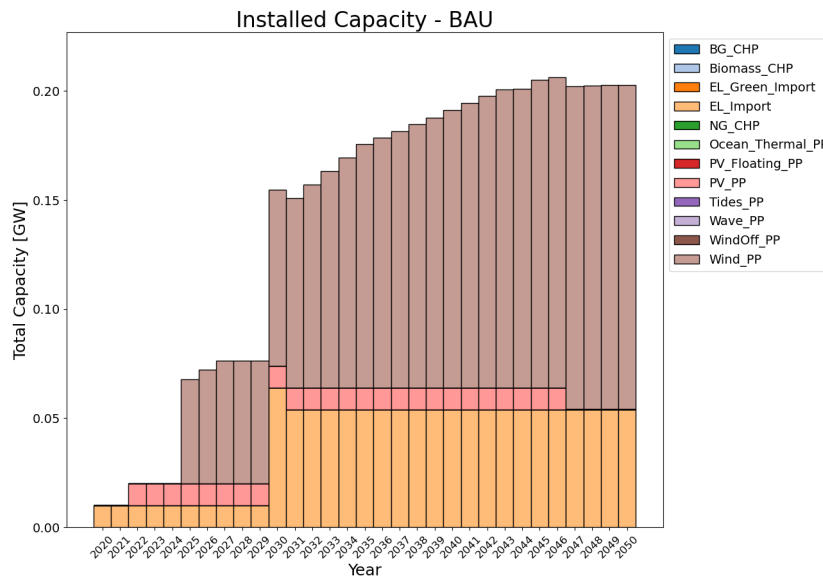


Figure 4.8: Installed Capacity of Electricity Generation Technologies - BAU Scenario.

Hydrogen and E-Fuels Production

In terms of hydrogen production and use, results show activity between 2026 and 2029, which explains why it does not appear in the sankey diagrams.

During this period, hydrogen fuel cell cranes are invested in and, hence, grey hydrogen is pro-

duced, as Figure 4.9 illustrates (presented on the next page), through the process of steam methane reforming, using natural gas as feedstock. This investment lasts only three years since electricity costs drop in 2030, making electric cranes a more cost-effective option, once again. The steam methane reforming investment option is revealed to be more economical.

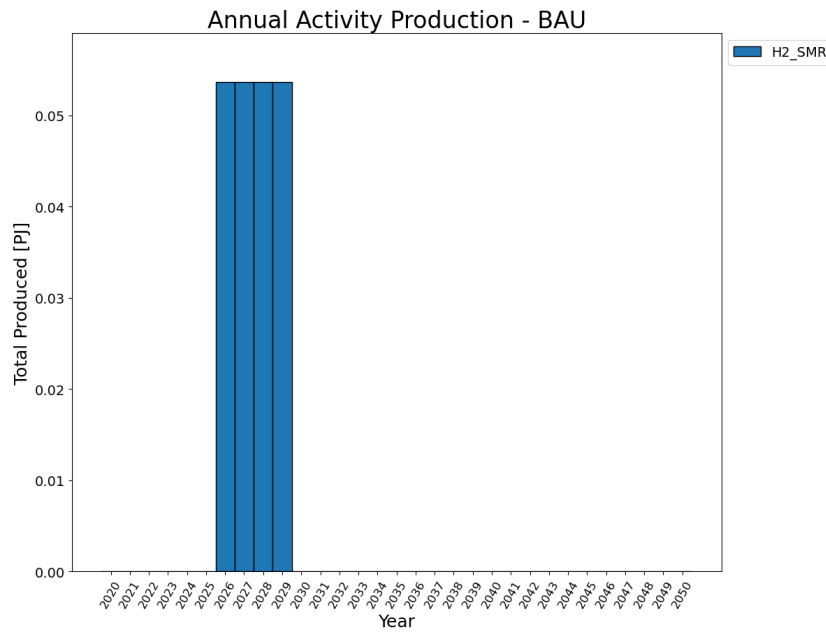


Figure 4.9: Total Annual Activity of H2 Production Technologies - BAU Scenario.

End-Use Technologies

The activity of the different groups of technologies which exist in a port - namely harbour crafts and cargo handling equipment - is depicted on the graphs below.

As illustrated in Figure 4.10, the energy needs for bunker barge boats are disproportionally superior to the ones from tugboats and pilot vessels. This is closely linked to the immense amount of energy that ocean-going vessels receive, when at berth. In reality, numbers might not be that disproportional, since vessels may also receive fuel by other methods, such as refuelling stations.

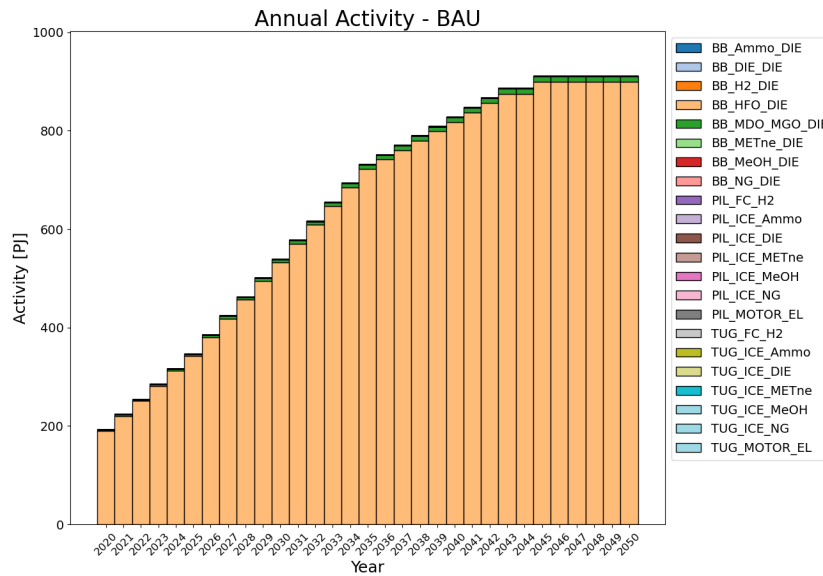


Figure 4.10: Total Annual Activity of Harbour Crafts - BAU Scenario.

If only tugboats and pilot vessels are analysed, both included in Figure 4.11, the evolution portrayed by the sankey diagrams is proved here. There is an investment in natural gas technologies during a brief period, electrical boats are more and more adopted but, until 2050, the dependence on fossil fuels remains. However, notice that fossil fuels technology activities begin to decrease in the final years of our time interval.

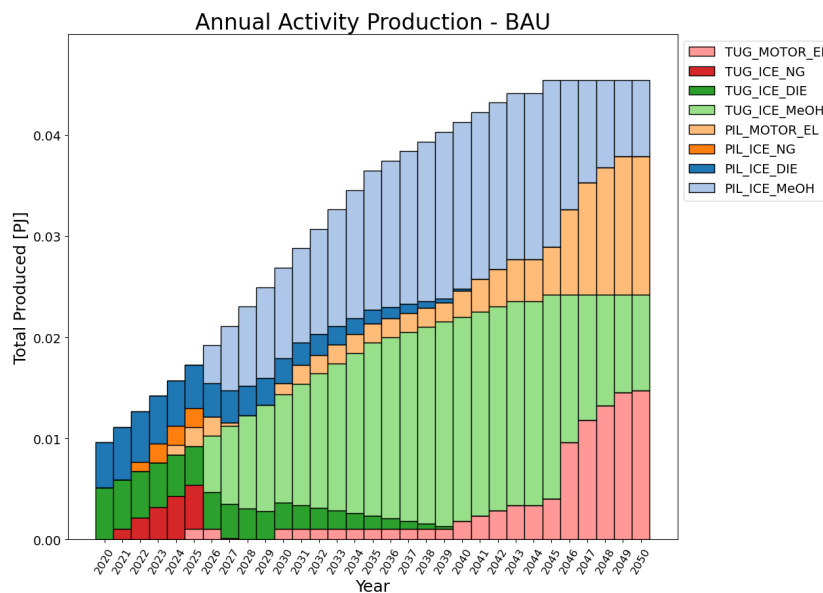


Figure 4.11: Total Annual Activity of Tugboats and Pilot Vessels - BAU Scenario.

By analysing cranes' evolution, in Figure 4.12, the electrical cranes use pattern is, once again, more and more present, instead of adopting diesel cranes. As earlier mentioned, it is expected to be investment in hydrogen cranes in the final years of this decade, from 2026 to 2029.

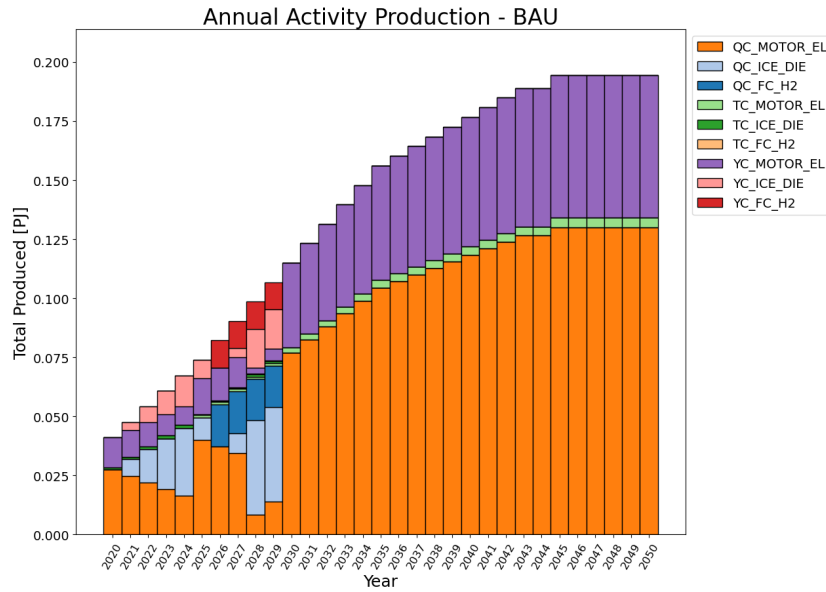


Figure 4.12: Total Annual Activity of Cranes - BAU Scenario.

The cargo handling equipment analysis, in Figure 4.13, turns evident that trucks are also expected to be electrical. Refrigerated containers' large share of energy consumption within the yard area will continue in the following years, which is in line with the predicted demand evolution.

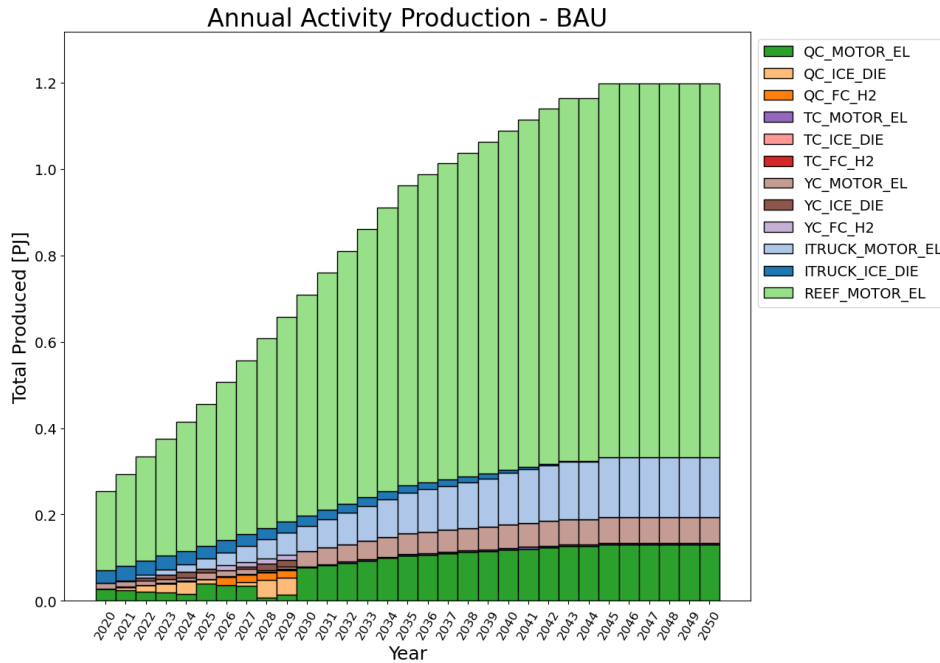


Figure 4.13: Total Annual Activity of Cargo Handling Equipment - BAU Scenario.

4.1.2 Emissions

As expected, emissions, either of carbon dioxide (Figure 2.3) or nitrogen oxides (Figure 4.16), experience a significant increase, which only slows down to a constant value near 2050.

These vast emissions of greenhouse gases are mostly driven by the presence of ocean-going ves-

sels in ports, whose energy demand depends on the type of engines they have and, hence, is not controlled by the Port Authority. Hence, it is relevant to analyse emissions from the Port Authority's point of view, as Figure 4.15 demonstrates. The expected electrification trend reduces the emissions but is not enough to achieve carbon neutrality, by 2050, in the BAU scenario. This is explained by the use of fossil fuels, such as methanol. It should once again be mentioned that the electrification influence on emissions is also dependent on the grid mix of energy sources.

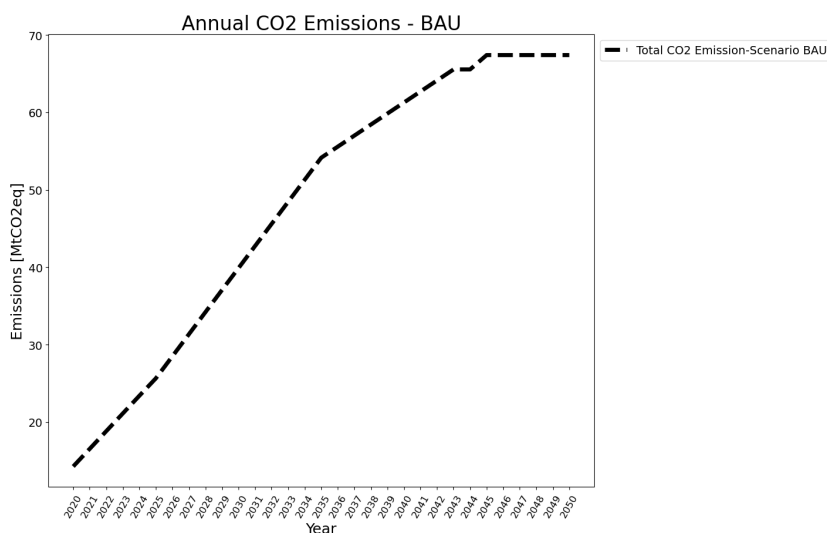


Figure 4.14: Total CO2 Emissions - BAU Scenario.

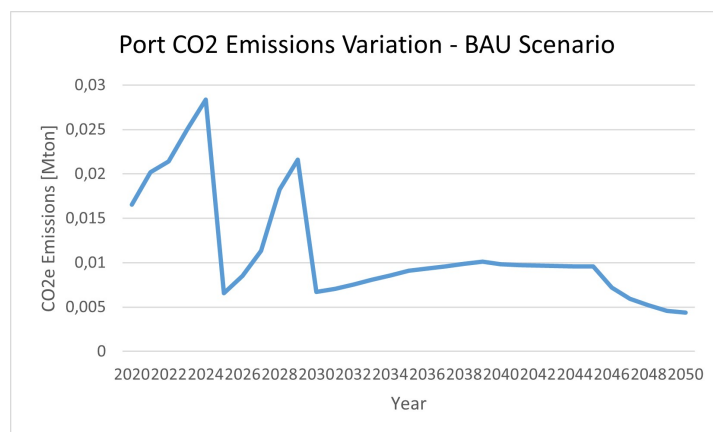


Figure 4.15: Port CO2 Emissions - BAU Scenario.

The carbon intensity indicator measures the carbon emissions per unit of activity. In 2020, the carbon emissions per unit of energy are around 227 g/kWh. In 2030, there is already a decrease to 33 g/kWh and, by 2050, the carbon intensity considering only the port's authority emissions is 13 g/kWh.

The NO_x emissions follow a similar path of growth, mainly driven by OGV demand, which has a reflection on bunker barge boats' activity.

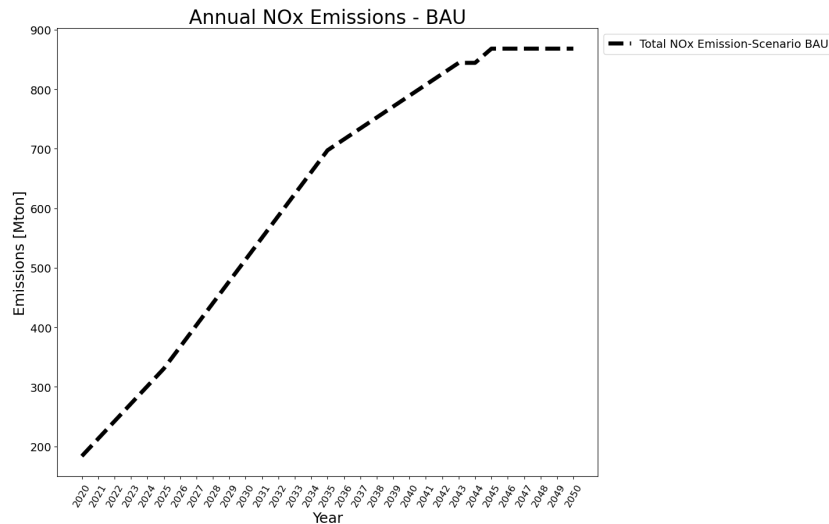


Figure 4.16: Total NOx Emissions - BAU Scenario.

4.1.3 Costs

The cost assessment is conducted with a focus on electricity generation, energy import and harbour crafts and cargo handling equipment technologies.

Starting by analysing electricity generation and energy import, whose costs can be observed in Figures 4.17 and 4.18, variable costs illustrate the expenditure with the import of fuels, which happen to be more significant during the first four years of our time interval, where the vast majority of electricity and diesel consumed are imported. This period is followed by a significant investment, corresponding to capital costs in the graph, in onshore wind power plants. For instance, in 2025, the port is expected to invest more than 60 million euros in eolic turbines. As expected, fixed costs, which represent the operation and maintenance needs, also witness an increase, due to the increased activity of wind energy generation technologies, leading to more maintenance.

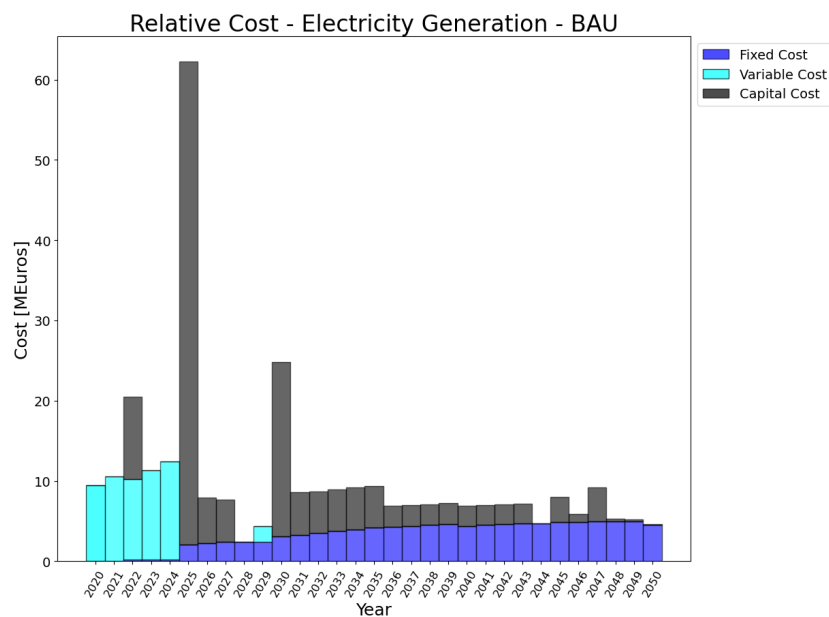


Figure 4.17: Capital, Fixed and Variable Costs of Electricity Generation - BAU Scenario.

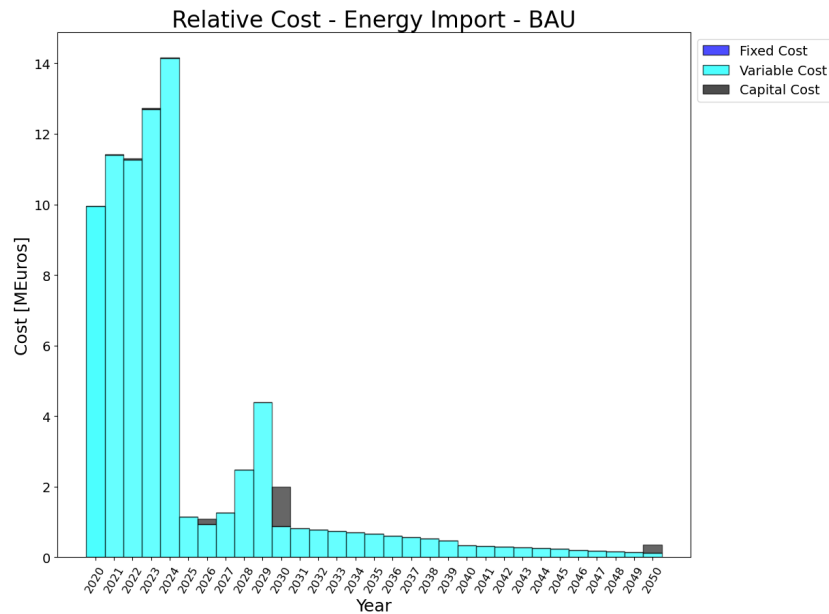


Figure 4.18: Capital, Fixed and Variable Costs of Energy Import - BAU Scenario.

From 2020 to 2050, the Port of Sines has to invest in new technologies, considering the evolution in demand assumed. The analysis illustrated in Figure 4.19, reveals a consistent pattern of investment in quay and yard cranes and reefer technologies, which is coherent with the evolution in demand. The adoption of electrical technologies, such as electric trucks, can also be visualized.

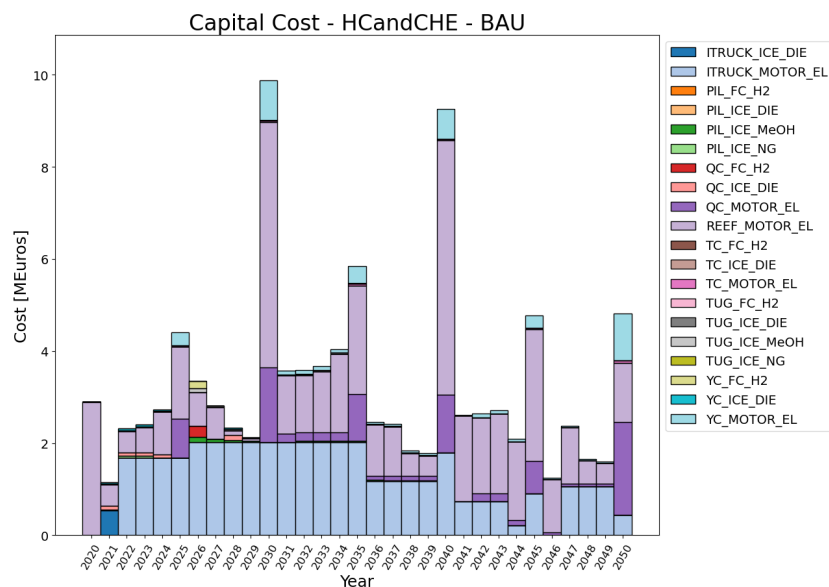


Figure 4.19: Capital Costs of Harbour Crafts and Cargo Handling Equipment - BAU Scenario.

The increase in the movement of a port also anticipates the growth in operation costs, either in harbour crafts or in cargo handling equipment, as is visible in both graphs, Figures 4.20 and 4.21. However, notice that the fixed costs for harbour crafts are unrealistically high. This is, once again, due to bunker barge boats. The disproportion between fixed and capital costs for harbour crafts and cargo handling equipment might also be related to the type of equipment expected to be used in the upcoming decades. While some harbour crafts keep internal combustion engines,

with fossil fuels, every crane, truck or reefer is expected to be electrified, by 2050. As it is known, electric engines have lower operating costs, which might also explain the significant difference in fixed costs. Variable costs of harbour crafts or cargo handling equipment are not displayed since it is related to the energy carrier used in the conversion device and, hence, the model incorporates them when the fuel is being generated or imported.

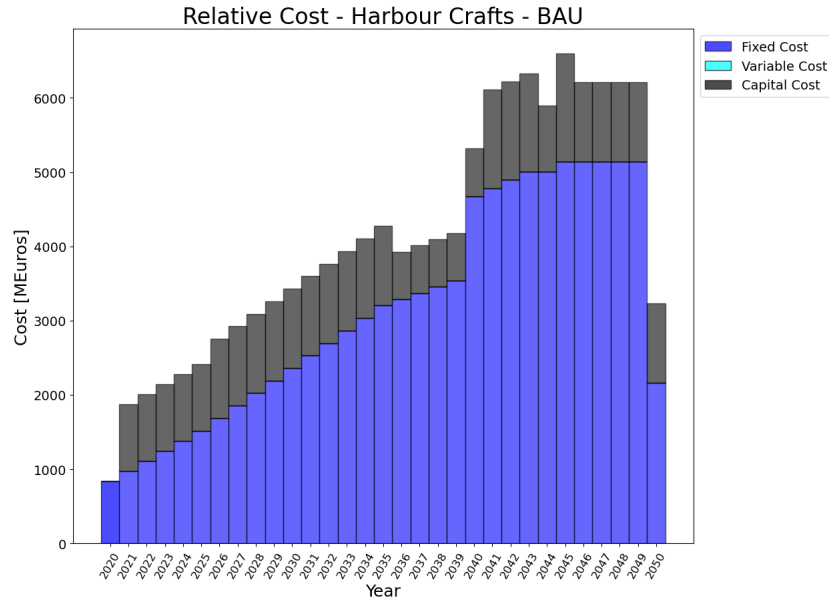


Figure 4.20: Capital, Fixed and Variable Costs of Harbour Crafts - BAU Scenario.

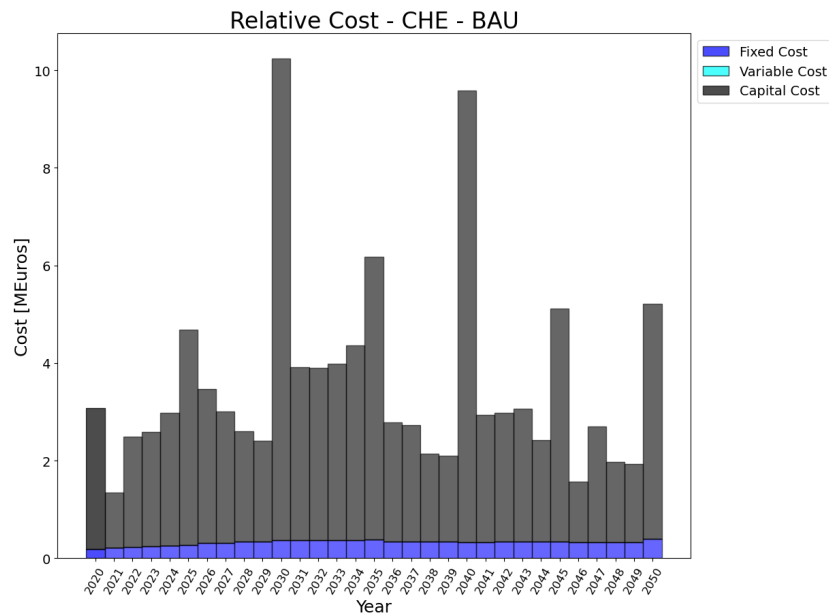


Figure 4.21: Capital, Fixed and Variable Costs of Cargo Handling Equipment - BAU Scenario.

All in all, the business-as-usual scenario depicts an evolution of Port of Sines where electrification is a possible and likely scenario. This is considering the higher efficiency of electric technologies, which results in a more efficient energy use in the energy chain of the port. Furthermore, in the upcoming decades, it is expected that electric technologies become more and more competitive, just like local renewable energy generation technologies. Another aspect worth mentioning is the

significant increase in energy demand that is expected for the Port of Sines, which implies the need for more new technologies.

Nonetheless, a reduction in emissions requires a greater effort. By 2050, fossil fuels are expected to still be used and, hence, carbon neutrality is not possible by maintaining the same action steps.

4.2 Scenarios Comparison

As previously explained, the following scenarios pretend to assess the feasibility of emissions reduction goals'. To do this, annual emission limits (scenario 2) and a carbon tax (scenario 3) are imposed. Assuming the ocean-going vessel fleet will also adopt greener fuels in the upcoming decades, the effect of this potential change is also verified (scenarios 4 and 5).

A useful note related to the graphs - even though some of them do not have subtitles on the corresponding bar, the scenarios order is always from scenario 1 (BAU) to scenario 3 (or to scenario 5, when the ocean-going vessels energy demand is being compared to the BAU scenario), this is from left to right.

4.2.1 Energy Use

Every single scenario has the same reference year, i.e., 2020. From here, each one follows its own unique investment path.

The following Sankey diagrams pretend to depict certain aspects of the different scenarios evolution, in certain years of our interval. Initially, our analysis highlights scenarios 2 and 3. Figures 4.22 and 4.23 depict the energy chain in 2025, while Figures 4.24 and 4.25 illustrate the flow of energy in 2050.

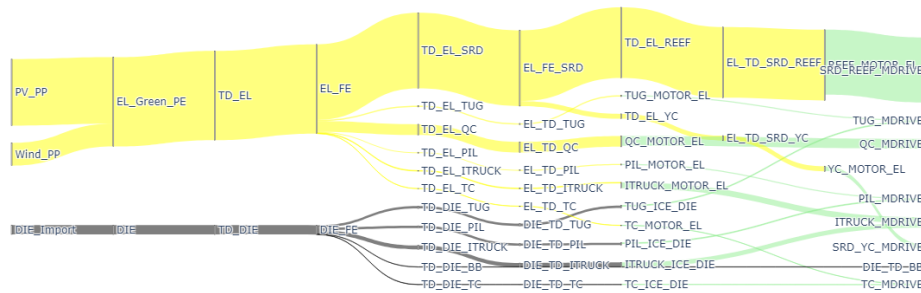


Figure 4.22: Sankey Diagram - Scenario 2 - 2025.

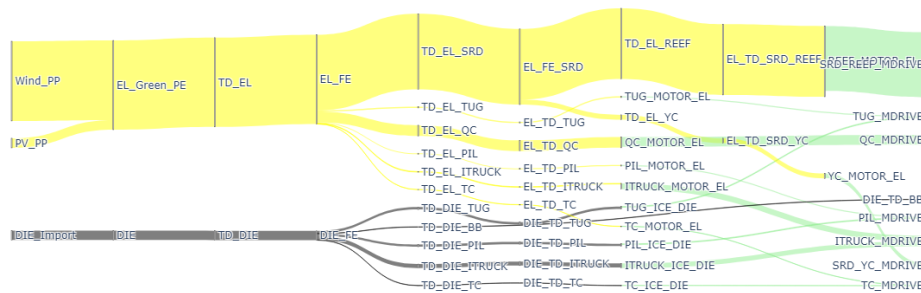


Figure 4.23: Sankey Diagram - Scenario 3 - 2025.

Scenarios 2 and 3 ended up being similar. The restrictions accelerated the electrification trend and caused an earlier phase-out of the fossil fuels. When compared to the BAU scenario, natural gas and methanol are no longer used, being electrical technologies adopted instead, since the first years of our simulation, as Figures 4.22 and 4.23 illustrate. In both of these scenarios, onshore wind power plants are an option, just like hydrogen fuel cell cranes. Even though the investment in these cranes only occurs in 2044, hydrogen is started to be produced through solid oxide electrolyzers during the decade before. It was not possible to find an explanation that justifies the inverted investment in wind and solar energy technologies, observed in the diagrams of scenarios 2 and 3.

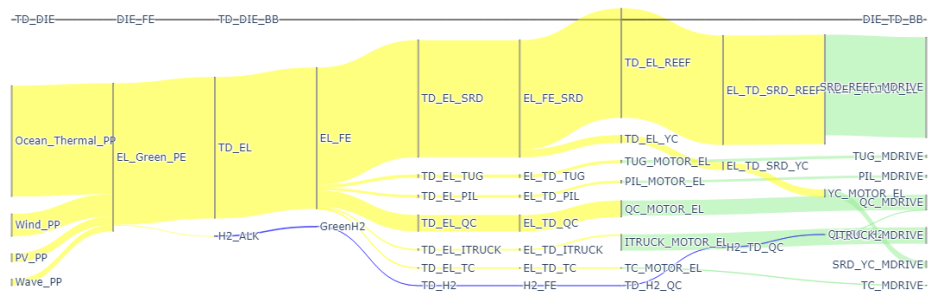


Figure 4.24: Sankey Diagram - Scenario 2 - 2050.

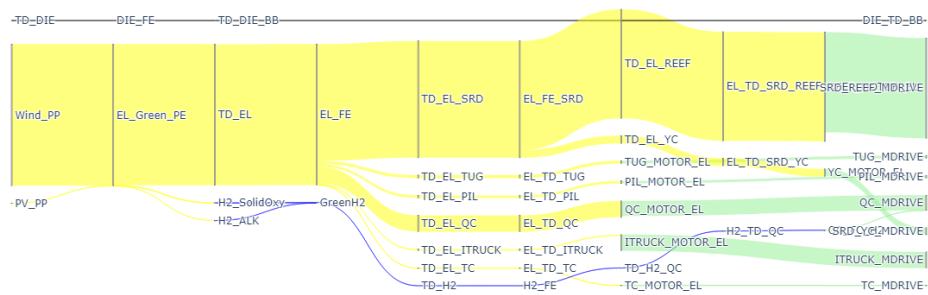


Figure 4.25: Sankey Diagram - Scenario 3 - 2050.

Scenario 2, as Figure 4.24 reveals, ends up investing in a wider range of renewable technologies, in comparison to BAU and SC3 scenarios, such as ocean thermal, tides and waves energy conversion technologies. The reason for ocean thermal energy conversion technology being preferred over off-shore wind energy is, despite its significant differences in cost, the capacity factor parameter. The model did not restrict the availability of OTEC technology and, hence, decided to invest in it. This should be corrected in a future version of the model.

By 2050, year depicted in Figures 4.24 and 4.25, diesel is, in fact, no longer imported, but diesel bunker barge boats still operate. CO₂ emissions are, hence, theoretically zero, but in reality, diesel technologies still exist. A plausible explanation for this to happen was not found and it may be a simulator's weakness. The inclusion of an electric bunker barge boat in the model, if realistic, may resolve this issue.

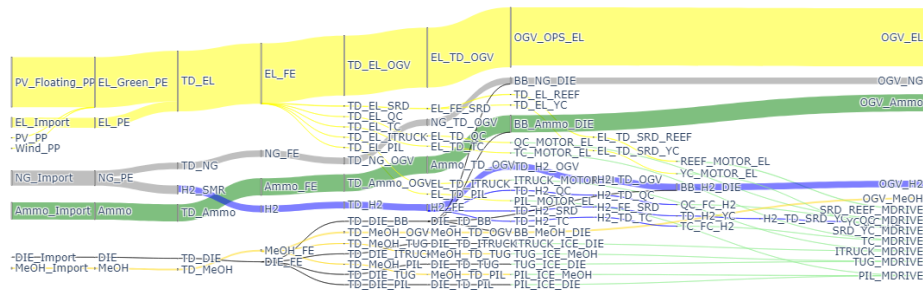


Figure 4.26: Sankey Diagram - Scenario 4 - 2030.

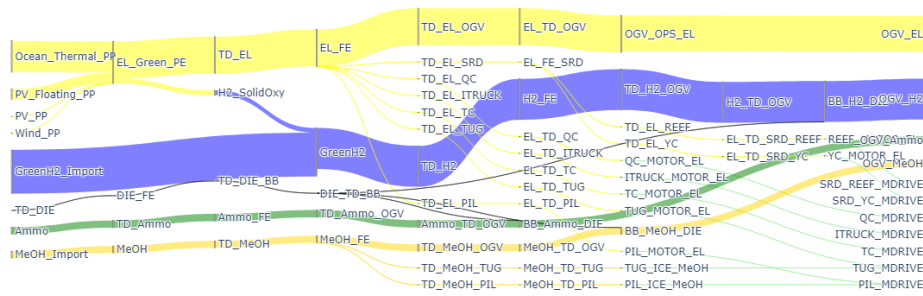


Figure 4.27: Sankey Diagram - Scenario 4 - 2050.

Scenarios 4 and 5 are similar and, hence, only the first is presented, in Figures 4.26 and 4.27, which represent the energy flow in 2030 and 2050. The numerous technologies and energy carriers may make it difficult to comprehend, but the general ideas are explained in the next paragraphs.

The analysis of scenarios 4 and 5 reveals, as expected, also two similar simulations and a drastic change in the energy flow of the port, by 2050. The increased electricity demand leads to new energy sources, such as floating photovoltaic technologies and cogeneration plants. Hydrogen is imported but also locally produced, initially through steam methane reforming processes, but later through electrolyzers. In addition, the new fuels used, such as ammonia, are imported.

Energy Imports and Electricity Generation

The results comparison between scenarios is divided in two, one comparison between scenarios where an emissions tax or cap is tested (SC 2 and 3) and another comparison studying the effect of changes in the ocean-going vessels fleet (SC 4 and 5).

Starting with the first comparison, the annual activity visible in Figure 4.28 turns evident the earlier phase-out of fossil fuels in scenarios 2 and 3 - methanol and natural gas are not imported from 2030. Diesel phases out until the last years of our simulation. The installed capacity, in Figure 4.29, helps understand the activity results, since in SC 2 there is a higher investment in renewable energy capacity - wind and photovoltaic in an initial phase, but later in other technologies such as ocean thermal or waves energy technology.

The comparison between the installed capacity results of our scenarios and the actual Port of Sines' plans, mentioned in chapter 3.4, reveals a significant difference. While the port plans to have 48,5 MW installed by 2050, model results invest in, approximately, 100 MW, discounting energy import capacity. This is explained by the demand growth projections, which took a conservative value in this case study.

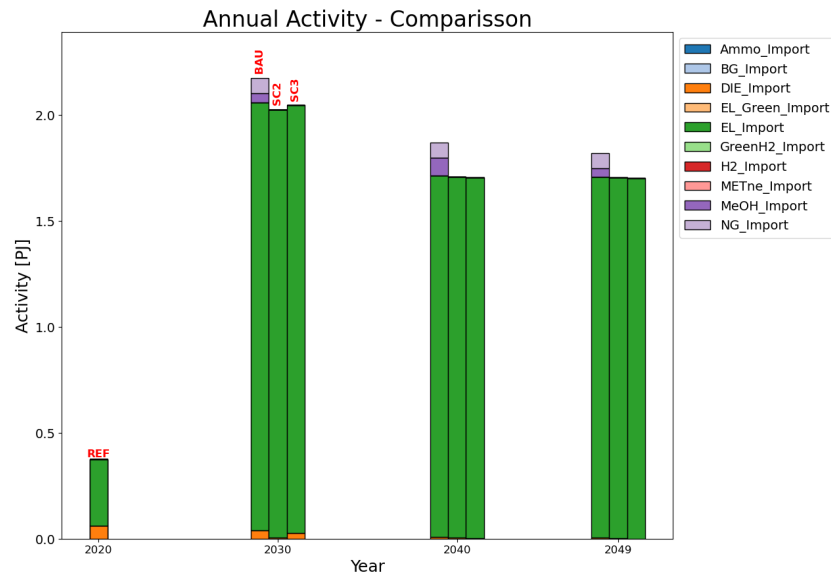


Figure 4.28: Total Annual Activity of Energy Import Technologies- Scenarios BAU, 2 and 3 Comparison.

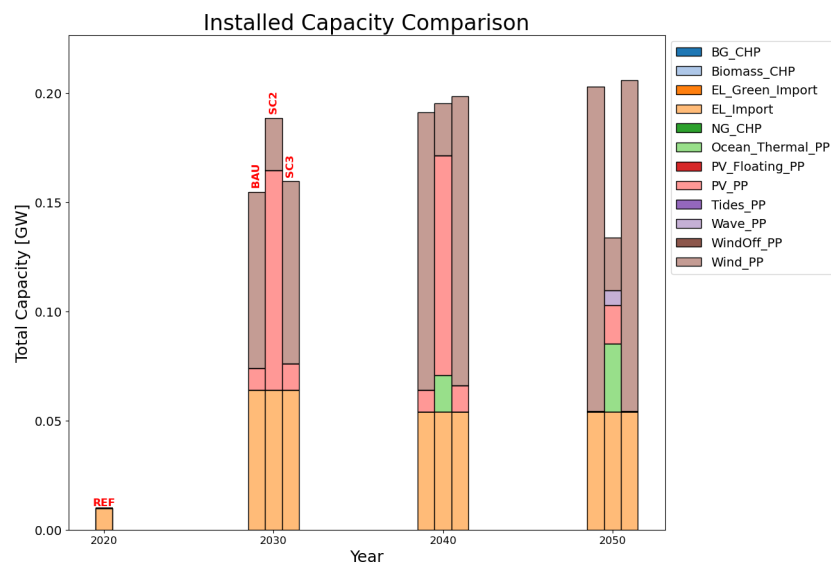


Figure 4.29: Installed Capacity of Electricity Generation Technologies - Scenarios BAU, 2 and 3 Comparison.

The comparison between scenarios BAU, 4 and 5, in Figure 4.30, depicts a different picture of the different energy carriers demand. As anticipated, a different fleet of vessels berthed at the port provokes different fuel demands, which affects imports and local energy generation technologies. Ammonia and methanol, which correspond to Ammo_Import and MeOH_Import, respectively, in the graph, are imported in greater quantities and there is less relative demand of heavy fuel oil. The importation of these fuels does not ensure that they are renewable fuels.

Electricity is mostly generated locally, as Figure 4.31 reveals, either from photovoltaic and ocean thermal technologies or through natural gas cogeneration power plants. This justifies the significant import of natural gas.

Hydrogen is initially generated locally, as the next section reveals, but, by 2050, green hydrogen is

already imported, indicating a competitive and appealing price.

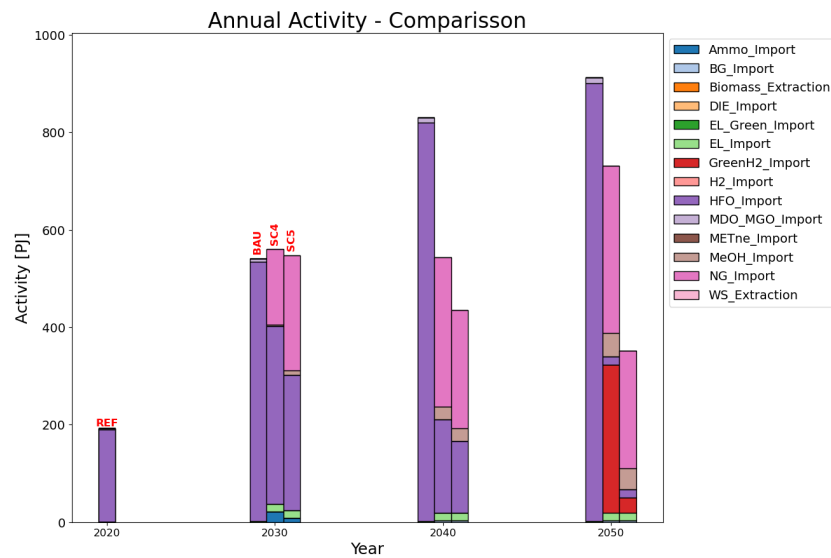


Figure 4.30: Total Annual Activity of Energy Import Technologies- Scenarios BAU, 4 and 5 Comparison.

The analysis of installed capacity illustrates a tremendous increase in installed capacity when compared to the BAU scenario. This is due to MDO and HFO needs being covered strictly by imports, while in scenarios 4 and 5 there is the possibility of generating the energy needed locally. However, the total capacity that is revealed to be installed is immense and unrealistic. For example, for floating photovoltaic panels, physical limitations turn this into an impossibility. To overcome this issue, the profile of local energy generation technologies has to be more diverse and the electrical connections to the grid must be expanded notably.

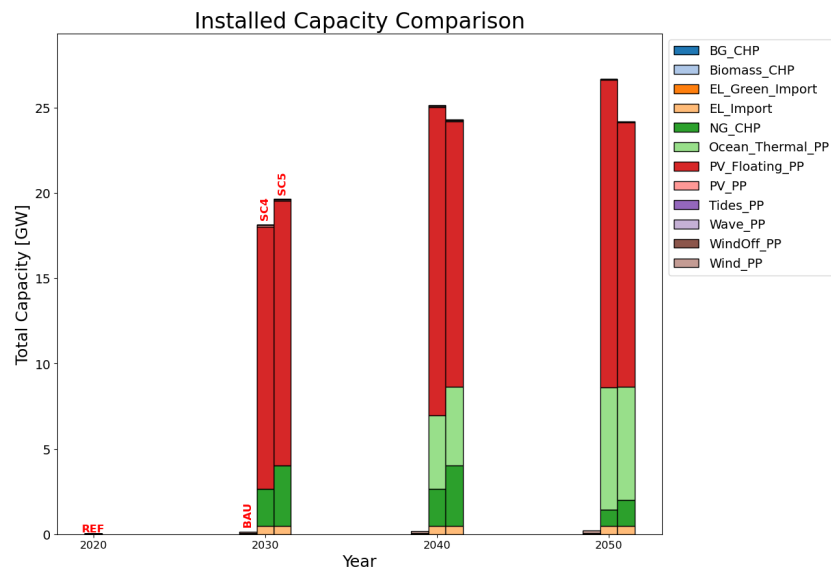


Figure 4.31: Installed Capacity of Electricity Generation Technologies - Scenarios BAU, 4 and 5 Comparison.

Another important aspect that results from these simulations is that even if ocean-going vessels are adapted to work with synfuels, electricity or hydrogen, the port must be restricted to the exclu-

sive use of renewable fuels, green electricity or hydrogen. Otherwise, as these results reveal, grey hydrogen and other fossil fuels may still be an option, attending their lower cost.

Hydrogen and E-Fuels Production

Hydrogen is used in every scenario. Starting by analysing scenarios 2 and 3, illustrated in Figure 4.32, the signs of green hydrogen production reaffirm what was previously mentioned: solid oxide electrolyers are the initial option and alkaline electrolyers are later adopted. In scenario 2, however, the investment in the alkaline technology occurs earlier, by 2040. Solid oxide electrolyers, despite being more expensive, offer a more efficient process, hence being more cost-effective.

An important detail in the BAU scenario is the competitive cost that green H₂ is expected to have by 2050. In the years before, as already shown, hydrogen is only produced using fossil fuels as feedstock.

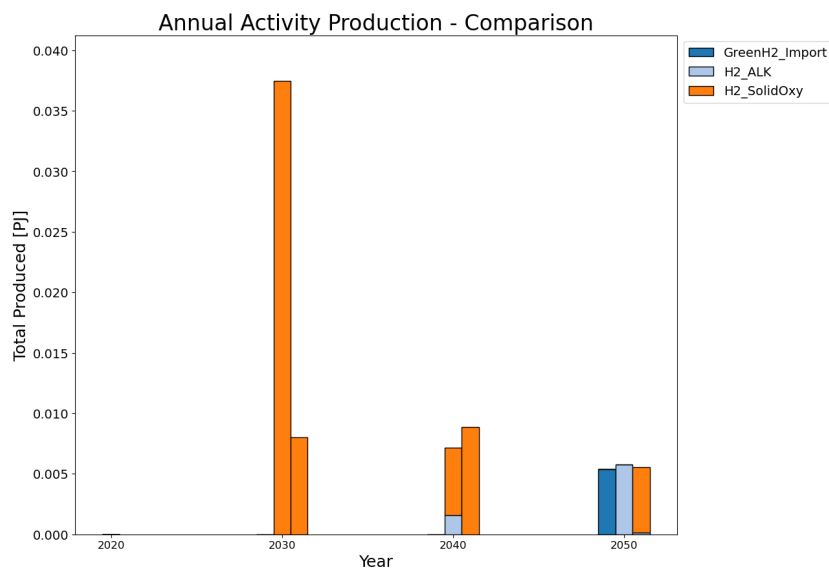


Figure 4.32: Total Annual Activity of Hydrogen Production or Import Technologies - Scenarios BAU, 2 and 3 Comparison.

Following what has been mentioned about scenarios 4 and 5, the increased need for hydrogen results in local production during the first years, as can be observed in Figure 4.33. Steam methane reforming, also using imported natural gas as feedstock, is the main process used, but electrolyers are also utilised, as Figure 4.33 illustrates. Solid oxide electrolyers are, once again, preferred over alkaline due to their higher efficiency, which compensates for the cost difference. By 2050, the competitive cost of green hydrogen allows it to be imported.

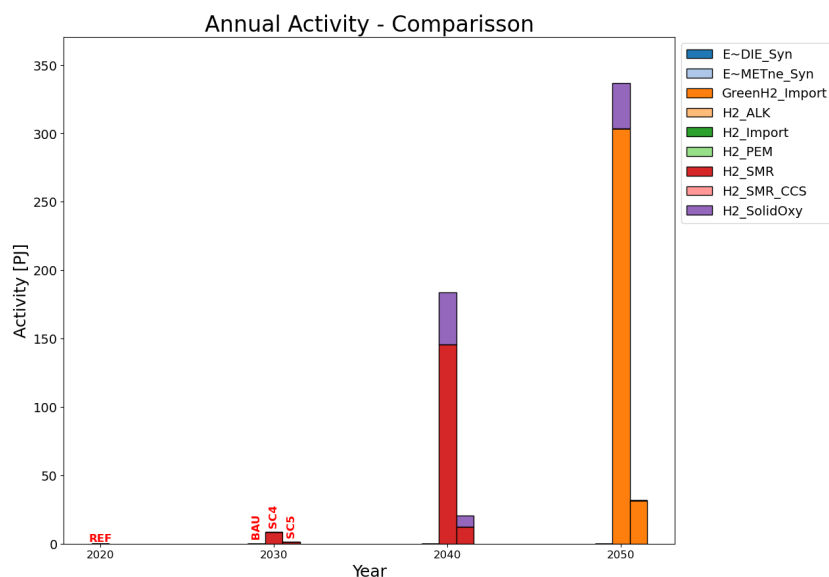


Figure 4.33: Total Annual Activity of Hydrogen or E-Fuels Production or Import Technologies - Scenarios BAU, 4 and 5 Comparison.

End-Use Technologies

The annual activity of our end-use technologies, either harbour crafts (in Figure 4.34) or cargo handling equipment (Figure 4.36) illustrates, once again, the rapid electrification trend present in scenarios 2 and 3. Concerning tugboats and pilot vessels, these will be electric from 2040, a different reality from BAU scenario, which by 2050 will still rely on fossil fuels.

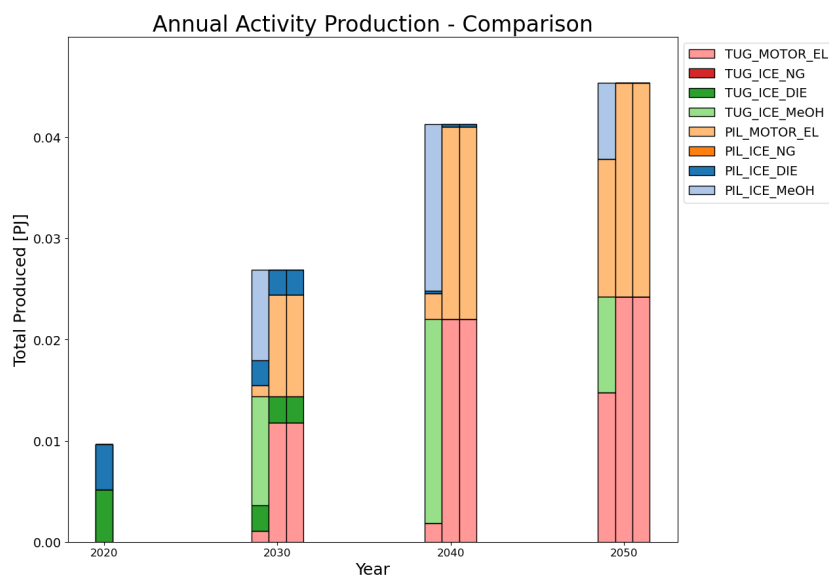


Figure 4.34: Total Annual Activity of Tugboats and Pilot Vessels - Scenarios BAU, 2 and 3 Comparison.

Cranes, comparison in Figure 4.35, and other cargo handling equipment, in Figure 4.36, evolution is more similar between scenarios, being the total electrification the most likely scenario by 2040. No major differences are registered between scenarios 2 and 3 on these technologies.

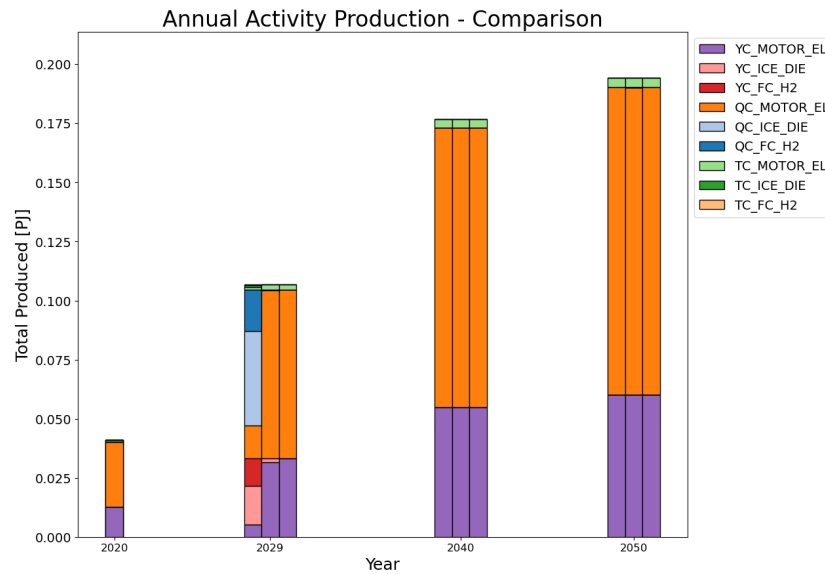


Figure 4.35: Total Annual Activity of Cranes - Scenarios BAU, 2 and 3 Comparison.

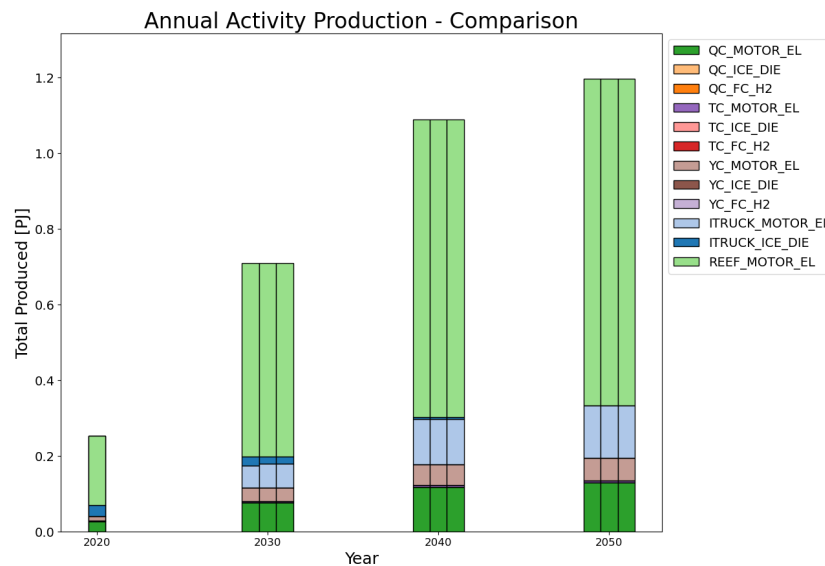


Figure 4.36: Total Annual Activity of Cargo Handling Equipment - Scenarios BAU, 2 and 3 Comparison.

The evolution of the ocean-going vessels' fleet influences the activity of our harbour crafts, namely bunker barge boats and also the on-shore power supply technology. The remaining activity, coming from tugboats, pilot vessels or cargo handling equipment is not included in this analysis, since these scenarios show, as expected, no changes in activity when compared to the business-as-usual scenario. The bunker barge boat activity, in Figure 4.37, is in line with the final energy demand of ocean-going vessels. Hence, these boats transport less heavy fuel oil in scenarios 4 and 5 and more of the other liquid fuels. On the other hand, on-shore power supply activity represents a higher share of the energy demand and gradually increases until 2050. The total activity differences from scenario to scenario are normal because this activity is presented in final energy, thus depending on the efficiency of the conversion technology. Also, the different transported fuels have different energy densities, which influences the transportation activity performed by bunker barge boats.

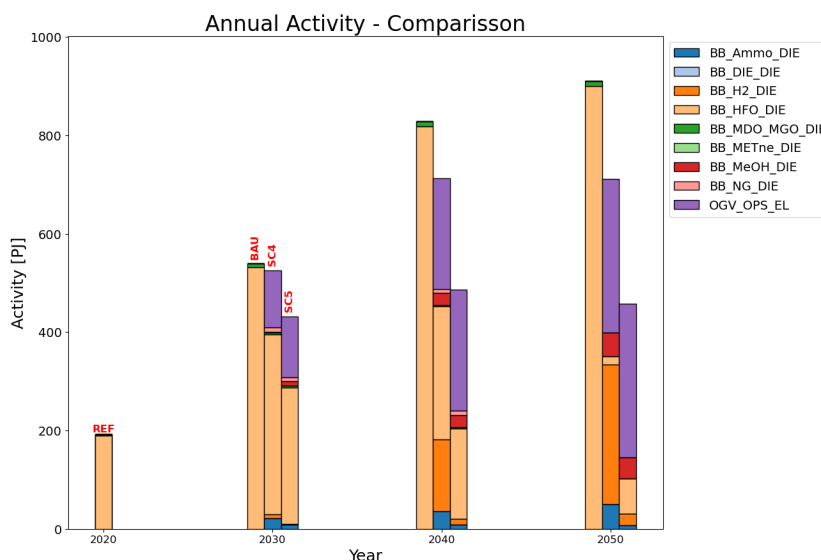


Figure 4.37: Total Annual Activity of Bunker Barge Boats and OPS Technology - Scenarios BAU, 4 and 5 Comparison.

4.2.2 Emissions

Emissions analysis requires a focus on the pollutants that the port's authority can control. Hence, initially, the fuel needs related to ocean-going vessels and the associated emissions are not considered in this analysis. Both the cap and tax on emissions are directed to CO₂ emissions and, thus, only those results are analysed.

When comparing the port emissions trajectory, visible in Figure 4.38, the expected electrification of the port's technologies as things stand is not sufficient to achieve carbon neutrality by 2050. When it comes to scenarios 2 and 3, emissions are reduced to a large extent in the first decade, but carbon neutrality is only achieved in the final years of our time interval. However, it is possible to conclude that a carbon tax mechanism can, indeed, act as an incentive to reduce emissions and achieve carbon neutrality by 2050.

The carbon intensity indicator demonstrates this emissions reduction. When compared to the BAU scenario, by 2030, the indicator registers a 96% decrease for scenario 2 (and 82% for SC 3). By 2050, given the total emissions reduction within the technologies controlled by the port, this indicator gets to zero.

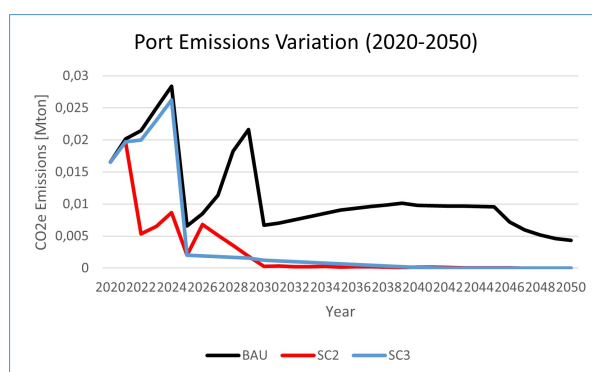


Figure 4.38: Port CO₂ Emissions - Scenario BAU, 2 and 3 Comparison.

The influence of ocean-going vessels' fuel is significant in the port total emissions, as Figure 4.39 illustrates. Decarbonising these vessels is crucial to fully minimize the impact of a container terminal within a city or a region. If, by 2050, as climate legislative regulations suggest, every ship uses a renewable fuel or electricity at berth, these emissions will be drastically reduced, which is proved in scenarios 4 or 5. The difference is the velocity of the emissions reduction. In a more ambitious and innovative scenario, represented by the red line, it is possible to achieve carbon neutrality more easily and, probably, faster. However, notice that emissions do not go down to zero. That is due to the emissions associated to the import of certain fuels, such as ammonia and methanol. As already mentioned, if these are not mandatory to be synthetic fuels, emissions are not fully reduced.

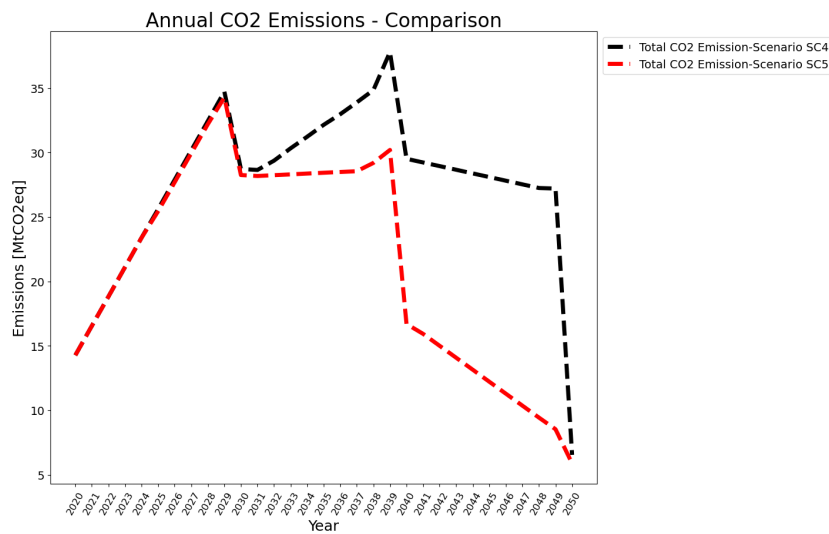


Figure 4.39: Total CO2 Emissions - Scenario 4 and 5 Comparison.

4.2.3 Costs

The analysis on the costs of scenarios 2 and 3 is first revealed. The results relative to total costs on electricity generation technologies, illustrated in Figure 4.40, disclose a peak of investment by 2040, in SC 2, related to the significant investment in local energy generation technologies, namely on photovoltaic and ocean thermal technologies. This peak is not present in SC 3 since this model has a lower installed capacity by 2030, while investing more in wind technologies, instead of photovoltaic. Another interesting aspect is that, by 2050, there are only fixed costs, related to the operation and maintenance needs and no investment in new technologies.

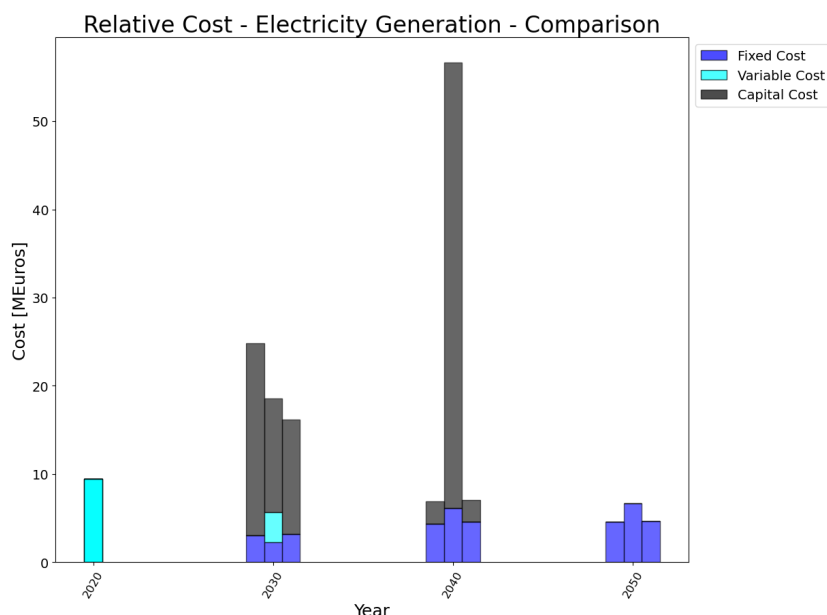


Figure 4.40: Capital, Fixed and Variable Costs of Electricity Generation - Scenarios BAU, 2 and 3 Comparison.

The investment in harbour crafts - only considering tugboats and pilot vessels - and in cargo handling equipment is similar, when considering the type of technologies and the sum of the costs throughout the time interval, for the three different scenarios, as observed in Figure 4.41.

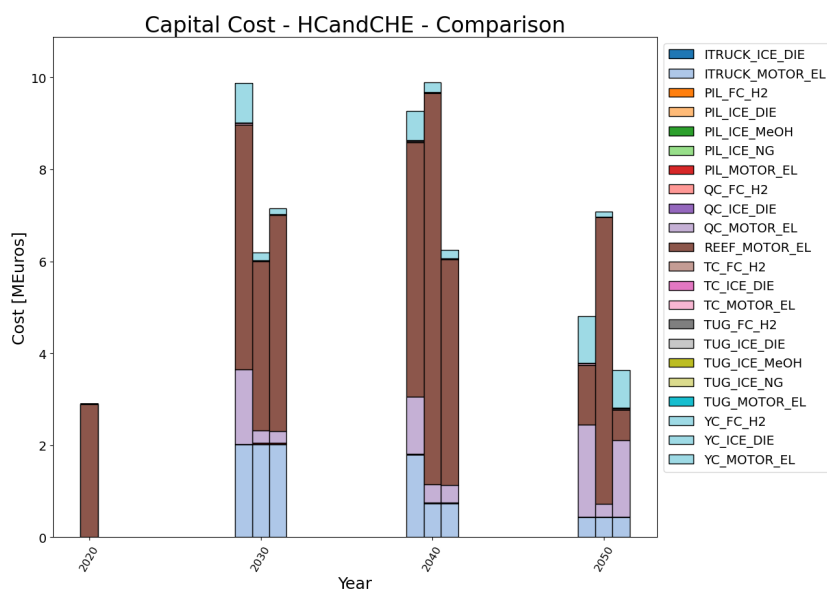


Figure 4.41: Capital, Fixed and Variable Costs of Harbour Crafts and Cargo Handling Equipment - Scenarios BAU, 2 and 3 Comparison.

Relatively to the comparison with scenarios 4 and 5, visible in Figures 4.42 and 4.43, the expenditure in the following decades in electricity generation capacity will grow considerably, once again reaching unrealistic figures. When it comes to import costs, the capital cost peak is associated to the green hydrogen demand, which implies an appropriate infrastructure and, hence, significant investment in pipelines.

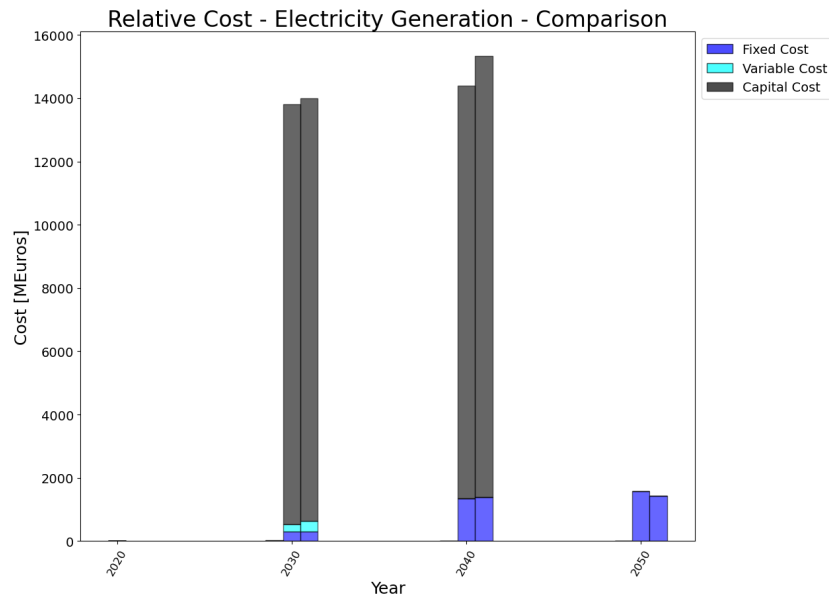


Figure 4.42: Capital, Fixed and Variable Costs of Electricity Generation Technologies - Scenarios BAU, 4 and 5 Comparison.

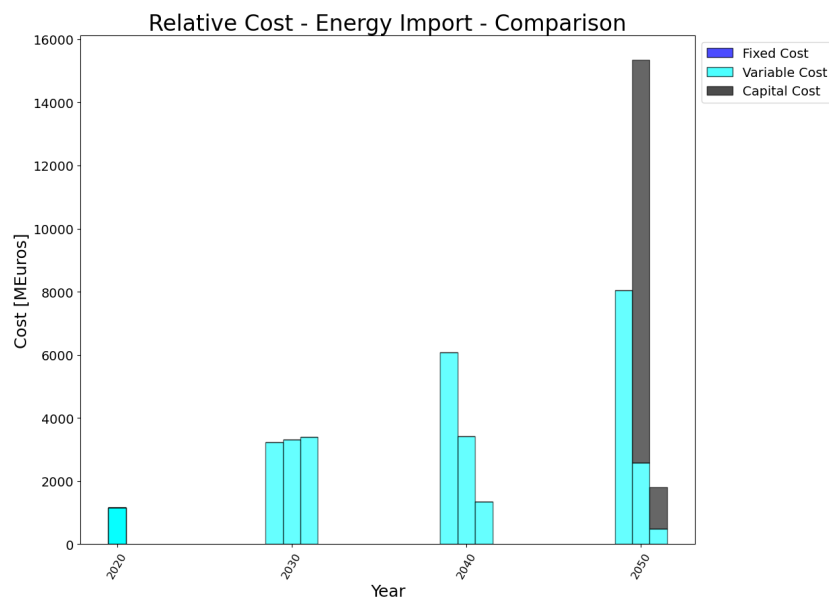


Figure 4.43: Capital, Fixed and Variable Costs of Energy Import Technologies - Scenarios BAU, 4 and 5 Comparison.

4.3 Replicability, Validation and Uncertainties

The data and method used here can be applied to different ports as well. The information concerning the case study applies only to Port of Sines. Due to a few imprecisions and uncertainties, it will still be relevant to improve and extend the existing maritime ports model.

The imprecisions here mentioned should be considered when analysing the results of this simulation. First, residual capacity should have remained until 2024 and only from then would phase out. Second, electrical technologies cost might have been underestimated, due to the use of retrofit

technologies and electric trucks as the characterization basis. Third, methanol and natural gas import costs may not refer to the same period of time, which affects the results, considering the constant price fluctuations. Finally, not all refuelling operations are performed necessarily by bunker barge boats, since it is also common to find stationary refuelling stations.

These imprecisions may have distorted the results. Nevertheless, the results are coherent, realistic and valid for a broader analysis.

Chapter 5

Conclusions

This section presents the main findings, the implications that this work has in port management, and policies for the decarbonization of ports. To conclude, some limitations and challenges are also addressed.

5.1 Summary of Main Findings

One of the primary goals of the thesis was to establish and construct an accurate, accessible and adaptable energy model that could be applied to maritime ports. The energy model was thoroughly developed, allowing for an appropriate energy use characterization of a port containers terminal and incorporating an end-use energy disaggregation, when possible. The attainment of this model was made possible by leveraging techno-economic data derived from the literature and by using certain assumptions and proxy technologies.

The other main objective was the application of the model to a case study of Port of Sines, defining the demand and applying real restrictions. Subsequently, this model was subjected to simulation within five distinct scenarios, each characterized by unique restrictions, with the goal of understanding how the system evolves from 2020 until 2050. Different energy transition pathways were analysed while identifying opportunities to improve energy efficiency in port operations.

The Business-As-Usual scenario depicts an evolution of Port of Sines where electrification is a possible and likely scenario. This suggests that electric solutions will likely offer superior cost-effectiveness in the upcoming decades, just as local renewable energy generation technologies. The significant increase in energy demand that is expected for the port will lead to a significant investment in new technologies, as a way of matching the demand. Even though port emissions are expected to decrease, if ocean-going vessels' demand is not considered, a total reduction in emissions requires a greater effort. By 2050, fossil fuels will still be used, carbon intensity indicator is expected to be around 13 g/kWh and, hence, carbon neutrality is not possible by maintaining the same action steps.

When the goal is to curtail GHG emissions and reach a zero carbon intensity indicator, with a focus on the port's authority scope, the system invariably leans towards investing more and more rapidly in electrical technologies and renewable energy sources. In the context of local energy production, the prevailing technology utilized was onshore wind generation, which experienced growth over the years. Additionally, alternative conversion technologies such as photovoltaic, ocean thermal or wave energy were also employed to a lesser extent. Hydrogen cranes and the respective alkaline and solid oxide electrolyzers are adopted but not as long-lasting solutions.

A carbon tax is revealed to be an efficient mechanism to incentivise to emissions reduction while

meeting the demand requirements. The decarbonization trajectory imposed by the several legislative packages implied, although, a significant and fast investment in the Port of Sines, especially in electricity generation technologies.

However, the total emissions of a port depend, mainly, on the ocean-going vessels fleet, despite these being not dependent on a port's authority efforts. A key insight from the outcomes of the fourth and fifth scenarios, wherein the model has to adapt to different ocean-going vessels' energy demands, is the immense capacity that has to be installed, either locally or as an import. There are physical limitations that are not fully considered in this model and, hence, the profile of local energy generation technologies must be more diverse, while reinforcing the electrical grid connections. In addition, it must be assured that the fuels produced or imported, by 2050, are synthetic fuels. As for electricity or hydrogen, both have to be green.

5.2 Limitations and Future work

Attending to the complexity of the work that was carried out and the overall goals of this dissertation, the time interval given to the work in hand, i.e., the elaboration of an energy model system for a port, was rather short. For that reason, several assumptions had to be defined and the system was simplified.

Energy models play a crucial role for governments and policymakers by helping improve energy efficiency, manage demand, and optimize the costs of energy systems. However, these models still have limitations, mainly related to the techno-economic data characterization.

The lack of information available in the literature meant that a meticulous characterization of the technologies was not always possible and simplifications and proxy technologies had to be used. Furthermore, a considerable portion of this data is predictive in nature, which means its accuracy might not always be optimal.

Thus, some caution must be exercised when interpreting the results, as the model does not account for certain limitations.

Attending the comprehensive nature of this topic and the time constraints, certain aspects warrant further exploration in the future. Hence, valuable contributions can improve the existing model and make it even more comprehensive, such as:

- Extend the model scope to allow the study of energy consumption and efficiency of port operations. Other pollutants, such as methane, can also be a valuable addition, to analyse the natural gas use effect.
- Incorporate additional and updated data throughout the port energy chain, ensuring enhanced reliability and consistency, to minimize the effect of certain imprecisions.
- Integrate additional technologies, either in the model or in the use-case. In a case study, reach stackers and empty container handlers can be included, while the model can be even more comprehensive with the addition of hybrid technologies. Supplementary fuels can also be added to clarify the distinction between, for instance, biogas and natural gas, when defining the ocean-going vessels final energy demand.

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Appendix A

OSeMOSYS Structure Description

A.1 Parameters and Variables

The following tables, Tables A.1 and A.2, present the main parameters and variables involved in this simulation model.

Table A.1: List of OSeMOSYS main parameters and a brief description of each.

Parameter Name	Description
YearSplit [l,y]	Duration of a modelled time slice, expressed as a fraction of the year. The sum of each entry over one modelled year should equal 1.
DaySplit [lh,y]	Length of one DailyTimeBracket in one specific day as a fraction of the year (e.g., when distinguishing between days and night).
SpecifiedAnnualDemand [r,f,y]	Total specified demand for the year, linked to a specific 'time of use' during the year.
SpecifiedDemandProfile [r,f,l,y]	Annual fraction of energy-service or commodity demand that is required in each time slice. For each year, all the defined SpecifiedDemandProfile input values should sum up to 1.
AccumulatedAnnualDemand [r,f,y]	Accumulated Demand for a certain commodity in one specific year. It cannot be defined for a commodity if its SpecifiedAnnualDemand for the same year is already defined and vice versa.
CapacityToActivityUnit [r,t]	Conversion factor relating the energy that would be produced when one unit of capacity is fully used in one year.
CapacityFactor [r,t,l,y]	Capacity available per each TimeSlice expressed as a fraction of the total installed capacity, with values ranging from 0 to 1. It gives the possibility to account for forced outages.
AvailabilityFactor [r,t,y]	Maximum time a technology can run in the whole year, as a fraction of the year ranging from 0 to 1. It gives the possibility to account for planned outages.
OperationalLife [r,t]	Useful lifetime of a technology, expressed in years.
ResidualCapacity [r,t,y]	Remained capacity available from before the modelling period.
InputActivityRatio [r,t,f,m,y]	Rate of use of a commodity by a technology, as a ratio of the rate of activity.
OutputActivityRatio [r,t,f,m,y]	Rate of commodity output from a technology, as a ratio of the rate of activity.
CapitalCost [r,t,y]	Capital investment cost of a technology, per unit of capacity.
VariableCost [r,t,m,y]	Cost of a technology for a given mode of operation (Variable O and M cost), per unit of activity.
FixedCost [r,t,y]	Fixed O and M cost of a technology, per unit of capacity.
TotalAnnualMaxCapacity [r,t,y]	Total maximum existing (residual plus cumulatively installed) capacity allowed for a technology in a specified year.
EmissionActivityRatio [r,t,e,m,y]	Emission factor of a technology per unit of activity, per mode of operation.
EmissionsPenalty [r,e,y]	Penalty per unit of emission.

Table A.2: List of OSeMOSSYS main variables and a brief description of each.

Variable Name	Description
Demand [r,l,f,y]	Demand for one fuel in one time slice.
NewCapacity [r,t,y]	Newly installed capacity of technology t in year y.
AccumulatedNewCapacity [r,t,y]	Cumulative newly installed capacity of technology t from the beginning of the time domain to year y.
TotalCapacityAnnual [r,t,y]	Total existing capacity of technology t in year y (sum of cumulative newly installed and pre-existing capacity).
RateOfActivity [r,l,t,m,y]	Intermediate variable. It represents the activity of technology t in one mode of operation and in time slice l, if the latter lasted the whole year.
TotalTechnologyAnnualActivity [r,t,y]	Total annual activity of technology t.
TotalAnnualTechnologyActivityByMode [r,t,m,y]	Annual activity of technology t in mode of operation m.
RateOfProduction [r,l,f,y]	Sum of the RateOfProductionByTechnology over all the technologies.
RateOfProductionByTechnology [r,l,t,f,y]	Sum of the RateOfProductionByTechnologyByMode over the modes of operation. Intermediate variable. It represents the quantity of fuel f that technology t would produce in one mode of operation and in time slice l, if the latter lasted the whole year. It is a function of the variable RateOfActivity and the parameter OutputActivityRatio.
RateOfProductionByTechnologyByMode [r,l,t,m,f,y]	
CapitalInvestment [r,t,y]	Undiscounted investment in new capacity of technology t. It is a function of the NewCapacity and the parameter CapitalCost.
OperatingCost [r,t,y]	Undiscounted sum of the annual variable and fixed operating costs of technology t.
AnnualVariableOperatingCost [r,t,y]	Annual variable operating cost of technology t. Derived from the TotalAnnualTechnologyActivityByMode and the parameter VariableCost.
AnnualFixedOperatingCost [r,t,y]	Annual fixed operating cost of technology t. Derived from the TotalCapacityAnnual and the parameter FixedCost.
AnnualTechnologyEmissionByMode [r,t,e,m,y]	Annual emission of agent e by technology t in mode of operation m. Derived from the RateOfActivity and the parameter EmissionActivityRatio.
AnnualTechnologyEmissionPenaltyByEmission [r,t,e,y]	Undiscounted annual cost of emission e by technology t. It is a function of the AnnualTechnologyEmission and the parameter EmissionPenalty.

Appendix B

List of Technologies and Fuels

The following tables show the technologies and fuels, with the respective code names considered in the simulation model.

B.1 Technologies

Table B.1, presented below, lists the technologies used in the simulation model.

Table B.1: Simulation Model - List of Technologies.

Name	Description
NG_Import	Natural Gas Imports
DIE_Import	Diesel Imports
EL_Import	Electricity Imports
Ammo_Import	Ammonia Imports
MeOH_Import	Methanol Imports
METne_Import	Methane Imports
MDO_MGO_Import	Marine Diesel Oil and Marine Gas Oil Imports
HFO_Import	Heavy Fuel Oil Imports
GreenH2_Import	Green Hydrogen Imports
H2_Import	Hydrogen Imports
BG_Import	Biogas Imports
Biomass_Extraction	Biomass Production
WS_Extraction	Residues Production
WS_Gasifier	Gasifier
NG_CHP	Natural Gas Cogeneration Plant
BG_CHP	Biogas Cogeneration Plant
Biomass_CHP	Biomass Cogeneration Plant
PV_Floating_PP	PV Centralised Generation Site
PV_PP	PV Centralised Generation Site
Wave_PP	Wave Generation Installation
Tides_PP	Wave Generation Installation
Ocean_Thermal_PP	Ocean Thermal Energy Installation
Wind_PP	Onshore Wind Large Installation
WindOff_PP	Offshore Wind Large Installation

Table B.1: Simulation Model - List of Technologies.

Name	Description
H2_SMR	Production of Hydrogen via Steam Reforming
H2_PEM	Production of Hydrogen via PEM Electrolysis
H2_ALK	Production of Hydrogen via Electrolysis (ALKALINE)
H2_SMR_CCS	Production of H2 via Steam Methane Reforming w/ Carbon Capture and Storage Technology
H2_SolidOxy	Production of Hydrogen via Electrolysis (Solid Oxide)
E-MeOH_Syn	Synthesizer for E-Methanol Production
MeOH_Gas	Gasifier for Methanol Production
E-DIE_Syn	Synthesizer for E-Diesel Production
METne_Gas	Gasifier for Methane Production
E-METne_Syn	Synthesizer for E-Methane Production
E-Ammono_Syn	Synthesizer for E-Ammonia Production
TD_EL	Electricity Transmission and Distribution
TD_DIE	Diesel Transmission and Distribution
TD_NG	Natural Gas Transmission and Distribution
TD_H2	Hydrogen Transmission and Distribution
TD_Ammo	Ammonia Transmission and Distribution
TD_MeOH	Methanol Transmission and Distribution
TD_MDO_MGO	MDO and MGO Transmission and Distribution
TD_HFO	Supply of HFO
TD_Heat	Heat Transmission and Distribution
TD_EL_SRD	T&D of Electricity to supply the Storage and Receipt-Delivery area
TD_DIE_SRD	T&D of Diesel to supply the Storage and Receipt-Delivery area
TD_NG_SRD	T&D of Natural Gas to supply the Storage and Receipt-Delivery area
TD_H2_SRD	T&D of Hydrogen to supply the Storage and Receipt-Delivery area
TD_EL_OGV	Transmission and Distribution of Electricity to supply an OGV
TD_DIE_OGV	Transmission and Distribution of Diesel to supply an OGV
TD_NG_OGV	Transmission and Distribution of Natural Gas to supply an OGV
TD_H2_OGV	Transmission and Distribution of Hydrogen to supply an OGV

Table B.1: Simulation Model - List of Technologies.

Name	Description
TD_Ammo_OGV	Transmission and Distribution of Ammonia to supply an OGV
TD_MeOH_OGV	Transmission and Distribution of Methanol to supply an OGV
TD_MDO_MGO_OGV	Transmission and Distribution of MDO/MGO to supply an OGV
TD_HFO_OGV	Transmission and Distribution of HFO to supply an OGV
TD_EL_TUG	Transmission and Distribution of Electricity to supply a Tugboat
TD_DIE_TUG	Transmission and Distribution of Diesel to supply a Tugboat
TD_NG_TUG	Transmission and Distribution of Natural Gas to supply a Tugboat
TD_H2_TUG	Transmission and Distribution of Hydrogen to supply a Tugboat
TD_Ammo_TUG	Transmission and Distribution of Ammonia to supply a Tugboat
TD_MeOH_TUG	Transmission and Distribution of Methanol to supply a Tugboat
TD_EL_PIL	Transmission and Distribution of Electricity to supply a Pilot Boat
TD_DIE_PIL	Transmission and Distribution of Diesel to supply a Pilot Boat
TD_NG_PIL	Transmission and Distribution of Natural Gas to supply a Pilot Boat
TD_H2_PIL	Transmission and Distribution of Hydrogen to supply a Pilot Boat
TD_Ammo_PIL	Transmission and Distribution of Ammonia to supply a Pilot Boat
TD_MeOH_PIL	Transmission and Distribution of Methanol to supply a Pilot Boat

Table B.1: Simulation Model - List of Technologies.

Name	Description
TD_EL_BB	Transmission and Distribution of Electricity to supply a Bunker Barge Boat
TD_DIE_BB	Transmission and Distribution of Diesel to supply a Bunker Barge Boat
TD_NG_BB	Transmission and Distribution of Natural Gas to supply a Bunker Barge Boat
TD_H2_BB	Transmission and Distribution of Hydrogen to supply a Bunker Barge Boat
TD_Ammo_BB	Transmission and Distribution of Ammonia to supply a Bunker Barge Boat
TD_MeOH_BB	Transmission and Distribution of Methanol to supply a Bunker Barge Boat
TD_EL_QC	Transmission and Distribution of Electricity to supply a Quay Crane
TD_DIE_QC	Transmission and Distribution of Diesel to supply a Quay Crane
TD_H2_QC	Transmission and Distribution of Hydrogen to supply a Quay Crane
TD_EL_ITRUCK	Transmission and Distribution of Electricity to supply a Truck
TD_DIE_ITRUCK	Transmission and Distribution of Diesel to supply a Truck
TD_NG_ITRUCK	Transmission and Distribution of Natural Gas to supply a Truck
TD_H2_ITRUCK	Transmission and Distribution of Hydrogen to supply a Truck
TD_MeOH_ITRUCK	Transmission and Distribution of Methanol to supply a Truck
TD_Ammo_ITRUCK	Transmission and Distribution of Ammonia to supply a Truck
TD_EL_REEF	Transmission and Distribution of Electricity to supply a Reefer

Table B.1: Simulation Model - List of Technologies.

Name	Description
TD_EL_YC	Transmission and Distribution of Electricity to supply a Yard Crane
TD_DIE_YC	Transmission and Distribution of Diesel to supply a Yard Crane
TD_H2_YC	Transmission and Distribution of Hydrogen to supply a Yard Crane
TD_EL_FL	Transmission and Distribution of Electricity to supply a Forklift
TD_DIE_FL	Transmission and Distribution of Diesel to supply a Forklift
TD_NG_FL	Transmission and Distribution of Natural Gas to supply a Forklift
TD_H2_FL	Transmission and Distribution of Hydrogen to supply a Forklift
TD_EL_RS	Transmission and Distribution of Electricity to supply a Reach Stacker
TD_DIE_RS	Transmission and Distribution of Diesel to supply a Reach Stacker
TD_NG_RS	Transmission and Distribution of Natural Gas to supply a Reach Stacker
TD_H2_RS	Transmission and Distribution of Hydrogen to supply a Reach Stacker
TD_EL_ECH	Transmission and Distribution of Electricity to supply a ECH
TD_DIE_ECH	Transmission and Distribution of Diesel to supply a ECH
TD_NG_ECH	Transmission and Distribution of Natural Gas to supply a ECH
TD_H2_ECH	Transmission and Distribution of Hydrogen to supply a ECH
TD_EL_ETRUCK	Transmission and Distribution of Electricity to supply a Truck

Table B.1: Simulation Model - List of Technologies.

Name	Description
TD_DIE_ETRUCK	Transmission and Distribution of Diesel to supply a Truck
TD_NG_ETRUCK	Transmission and Distribution of Natural Gas to supply a Truck
TD_H2_ETRUCK	Transmission and Distribution of Hydrogen to supply a Truck
TD_MeOH_ETRUCK	Transmission and Distribution of Methanol to supply a Truck
TD_Ammo_ETRUCK	Transmission and Distribution of Ammonia to supply a Truck
TD_EL_LOC	Transmission and Distribution of Electricity to supply a Shunt Locomotive
TD_DIE_LOC	Transmission and Distribution of Diesel to supply a Shunt Locomotive
TD_H2_LOC	Transmission and Distribution of Hydrogen to supply a Shunt Locomotive
TD_EL_TC	Transmission and Distribution of Electricity to supply a Train Terminal Crane
TD_DIE_TC	Transmission and Distribution of Diesel to supply a Train Terminal Crane
TD_H2_TC	Transmission and Distribution of Hydrogen to supply a Train Terminal Crane
TD_EL_TRAIN	Transmission and Distribution of Electricity to supply a Train
TD_DIE_TRAIN	Transmission and Distribution of Diesel to supply a Train
TD_H2_TRAIN	Transmission and Distribution of Hydrogen to supply a Train
OGV_OPS_EL	Onshore Power Supply to a EL OGV
BB_DIE_H2	Diesel Supply using a H2 FC Bunker Barge Boat
BB_NG_H2	Natural Gas Supply using a H2 FC Bunker Barge Boat
BB_H2_H2	H2 Supply using a H2 FC Bunker Barge Boat

Table B.1: Simulation Model - List of Technologies.

Name	Description
BB_Ammo_H2	Ammonia Supply using a H2 FC Bunker Barge Boat
BB_MeOH_H2	Methanol Supply using a H2 FC Bunker Barge Boat
BB_MDO_MGO_H2	MDO or MGO Supply using a H2 FC Bunker Barge Boat
BB_HFO_H2	HFO Supply using a H2 FC Bunker Barge Boat
BB_DIE_DIE	Diesel Supply using a Diesel ICE Bunker Barge Boat
BB_NG_DIE	Natural Gas Supply using a Diesel ICE Bunker Barge Boat
BB_DIE_DIE	H2 Supply using a Diesel ICE Bunker Barge Boat
BB_Ammo_DIE	Ammonia Supply using a Diesel ICE Bunker Barge Boat
BB_MeOH_DIE	Methanol Supply using a Diesel ICE Bunker Barge Boat
BB_MDO_MGO_DIE	MDO or MGO Supply using a Diesel ICE Bunker Barge Boat
BB_HFO_DIE	HFO Supply using a Diesel ICE Bunker Barge Boat
BB_DIE_NG	Diesel Supply using a Natural Gas ICE Bunker Barge Boat
BB_NG_NG	Natural Gas Supply using a Natural Gas ICE Bunker Barge Boat
BB_H2_NG	H2 Supply using a Natural Gas ICE Bunker Barge Boat
BB_Ammo_NG	Ammonia Supply using a Natural Gas ICE Bunker Barge Boat
BB_MeOH_NG	Methanol Supply using a Natural Gas ICE Bunker Barge Boat
BB_MDO_MGO_NG	MDO or MGO Supply using a Natural Gas ICE Bunker Barge Boat
BB_HFO_NG	HFO Supply using a Natural Gas ICE Bunker Barge Boat
TUG_MOTOR_EL	Electric Motor of a Tugboat
TUG_ICE_NG	Natural Gas ICE of a Tugboat
TUG_ICE_DIE	Diesel ICE of a Tugboat
TUG_FC_H2	Hydrogen FC of a Tugboat
TUG_ICE_Ammo	Ammonia ICE of a Tugboat
TUG_ICE_MeOH	Methanol ICE of a Tugboat
PIL_MOTOR_EL	Electric Motor of a Pilot Boat
PIL_ICE_NG	Natural Gas ICE of a Pilot Boat
PIL_ICE_DIE	Diesel ICE of a Pilot Boat
PIL_FC_H2	Hydrogen FC of a Pilot Boat
PIL_ICE_Ammo	Ammonia ICE of a Pilot Boat
PIL_ICE_MeOH	Methanol ICE of a Pilot Boat
QC_MOTOR_EL	Electric Motor of a Quay Crane
QC_ICE_DIE	Diesel ICE of a QC
QC_FC_H2	H2 FC of a QC
PUMP_MOTOR_EL	Electric Pump
ITRUCK_MOTOR_EL	Electric Motor of an Internal Truck
ITRUCK_ICE_NG	Natural Gas ICE of an Internal Truck
ITRUCK_ICE_DIE	Diesel ICE of an Internal Truck
ITRUCK_FC_H2	Hydrogen FC of an Internal Truck
ITRUCK_ICE_Ammo	Ammonia ICE of an Internal Truck
ITRUCK_ICE_MeOH	Methanol ICE of an Internal Truck
CS_MOTOR_EL	Electrical Motor of a Conveyor System
CS_ICE_DIE	Diesel ICE of a Conveyor System
REEF_MOTOR_EL	Electrical Motor of a Refrigerated Container
YC_MOTOR_EL	Electric Motor of a Yard Crane
YC_ICE_DIE	Diesel ICE of a YC
YC_FC_H2	H2 FC of a YC

Table B.1: Simulation Model - List of Technologies.

Name	Description
FL_MOTOR_EL	Electric Motor of a Forklift
FL_ICE_NG	Natural Gas ICE of a Forklift
FL_ICE_DIE	Diesel ICE of a Forklift
FL_FC_H2	Hydrogen FC of a Forklift
RS_MOTOR_EL	Electric Motor of a Reach Stacker
RS_ICE_NG	Natural Gas ICE of a Reach Stacker
RS_ICE_DIE	Diesel ICE of a Reach Stacker
RS_FC_H2	Hydrogen FC of a Reach Stacker
ECH_MOTOR_EL	Electric Motor of a Empty Container Handler
ECH_ICE_NG	Natural Gas ICE of a Empty Container Handler
ECH_ICE_DIE	Diesel ICE of a Empty Container Handler
ECH_FC_H2	Hydrogen FC of a Empty Container Handler
ETRUCK_MOTOR_EL	Electric Motor of an External Truck
ETRUCK_ICE_NG	Natural Gas ICE of an External Truck
ETRUCK_ICE_DIE	Diesel ICE of an External Truck
ETRUCK_FC_H2	Hydrogen FC of an External Truck
ETRUCK_ICE_Ammo	Ammonia ICE of an External Truck
ETRUCK_ICE_MeOH	Methanol ICE of an External Truck
LOC_MOTOR_EL	Electric Motor of a Shunt Locomotive
LOC_ICE_DIE	Diesel ICE of a Shunt Locomotive
LOC_FC_H2	H2 FC of a Shunt Locomotive
TC_MOTOR_EL	Electric Motor of a Rail Mounted Gantry Cranes (Train Crane)
TC_ICE_DIE	Diesel ICE of a Rail Mounted Gantry Cranes
TC_FC_H2	H2 FC of a Rail Mounted Gantry Cranes
TRAIN_MOTOR_EL	Electric Motor of a Train
TRAIN_ICE_DIE	Diesel ICE of a Train
TRAIN_FC_H2	H2 FC of a Train

B.2 Fuels

Table B.2, presented below, lists every fuel used in the simulation model, alongside with a description and the respective group, when suitable.

Table B.2: Simulation Model - List of Fuels.

Name	Description	Group
NG_PE	Natural Gas Primary Source	Primary sources
EL_PE	Electricity Primary Source	Primary sources
EL_Green_PE	Electricity with a Guarantee of Origin	Primary sources
BG_PE	Biomethane Primary Source	Primary sources
BIOMASS_PE	Biomass Primary Source	Primary sources
WS_PE	Residues Primary Source	Primary sources
MDO_MGO	Marine Diesel Oil or Marine Gas Oil	Secondary sources
HFO	Heavy Fuel Oil	Secondary sources
Heat	Distributed Heat from PP to Transmission Level	Secondary sources
H2	Hydrogen Primary Source	Secondary sources

Table B.2: Simulation Model - List of Fuels.

Name	Description	Group
GreenH2	H2 Produced with green electricity	Secondary sources
DIE	Diesel	Secondary sources
E-DIE	E-Diesel	Secondary sources
Ammo	Ammonia	Secondary sources
SynMeOH	E-Methanol at the end-user level	Secondary sources
MeOH	Methanol	Secondary sources
METne	Methane	Secondary sources
NG_FE	Natural Gas at the end-user level	Final energy
DIE_FE	Diesel at the end-user level	Final energy
EL_FE	Electricity at the end-user level	Final energy
Ammo_FE	Ammonia at the end-user level	Final energy
MeOH_FE	Methanol at the end-user level	Final energy
MDO_MGO_FE	MDO_MGO at the end-user level	Final energy
HFO_FE	HFO at the end-user level	Final energy
H2_FE	H2 at the end-user level	Final energy
Heat_FE	Heat at the end-user level	Final energy
EL_FE_SRD	Electricity Demand for the Storage and Receipt Delivery Area	
DIE_FE_SRD	Diesel Demand for the Storage and Receipt Delivery Area	
NG_FE_SRD	Natural Gas Demand for the Storage and Receipt Delivery Area	
H2_FE_SRD	Hydrogen Demand for the Storage and Receipt Delivery Area	
EL_TD_OGV	Electricity Transmission and Distribution for OGV	
DIE_TD_OGV	Diesel Transmission and Distribution for OGV	
NG_TD_OGV	Natural Gas Transmission and Distribution for OGV	
H2_TD_OGV	Hydrogen Transmission and Distribution for OGV	
Ammo_TD_OGV	Ammonia Transmission and Distribution for OGV	
MeOH_TD_OGV	Methanol Transmission and Distribution for OGV	
MDO_MGO_TD_OGV	MDO/MGO Transmission and Distribution for OGV	
HFO_TD_OGV	HFO Transmission and Distribution for OGV	
EL_TD_TUG	Electricity Transmission and Distribution for Tugboats	
DIE_TD_TUG	Diesel Transmission and Distribution for Tugboats	
NG_TD_TUG	Natural Gas Transmission and Distribution for Tugboats	
H2_TD_TUG	Hydrogen Transmission and Distribution for Tugboats	
Ammo_TD_TUG	Ammonia Transmission and Distribution for Tugboats	
MeOH_TD_TUG	Methanol Transmission and Distribution for Tugboats	
EL_TD_PIL	Electricity Transmission and Distribution for Pilot Boats	
DIE_TD_PIL	Diesel Transmission and Distribution for Pilot Boats	
NG_TD_PIL	Natural Gas Transmission and Distribution for Pilot Boats	
H2_TD_PIL	Hydrogen Transmission and Distribution for Pilot Boats	
Ammo_TD_PIL	Ammonia Transmission and Distribution for Pilot Boats	
MeOH_TD_PIL	Methanol Transmission and Distribution for Pilot Boats	
EL_TD_BB	Electricity Transmission and Distribution for Bunker Barge Boats	
DIE_TD_BB	Diesel Transmission and Distribution for Bunker Barge Boats	
NG_TD_BB	Natural Gas Transmission and Distribution for Bunker Barge Boats	
H2_TD_BB	Hydrogen Transmission and Distribution for Bunker Barge Boats	
Ammo_TD_BB	Ammonia Transmission and Distribution for Bunker Barge Boats	

Table B.2: Simulation Model - List of Fuels.

Name	Description	Group
MeOH_TD_BB	Methanol Transmission and Distribution for Bunker Barge Boats	
EL_TD_QC	Electricity Transmission and Distribution for Quay Crane	
DIE_TD_QC	Diesel Transmission and Distribution for Quay Crane	
H2_TD_QC	Hydrogen Transmission and Distribution for Quay Crane	
EL_TD_ITRUCK	Electricity Transmission and Distribution for Trucks	
DIE_TD_ITRUCK	Diesel Transmission and Distribution for Trucks	
NG_TD_ITRUCK	Natural Gas Transmission and Distribution for Trucks	
H2_TD_ITRUCK	Hydrogen Transmission and Distribution for Trucks	
MeOH_TD_ITRUCK	Methanol Transmission and Distribution for Trucks	
Ammono_TD_ITRUCK	Ammonia Transmission and Distribution for Trucks	
EL_TD_SRD_REEF	Electricity Transmission and Distribution for Reefers	
EL_TD_SRD_YC	Electricity Transmission and Distribution for Yard Cranes	
DIE_TD_SRD_YC	Diesel Transmission and Distribution for Yard Cranes	
H2_TD_SRD_YC	Hydrogen Transmission and Distribution for Yard Cranes	
EL_TD_SRD_FL	Electricity Transmission and Distribution for Forklifts	
DIE_TD_SRD_FL	Diesel Transmission and Distribution for Forklifts	
NG_TD_SRD_FL	Natural Gas Transmission and Distribution for Forklifts	
H2_TD_SRD_FL	Hydrogen Transmission and Distribution for Forklifts	
EL_TD_SRD_RS	Electricity Transmission and Distribution for Reach Stackers	
DIE_TD_SRD_RS	Diesel Transmission and Distribution for Reach Stackers	
NG_TD_SRD_RS	Natural Gas Transmission and Distribution for Reach Stackers	
H2_TD_SRD_RS	Hydrogen Transmission and Distribution for Reach Stackers	
EL_TD_SRD_ECH	Electricity Transmission and Distribution for ECH	
DIE_TD_SRD_ECH	Diesel Transmission and Distribution for ECH	
NG_TD_SRD_ECH	Natural Gas Transmission and Distribution for ECH	
H2_TD_SRD_ECH	Hydrogen Transmission and Distribution for ECH	
EL_TD_ETRUCK	Electricity Transmission and Distribution for Trucks	
DIE_TD_ETRUCK	Diesel Transmission and Distribution for Trucks	
NG_TD_ETRUCK	Natural Gas Transmission and Distribution for Trucks	
H2_TD_ETRUCK	Hydrogen Transmission and Distribution for Trucks	
MeOH_TD_ETRUCK	Methanol Transmission and Distribution for Trucks	
Ammono_TD_ETRUCK	Ammonia Transmission and Distribution for Trucks	
EL_TD_LOC	Electricity Transmission and Distribution for Shunt Locomotives	
DIE_TD_LOC	Diesel Transmission and Distribution for Shunt Locomotives	
H2_TD_LOC	Hydrogen Transmission and Distribution for Shunt Locomotives	
EL_TD_TC	Electricity Transmission and Distribution for Train Terminal Cranes	
DIE_TD_TC	Diesel Transmission and Distribution for Train Terminal Cranes	
H2_TD_TC	Hydrogen Transmission and Distribution for Train Terminal Cranes	
EL_TD_TRAIN	Electricity Transmission and Distribution for Trains	
DIE_TD_TRAIN	Diesel Transmission and Distribution for Trains	
H2_TD_TRAIN	Hydrogen Transmission and Distribution for Trains	
OGV_EL	OGV Electricity Demand	FE OGV
OGV_DIE	OGV Diesel Demand	FE OGV
OGV_NG	OGV NG Demand	FE OGV
OGV_H2	OGV H2 Demand	FE OGV
OGV_Ammo	OGV Ammonia Demand	FE OGV
OGV_MeOH	OGV Methanol Demand	FE OGV

Table B.2: Simulation Model - List of Fuels.

Name	Description	Group
OGV_MDO_MGO	OGV MDO/MGO Demand	FE OGV
OGV_HFO	OGV HFO Demand	FE OGV
TUG_MDRIVE	Tugboat Machine Drive	Useful Energy
PIL_MDRIVE	Pilot Boat Machine Drive	Useful Energy
QC_MDRIVE	Quay Crane Machine Drive	Useful Energy
ITRUCK_MDRIVE	Truck Machine Drive	Useful Energy
SRD_REEF_MDRIVE	Reefer Machine Drive	Useful Energy
SRD_YC_MDRIVE	Yard Crane Machine Drive	Useful Energy
SRD_FL_MDRIVE	Forklift Machine Drive	Useful Energy
SRD_RS_MDRIVE	Reach Stacker Machine Drive	Useful Energy
SRD_ECH_MDRIVE	ECH Machine Drive	Useful Energy
ETRUCK_MDRIVE	Truck Machine Drive	Useful Energy
LOC_MDRIVE	Shunt Locomotive Machine Drive	Useful Energy
TC_MDRIVE	Train Terminal Crane Machine Drive	Useful Energy
TRAIN_MDRIVE	Train Machine Drive	Useful Energy

Appendix C

Reference Energy System - Diagram

The parts of our reference energy system missing in the main body of this thesis are presented here. Hence, the following energy flow diagrams are here listed: pilot vessels (Figure C.1), reefers, yard cranes and forklifts (Figure C.2), reach stackers and empty container handlers (Figure C.3), external trucks, shunt locomotives and train terminal cranes (Figure C.4) and, finally, trains (Figure C.5).

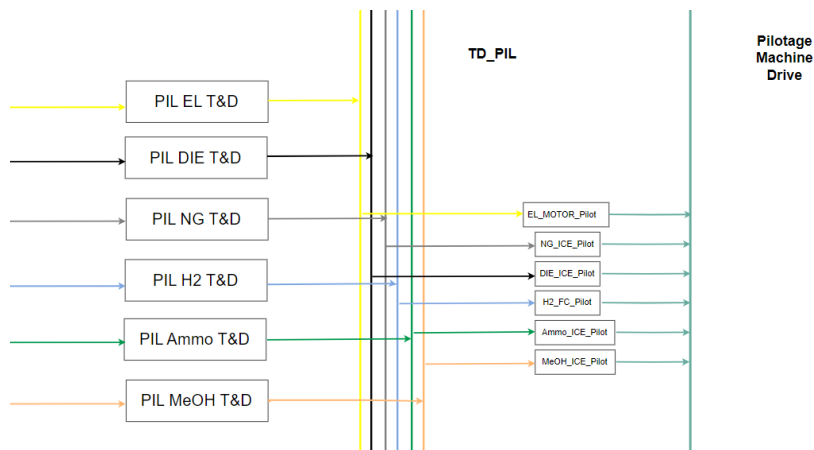


Figure C.1: REF - Pilot Vessels.

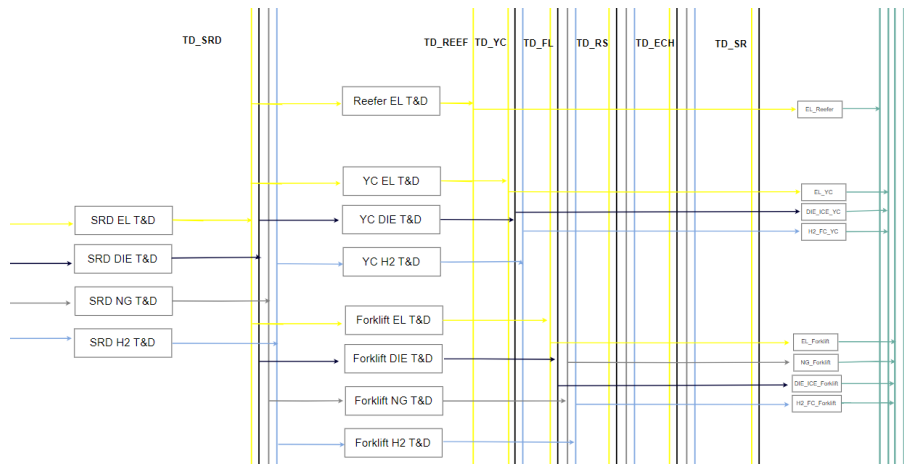


Figure C.2: REF - Reefers, Yard Cranes and Forklifts.

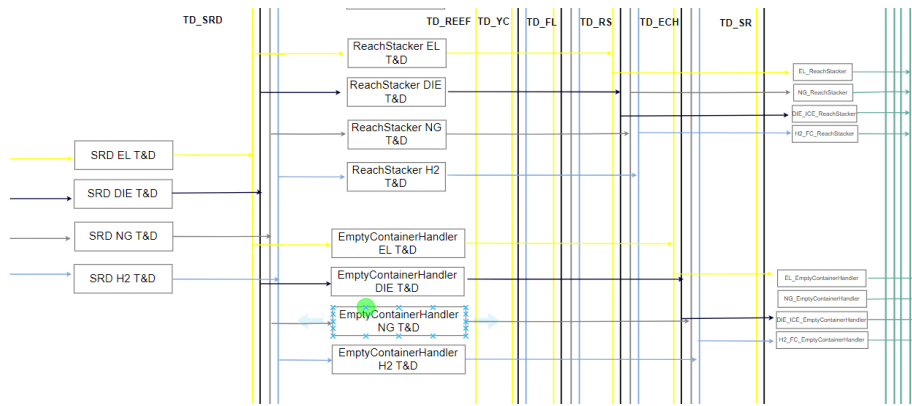


Figure C.3: REF - Reach Stackers and Empty Container Handlers.

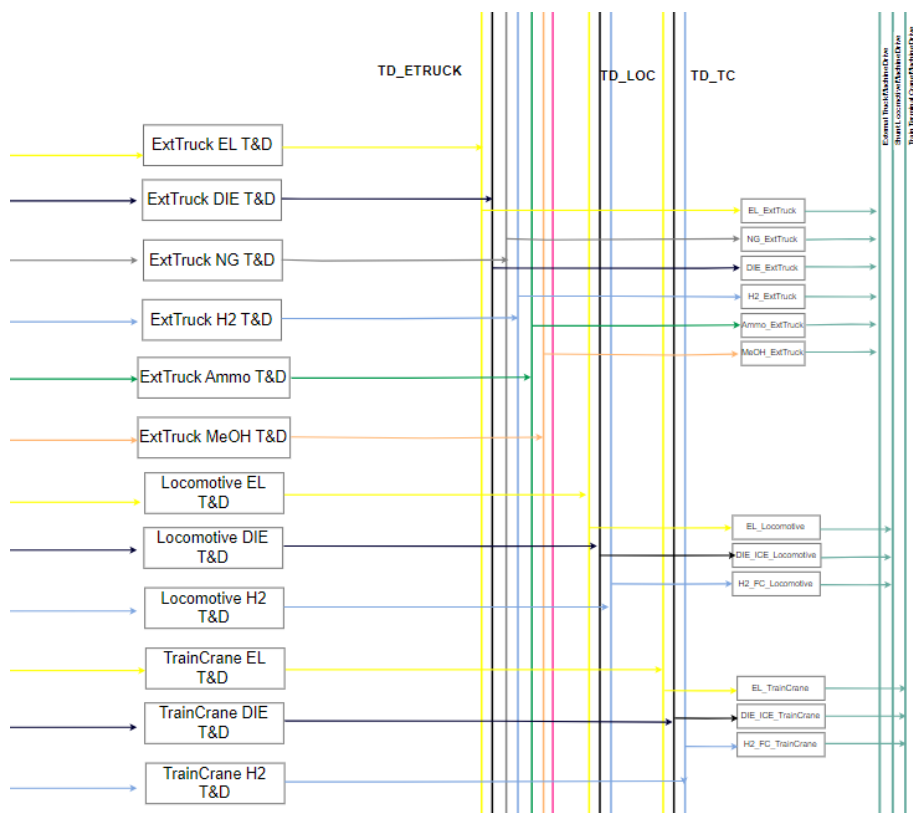


Figure C.4: REF - External Trucks, Shunt Locomotives and Train Terminal Cranes.

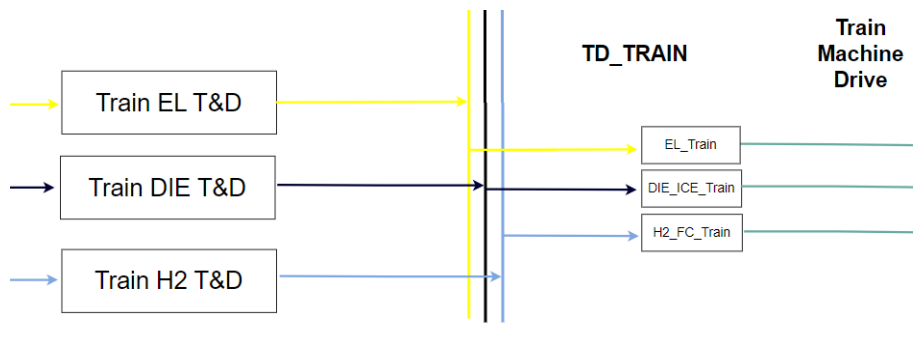


Figure C.5: REF - Trains.

Appendix D

Technologies Characterization

The tables in this chapter present the techno-economic characterization of this model technologies. The information is shown in the following order: Capital Cost (Table D.1), Fixed Cost (Table D.2), Variable Cost (Table D.3), Efficiency (Table D.4), Capacity Factor (Table D.5), Emissions Factor (Table D.6), Availability Factor, Operation Lifetime and Capacity to Activity Unit (Table D.7).

A piece of useful information for a better understanding of the tables - Non-Applicable (NA) refers to technologies which are either not characterized, such as transmission and distribution technologies, or whose description was realized through proxy technologies.

Table D.1: Technologies Techno-Economic Characterization: Capital Costs.

Code	CAPEX				Units	REF
	2020	2030	2040	2050		
NG_Import		4			M€/GW	[109]
DIE_Import		not applicable			-	NA
EL_Import		21			M€/GW	[110]
Ammo_Import		not applicable			-	NA
MeOH_Import		not applicable			-	NA
METne_Import		4			M€/GW	[109]
MDO_MGO_Import		not applicable			-	NA
HFO_Import		not applicable			-	NA
GreenH2_Import		42			M€/GW	[109]
H2_Import		42			M€/GW	[109]
BG_Import		4			M€/GW	[109]
Biomass_Extraction		not applicable			-	NA
WS_Extraction		not applicable			-	NA
WS_Gasifier	2112	1681	1681	1681	M€/GW	[84]
NG_CHP	991	914	881	849	M€/GW	[84]
BG_CHP	2436	1908	1807	1506	M€/GW	[84]
Biomass_CHP	4989	3997	3231	2693	M€/GW	[84]
PV_Floating_PP	42	27	24	22	M€/PJ	NA
PV_PP	33	21	19	17	M€/PJ	[81]
Wave_PP	4221	3365	2776	2282	M€/GW	[84]
Tides_PP	4280	3800	3380	2960	€/kW	[111]
Ocean_Thermal_PP	11000	9790	3008	2634	€/kW	[112]
Wind_PP	39	26	24	21	M€/PJ	[81]

Table D.1: Technologies Techno-Economic Characterization: Capital Costs.

Code	CAPEX				Units	REF
	2020	2030	2040	2050		
WindOff_PP	85	69	62	58	M€/PJ	[81]
H2_SMR	201	158	158	158	€/kW	[80]
H2_PEM	1200	950	600	186	€/kW	[80] [83]
H2_ALK	625	377	157	186	€/kW	[80] [83]
H2_SMR_CCS	272	191	191	191	€/kW	[80]
H2_SolidOxy	785	450	380	280	€/kW	[83]
E-MeOH_Syn	705	531	351	339	€/ton/y	[82]
MeOH_Gas	2112	1681	1681	1681	€/kW	NA
E-DIE_Syn	2050	1557	1200	880	€/kW	[85]
METne_Gas	2112	1681	1681	1681	€/kW	NA
E-METne_Syn	880	739	600	440	€/kW	[85]
E-Ammo_Syn	678				€/ton/y	[85]
TD_EL	not applicable				-	NA
TD_DIE	not applicable				-	NA
TD_NG	not applicable				-	NA
TD_H2	not applicable				-	NA
TD_Ammo	not applicable				-	NA
TD_MeOH	not applicable				-	NA
TD_MDO_MGO	not applicable				-	NA
TD_HFO	not applicable				-	NA
TD_Heat	not applicable				-	NA
TD_EL_SRD	not applicable				-	NA
TD_DIE_SRD	not applicable				-	NA
TD_NG_SRD	not applicable				-	NA
TD_H2_SRD	not applicable				-	NA
TD_EL_OGV	not applicable				-	NA
TD_DIE_OGV	not applicable				-	NA
TD_NG_OGV	not applicable				-	NA
TD_H2_OGV	not applicable				-	NA
TD_Ammo_OGV	not applicable				-	NA
TD_MeOH_OGV	not applicable				-	NA
TD_MDO_MGO_OGV	not applicable				-	NA
TD_HFO_OGV	not applicable				-	NA
TD_EL_TUG	not applicable				-	NA
TD_DIE_TUG	not applicable				-	NA
TD_NG_TUG	not applicable				-	NA
TD_H2_TUG	not applicable				-	NA
TD_Ammo_TUG	not applicable				-	NA
TD_MeOH_TUG	not applicable				-	NA
TD_EL_PIL	not applicable				-	NA
TD_DIE_PIL	not applicable				-	NA
TD_NG_PIL	not applicable				-	NA
TD_H2_PIL	not applicable				-	NA
TD_Ammo_PIL	not applicable				-	NA
TD_MeOH_PIL	not applicable				-	NA

Table D.1: Technologies Techno-Economic Characterization: Capital Costs.

Code	CAPEX				Units	REF
	2020	2030	2040	2050		
TD_EL_BB	not applicable				-	NA
TD_DIE_BB	not applicable				-	NA
TD_NG_BB	not applicable				-	NA
TD_H2_BB	not applicable				-	NA
TD_Ammo_BB	not applicable				-	NA
TD_MeOH_BB	not applicable				-	NA
TD_EL_QC	not applicable				-	NA
TD_DIE_QC	not applicable				-	NA
TD_H2_QC	not applicable				-	NA
TD_EL_ITRUCK	not applicable				-	NA
TD_DIE_ITRUCK	not applicable				-	NA
TD_NG_ITRUCK	not applicable				-	NA
TD_H2_ITRUCK	not applicable				-	NA
TD_MeOH_ITRUCK	not applicable				-	NA
TD_Ammo_ITRUCK	not applicable				-	NA
TD_EL_REEF	not applicable				-	NA
TD_EL_YC	not applicable				-	NA
TD_DIE_YC	not applicable				-	NA
TD_H2_YC	not applicable				-	NA
TD_EL_FL	not applicable				-	NA
TD_DIE_FL	not applicable				-	NA
TD_NG_FL	not applicable				-	NA
TD_H2_FL	not applicable				-	NA
TD_EL_RS	not applicable				-	NA
TD_DIE_RS	not applicable				-	NA
TD_NG_RS	not applicable				-	NA
TD_H2_RS	not applicable				-	NA
TD_EL_ECH	not applicable				-	NA
TD_DIE_ECH	not applicable				-	NA
TD_NG_ECH	not applicable				-	NA
TD_H2_ECH	not applicable				-	NA
TD_EL_ETRUCK	not applicable				-	NA
TD_DIE_ETRUCK	not applicable				-	NA
TD_NG_ETRUCK	not applicable				-	NA
TD_H2_ETRUCK	not applicable				-	NA
TD_MeOH_ETRUCK	not applicable				-	NA
TD_Ammo_ETRUCK	not applicable				-	NA
TD_EL_LOC	not applicable				-	NA
TD_DIE_LOC	not applicable				-	NA
TD_H2_LOC	not applicable				-	NA
TD_EL_TC	not applicable				-	NA
TD_DIE_TC	not applicable				-	NA
TD_H2_TC	not applicable				-	NA
TD_EL_TRAIN	not applicable				-	NA
TD_DIE_TRAIN	not applicable				-	NA

Table D.1: Technologies Techno-Economic Characterization: Capital Costs.

Code	CAPEX				Units	REF
	2020	2030	2040	2050		
TD_H2_TRAIN	not applicable				-	NA
OGV_OPS_EL	500	500	500	500	€/kW	[113]
BB_DIE_DIE	700	700	700	700	€/kW	NA
BB_NG_DIE						
BB_H2_DIE						
BB_Ammo_DIE						
BB_MeOH_DIE						
BB_MGO/MDO_DIE						
BB_HFO_DIE	1400	1400	1400	1400	€/kW	NA
BB_DIE_NG						
BB_NG_NG						
BB_H2_NG						
BB_Ammo_NG						
BB_MeOH_NG						
BB_MGO/MDO_NG						
BB_HFO_NG						
BB_DIE_H2	5600	5600	3360	1109	€/kW	NA
BB_NG_H2						
BB_H2_H2						
BB_Ammo_H2						
BB_MeOH_H2						
BB_MGO/MDO_H2						
TUG_MOTOR_EL	265	265	167	70	€/kW	[114]
TUG_ICE_NG	460	460	460	460	€/kW	[114]
TUG_ICE_DIE	225	225	225	225	€/kW	[114]
TUG_FC_H2	1860	1860	1116	368	€/kW	[115]
TUG_ICE_Ammo	744	744	670	603	€/kW	NA
TUG_ICE_MeOH	475	475	475	475	€/kW	NA
PIL_MOTOR_EL	800	800	504	212	€/kW	NA
PIL_ICE_NG	1400	1400	1400	1400	€/kW	NA
PIL_ICE_DIE	700	700	700	700	€/kW	NA
PIL_FC_H2	5600	5600	3360	1109	€/kW	NA
PIL_ICE_Ammo	1615	1615	1453	1308	€/kW	NA
PIL_ICE_MeOH	950	950	950	950	€/kW	NA
QC_MOTOR_EL	1010	1010	636	267	€/kW	[116]
QC_ICE_DIE	334	334	334	334	€/kW	NA
QC_FC_H2	436	436	261	86	€/kW	NA
ITRUCK_MOTOR_EL	287	287	181	75	M€/Gtkm	[81]
ITRUCK_ICE_NG	272	272	272	272	M€/Gtkm	[81]
ITRUCK_ICE_DIE	93	93	93	93	M€/Gtkm	[81]
ITRUCK_FC_H2	370	370	223	76	M€/Gtkm	[81]
ITRUCK_ICE_Ammo	215	215	193	174	M€/Gtkm	[81]
ITRUCK_ICE_MeOH	272	272	272	272	M€/Gtkm	[81]
REEF_MOTOR_EL	500	500	500	500	€/kW	NA
YC_MOTOR_EL	1010	1010	636	267	€/kW	NA

Table D.1: Technologies Techno-Economic Characterization: Capital Costs.

Code	CAPEX				Units	REF
	2020	2030	2040	2050		
YC_ICE_DIE	334	334	334	334	€/kW	[117]
YC_FC_H2	436	436	261	86	€/kW	NA
FL_MOTOR_EL	1415	1415	891	374	€/kW	[118]
FL_ICE_NG	1344	1344	1344	1344	€/kW	NA
FL_ICE_DIE	472	472	472	472	€/kW	NA
FL_FC_H2	5500	5500	3300	1089	€/kW	[80]
RS_MOTOR_EL	3468	3468	2185	918	€/kW	[119]
RS_ICE_NG	3295	3295	3295	3295	€/kW	NA
RS_ICE_DIE	755	755	755	755	€/kW	NA
RS_FC_H2	8803	8803	5282	1743	€/kW	NA
ECH_MOTOR_EL	3468	3468	2185	918	€/kW	NA
ECH_ICE_NG	3295	3295	3295	3295	€/kW	NA
ECH_ICE_DIE	755	755	755	755	€/kW	NA
ECH_FC_H2	8803	8803	5282	1743	€/kW	NA
ETRUCK_MOTOR_EL	287	287	181	75	M€/Gtkm	[81]
ETRUCK_ICE_NG	272	272	272	272	M€/Gtkm	[81]
ETRUCK_ICE_DIE	93	93	93	93	M€/Gtkm	[81]
ETRUCK_FC_H2	370	370	223	76	M€/Gtkm	[81]
ETRUCK_ICE_Ammo	215	215	193	174	M€/Gtkm	[81]
ETRUCK_ICE_MeOH	273	273	273	273	M€/Gtkm	[81]
LOC_MOTOR_EL	1133	1133	714	300	€/kW	NA
LOC_ICE_DIE	378	378	378	378	€/kW	NA
LOC_FC_H2	1 700	1 300	780	257	€/kW	NA
TC_MOTOR_EL	1010	1010	636	267	€/kW	NA
TC_ICE_DIE	334	334	334	334	€/kW	NA
TC_FC_H2	436	436	261	86	€/kW	NA
TRAIN_MOTOR_EL	1133	1133	714	299	€/kW	NA
TRAIN_ICE_DIE	378	378	378	378	€/kW	NA
TRAIN_FC_H2	1 700	1 300	780	257	€/kW	[120]

Table D.2: Technologies Techno-Economic Characterization: Fixed Costs.

Code	OPEX				Units	REF
	2020	2030	2040	2050		
NG_Import	not applicable				-	-
DIE_Import	not applicable				-	-
EL_Import	not applicable				-	-
Ammo_Import	not applicable				-	-
MeOH_Import	not applicable				-	-
METne_Import	not applicable				-	-
MDO_MGO_Import	not applicable				-	-
HFO_Import	not applicable				-	-
GreenH2_Import	not applicable				-	-
H2_Import	not applicable				-	-
BG_Import	not applicable				-	-

Table D.2: Technologies Techno-Economic Characterization: Fixed Costs.

Code	OPEX				Units	REF
	2020	2030	2040	2050		
Biomass_Extraction	not applicable				-	-
WS_Extraction	not applicable				-	-
WS_Gasifier	42,0	33,0	33,0	33,0	M€/GW	[84]
NG_CHP	9,00	7,00	6,00	5,00	M€/GW	[84]
BG_CHP	3,00	3,00	2,00	2,00	M€/GW	[84]
Biomass_CHP	84,0	67,0	54,0	45,0	M€/GW	[84]
PV_Floating_PP	0,763	0,565	0,528	0,492	M€/PJ	NA
PV_PP	0,606	0,449	0,420	0,390	M€/PJ	[81]
Wave_PP	25,5	20,4	16,5	13,7	M€/GW	[84]
Tides_PP	236	201	165	130	€/kW	[111]
Ocean_Thermal_PP	350	290	240	180	€/kW	[112]
Wind_PP	1,25	1,14	1,06	0,976	M€/PJ	[81]
WindOff_PP	2,80	2,28	2,03	1,87	M€/PJ	[81]
H2_SMR	9,84	7,65	7,65	7,65	€/kW	[80]
H2_PEM	36,0	28,5	28,5	28,5	€/kW	[80]
H2_ALK	40,0	10,3	10,3	10,3	€/kW	[80]
H2_SMR_CCS	14,2	11,4	11,4	11,4	€/kW	[80]
H2_SolidOxy	66,0	13,5	13,5	13,5	€/kW	[121]
E-MeOH_Syn	10,5	7,97	6,00	5,09	€/ton/y	[82]
MeOH_Gas	42,2	33,5	33,5	33,5	€/kW	NA
E-DIE_Syn	102,0	77,8	59,0	44,0	€/kW	[85]
METne_Gas	42,2	33,5	33,5	33,5	€/kW	NA
E-METne_Syn	35,2	29,6	24,0	17,6	€/kW	[85]
E-Ammo_Syn	19,6				€/ton/y	[85]
TD_EL	not applicable				-	-
TD_DIE	not applicable				-	-
TD_NG	not applicable				-	-
TD_H2	not applicable				-	-
TD_Ammo	not applicable				-	-
TD_MeOH	not applicable				-	-
TD_MDO_MGO	not applicable				-	-
TD_HFO	not applicable				-	-
TD_Heat	not applicable				-	-
TD_EL_SRD	not applicable				-	-
TD_DIE_SRD	not applicable				-	-
TD_NG_SRD	not applicable				-	-
TD_H2_SRD	not applicable				-	-
TD_EL_OGV	not applicable				-	-
TD_DIE_OGV	not applicable				-	-
TD_NG_OGV	not applicable				-	-
TD_H2_OGV	not applicable				-	-
TD_Ammo_OGV	not applicable				-	-
TD_MeOH_OGV	not applicable				-	-
TD_MDO_MGO_OGV	not applicable				-	-
TD_HFO_OGV	not applicable				-	-

Table D.2: Technologies Techno-Economic Characterization: Fixed Costs.

Code	OPEX				Units	REF
	2020	2030	2040	2050		
TD_EL_TUG		not applicable			-	-
TD_DIE_TUG		not applicable			-	-
TD_NG_TUG		not applicable			-	-
TD_H2_TUG		not applicable			-	-
TD_Ammo_TUG		not applicable			-	-
TD_MeOH_TUG		not applicable			-	-
TD_EL_PIL		not applicable			-	-
TD_DIE_PIL		not applicable			-	-
TD_NG_PIL		not applicable			-	-
TD_H2_PIL		not applicable			-	-
TD_Ammo_PIL		not applicable			-	-
TD_MeOH_PIL		not applicable			-	-
TD_EL_BB		not applicable			-	-
TD_DIE_BB		not applicable			-	-
TD_NG_BB		not applicable			-	-
TD_H2_BB		not applicable			-	-
TD_Ammo_BB		not applicable			-	-
TD_MeOH_BB		not applicable			-	-
TD_EL_QC		not applicable			-	-
TD_DIE_QC		not applicable			-	-
TD_H2_QC		not applicable			-	-
TD_EL_ITRUCK		not applicable			-	-
TD_DIE_ITRUCK		not applicable			-	-
TD_NG_ITRUCK		not applicable			-	-
TD_H2_ITRUCK		not applicable			-	-
TD_MeOH_ITRUCK		not applicable			-	-
TD_Ammo_ITRUCK		not applicable			-	-
TD_EL_REEF		not applicable			-	-
TD_EL_YC		not applicable			-	-
TD_DIE_YC		not applicable			-	-
TD_H2_YC		not applicable			-	-
TD_EL_FL		not applicable			-	-
TD_DIE_FL		not applicable			-	-
TD_NG_FL		not applicable			-	-
TD_H2_FL		not applicable			-	-
TD_EL_RS		not applicable			-	-
TD_DIE_RS		not applicable			-	-
TD_NG_RS		not applicable			-	-
TD_H2_RS		not applicable			-	-
TD_EL_ECH		not applicable			-	-
TD_DIE_ECH		not applicable			-	-
TD_NG_ECH		not applicable			-	-
TD_H2_ECH		not applicable			-	-
TD_EL_ETRUCK		not applicable			-	-
TD_DIE_ETRUCK		not applicable			-	-

Table D.2: Technologies Techno-Economic Characterization: Fixed Costs.

Code	OPEX				Units	REF
	2020	2030	2040	2050		
TD_NG_ETRUCK		not applicable			-	-
TD_H2_ETRUCK		not applicable			-	-
TD_MeOH_ETRUCK		not applicable			-	-
TD_Ammo_ETRUCK		not applicable			-	-
TD_EL_LOC		not applicable			-	-
TD_DIE_LOC		not applicable			-	-
TD_H2_LOC		not applicable			-	-
TD_EL_TC		not applicable			-	-
TD_DIE_TC		not applicable			-	-
TD_H2_TC		not applicable			-	-
TD_EL_TRAIN		not applicable			-	-
TD_DIE_TRAIN		not applicable			-	-
TD_H2_TRAIN		not applicable			-	-
OGV_OPS_EL	0,250	0,250	0,250	0,250	€/kW	[113]
BB_DIE_DIE					€/kW	NA
BB_NG_DIE					€/kW	NA
BB_H2_DIE					€/kW	NA
BB_Ammo_DIE	282	282	178	75	€/kW	NA
BB_MeOH_DIE					€/kW	NA
BB_MGO/MDO_DIE					€/kW	NA
BB_HFO_DIE					€/kW	NA
BB_DIE_NG					€/kW	NA
BB_NG_NG					€/kW	NA
BB_H2_NG					€/kW	NA
BB_Ammo_NG	138	138	138	138	€/kW	NA
BB_MeOH_NG					€/kW	NA
BB_MGO/MDO_NG					€/kW	NA
BB_HFO_NG					€/kW	NA
BB_DIE_H2					€/kW	NA
BB_NG_H2					€/kW	NA
BB_H2_H2					€/kW	NA
BB_Ammo_H2	992	992	595	196	€/kW	NA
BB_MeOH_H2					€/kW	NA
BB_MGO/MDO_H2					€/kW	NA
BB_HFO_H2					€/kW	NA
TUG_MOTOR_EL	248	248	248	248	€/kW	[114]
TUG_ICE_NG	138	138	138	138	€/kW	[114]
TUG_ICE_DIE	282	282	178	75	€/kW	[114]
TUG_FC_H2	992	992	595	196	€/kW	NA
TUG_ICE_Ammo	932	932	839	755	€/kW	NA
TUG_ICE_MeOH	475	475	475	475	€/kW	NA
PIL_MOTOR_EL	248	248	248	248	€/kW	NA
PIL_ICE_NG	138	138	138	138	€/kW	NA
PIL_ICE_DIE	282	282	178	75	€/kW	NA
PIL_FC_H2	992	992	595	196	€/kW	NA
PIL_ICE_Ammo	932	932	839	755	€/kW	NA

Table D.2: Technologies Techno-Economic Characterization: Fixed Costs.

Code	OPEX				Units	REF
	2020	2030	2040	2050		
PIL_ICE_MeOH	475	476	477	478	€/kW	NA
QC_MOTOR_EL	9,30	9,30	9,30	9,30	€/kW	NA
QC_ICE_DIE	27,9	27,9	17,6	7,40	€/kW	NA
QC_FC_H2	37,2	37,2	22,0	7,00	€/kW	NA
ITRUCK_MOTOR_EL	1,86	1,86	1,86	1,86	M€/PJ	[81]
ITRUCK_ICE_NG	5,45	5,45	5,45	5,45	M€/PJ	[81]
ITRUCK_ICE_DIE	5,74	5,74	3,62	1,50	M€/PJ	[81]
ITRUCK_FC_H2	7,41	7,41	4,47	1,53	M€/PJ	[81]
ITRUCK_ICE_Ammo	5,74	5,74	3,62	1,50	M€/PJ	NA
ITRUCK_ICE_MeOH	5,45	5,45	5,45	5,45	M€/PJ	NA
REEF_MOTOR_EL	0,25	0,25	0,25	0,25	€/kW	NA
YC_MOTOR_EL	9,30	9,30	9,30	9,30	€/kW	NA
YC_ICE_DIE	27,90	27,90	17,60	7,40	€/kW	NA
YC_FC_H2	37,2	37,2	22,0	7,00	€/kW	NA
FL_MOTOR_EL	60,0	60,0	60,0	60,0	€/kW	NA
FL_ICE_NG	176	176	176	176	€/kW	NA
FL_ICE_DIE	185	185	117	49,0	€/kW	NA
FL_FC_H2	239	239	144	50,0	€/kW	[122]
RS_MOTOR_EL	60,0	60,0	60,0	60,0	€/kW	NA
RS_ICE_NG	176	176	176	176	€/kW	NA
RS_ICE_DIE	185	185	117	49,0	€/kW	NA
RS_FC_H2	239	239	144	50,0	€/kW	NA
ECH_MOTOR_EL	60,0	60,0	60,0	60,0	€/kW	NA
ECH_ICE_NG	176	176	176	176	€/kW	NA
ECH_ICE_DIE	185	185	117	49,0	€/kW	NA
ECH_FC_H2	239	239	144	50,0	€/kW	NA
ETRUCK_MOTOR_EL	1,86	1,86	1,86	1,86	M€/PJ	[81]
ETRUCK_ICE_NG	5,45	5,45	5,45	5,45	M€/PJ	[81]
ETRUCK_ICE_DIE	5,74	5,74	3,62	1,50	M€/PJ	[81]
ETRUCK_FC_H2	7,41	7,41	4,47	1,53	M€/PJ	[81]
ETRUCK_ICE_Ammo	5,74	5,74	3,62	1,50	M€/PJ	NA
ETRUCK_ICE_MeOH	5,45	5,45	5,45	5,45	M€/PJ	NA
LOC_MOTOR_EL		-			-	-
LOC_ICE_DIE		-			-	-
LOC_FC_H2		-			-	-
TC_MOTOR_EL	9,30	9,30	9,30	9,30	€/kW	NA
TC_ICE_DIE	27,9	27,9	17,6	7,40	€/kW	NA
TC_FC_H2	37,2	37,2	22,0	7,00	€/kW	NA
TRAIN_MOTOR_EL		-			-	-
TRAIN_ICE_DIE		-			-	-
TRAIN_FC_H2		-			-	-

Table D.3: Technologies Techno-Economic Characterization: Variable Cost.

Code	VARCOST				Units	REF
	2020	2030	2040	2050		
NG_Import	24,0	37,4	-	49,8	EUR/MWh	[88]
DIE_Import	30,5	73,9	-	95,6	EUR/MWh	[88]
EL_Import (Mode 1)	140	70,0	70,0	75,0	EUR/MWh	[89]
EL_Import (Mode 2)	160,0	80,0	80,0	80,0	EUR/MWh	[90]
Ammo_Import	30,9	30,9	30,9	30,9	M€/PJ	NA
MeOH_Import	1,48	1,48	1,78	2,13	M€/PJ	NA
METne_Import	260	260	260	260	EUR/MWh	[91]
MDO_MGO_Import	1,48	1,48	1,78	2,13	M€/PJ	NA
HFO_Import	6,05	6,04	7,41	8,92	M€/PJ	NA
GreenH2_Import	43,8	43,8	25,0	7,70	M€/PJ	[93]
H2_Import	12,0	12,0	12,0	12,0	M€/PJ	[85]
BG_Import	13,9	11,1	8,37	4,65	M€/PJ	[84]
Biomass_Extraction [84]	4,65	8,37	8,37	9,30	M€/PJ	
WS_Extraction [84]	1,86	1,86	1,86	1,86	M€/PJ	
WS_Gasifier [84]	2,79	2,79	2,79	2,79	M€/PJ	
NG_CHP [84]	0,93	0,93	0,93	0,93	M€/PJ	
BG_CHP [84]	0,93	0,93	0,93	0,93	M€/PJ	
Biomass_CHP [84]	10,2	10,2	10,2	10,2	M€/PJ	
PV_Floating_PP	0	0	0	0	€/GJ	NA
PV_PP	0	0	0	0	€/GJ	[81]
Wave_PP	0	0	0	0	€/GJ	[84]
Tides_PP	0	0	0	0	€/GJ	[111]
Ocean_Thermal_PP	0	0	0	0	€/GJ	[112]
Wind_PP	0	0	0	0	€/GJ	[81]
WindOff_PP	0	0	0	0	€/GJ	[81]
H2_SMR	0,0800	0,0500	0,0500	0,0500	€/GJ	[80]
H2_PEM	-	-	-	-	-	-
H2_ALK	0,150	0,150	0,150	0,150	€/GJ	[80]
H2_SMR_CCS	0,530	0,0700	0,0700	0,0700	€/GJ	[80]
H2_SolidOxy	-	-	-	-	-	-
E-MeOH_Syn	4,20	3,50	2,80	2,10	€/GJ	[82]
MeOH_Gas	-	-	-	-	-	-
E-DIE_Syn	5,20	4,10	3	2,00	€/GJ	
METne_Gas	-	-	-	-	-	-
E-METne_Syn	4,20	3,50	2,80	2,10	€/GJ	[85]
E-Ammo_Syn	4,20	3,50	2,80	2,10	€/GJ	[85]
TD_EL		not applicable			-	-
TD_DIE		not applicable			-	-
TD_NG		not applicable			-	-

Table D.3: Technologies Techno-Economic Characterization: Variable Cost.

Code	VARCOST				Units	REF
	2020	2030	2040	2050		
TD_H2		not applicable			-	-
TD_Ammo		not applicable			-	-
TD_MeOH		not applicable			-	-
TD_MDO_MGO		not applicable			-	-
TD_HFO		not applicable			-	-
TD_Heat		not applicable			-	-
TD_EL_SRD		not applicable			-	-
TD_DIE_SRD		not applicable			-	-
TD_NG_SRD		not applicable			-	-
TD_H2_SRD		not applicable			-	-
TD_EL_OGV		not applicable			-	-
TD_DIE_OGV		not applicable			-	-
TD_NG_OGV		not applicable			-	-
TD_H2_OGV		not applicable			-	-
TD_Ammo_OGV		not applicable			-	-
TD_MeOH_OGV		not applicable			-	-
TD_MDO_MGO_OGV		not applicable			-	-
TD_HFO_OGV		not applicable			-	-
TD_EL_TUG		not applicable			-	-
TD_DIE_TUG		not applicable			-	-
TD_NG_TUG		not applicable			-	-
TD_H2_TUG		not applicable			-	-
TD_Ammo_TUG		not applicable			-	-
TD_MeOH_TUG		not applicable			-	-
TD_EL_PIL		not applicable			-	-
TD_DIE_PIL		not applicable			-	-
TD_NG_PIL		not applicable			-	-
TD_H2_PIL		not applicable			-	-
TD_Ammo_PIL		not applicable			-	-
TD_MeOH_PIL		not applicable			-	-
TD_EL_BB		not applicable			-	-
TD_DIE_BB		not applicable			-	-
TD_NG_BB		not applicable			-	-
TD_H2_BB		not applicable			-	-
TD_Ammo_BB		not applicable			-	-
TD_MeOH_BB		not applicable			-	-
TD_EL_QC		not applicable			-	-
TD_DIE_QC		not applicable			-	-
TD_H2_QC		not applicable			-	-
TD_EL_ITRUCK		not applicable			-	-
TD_DIE_ITRUCK		not applicable			-	-
TD_NG_ITRUCK		not applicable			-	-
TD_H2_ITRUCK		not applicable			-	-
TD_MeOH_ITRUCK		not applicable			-	-
TD_Ammo_ITRUCK		not applicable			-	-

Table D.3: Technologies Techno-Economic Characterization: Variable Cost.

Code	VARCOST				Units	REF
	2020	2030	2040	2050		
TD_EL_REEF		not applicable			-	-
TD_EL_YC		not applicable			-	-
TD_DIE_YC		not applicable			-	-
TD_H2_YC		not applicable			-	-
TD_EL_FL		not applicable			-	-
TD_DIE_FL		not applicable			-	-
TD_NG_FL		not applicable			-	-
TD_H2_FL		not applicable			-	-
TD_EL_RS		not applicable			-	-
TD_DIE_RS		not applicable			-	-
TD_NG_RS		not applicable			-	-
TD_H2_RS		not applicable			-	-
TD_EL_ECH		not applicable			-	-
TD_DIE_ECH		not applicable			-	-
TD_NG_ECH		not applicable			-	-
TD_H2_ECH		not applicable			-	-
TD_EL_SR		not applicable			-	-
TD_DIE_SR		not applicable			-	-
TD_EL_ETRUCK		not applicable			-	-
TD_DIE_ETRUCK		not applicable			-	-
TD_NG_ETRUCK		not applicable			-	-
TD_H2_ETRUCK		not applicable			-	-
TD_MeOH_ETRUCK		not applicable			-	-
TD_Ammo_ETRUCK		not applicable			-	-
TD_EL_LOC		not applicable			-	-
TD_DIE_LOC		not applicable			-	-
TD_H2_LOC		not applicable			-	-
TD_EL_TC		not applicable			-	-
TD_DIE_TC		not applicable			-	-
TD_H2_TC		not applicable			-	-
TD_EL_TRAIN		not applicable			-	-
TD_DIE_TRAIN		not applicable			-	-
TD_H2_TRAIN		not applicable			-	-
OGV_OPS_EL		0			€/GJ	-
BB_DIE_DIE		0			€/GJ	-
BB_NG_DIE		0			€/GJ	-
BB_H2_DIE		0			€/GJ	-
BB_Ammo_DIE		0			€/GJ	-
BB_MeOH_DIE		0			€/GJ	-
BB_MGO/MDO_DIE		0			€/GJ	-
BB_HFO_DIE		0			€/GJ	-
BB_DIE_NG		0			€/GJ	-
BB_NG_NG		0			€/GJ	-
BB_H2_NG		0			€/GJ	-
BB_Ammo_NG		0			€/GJ	-

Table D.3: Technologies Techno-Economic Characterization: Variable Cost.

Code	VARCOST				Units	REF
	2020	2030	2040	2050		
BB_MeOH_NG		0			€/GJ	-
BB_MGO/MDO_NG		0			€/GJ	-
BB_HFO_NG		0			€/GJ	-
BB_DIE_H2		0			€/GJ	-
BB_NG_H2		0			€/GJ	-
BB_H2_H2		0			€/GJ	-
BB_Ammo_H2		0			€/GJ	-
BB_MeOH_H2		0			€/GJ	-
BB_MGO/MDO_H2		0			€/GJ	-
BB_HFO_H2		0			€/GJ	-
TUG_MOTOR_EL		0			€/GJ	-
TUG_ICE_NG		0			€/GJ	-
TUG_ICE_DIE		0			€/GJ	-
TUG_FC_H2		0			€/GJ	-
TUG_ICE_Ammo		0			€/GJ	-
TUG_ICE_MeOH		0			€/GJ	-
PIL_MOTOR_EL		0			€/GJ	-
PIL_ICE_NG		0			€/GJ	-
PIL_ICE_DIE		0			€/GJ	-
PIL_FC_H2		0			€/GJ	-
PIL_ICE_Ammo		0			€/GJ	-
PIL_ICE_MeOH		0			€/GJ	-
QC_MOTOR_EL		0			€/GJ	-
QC_ICE_DIE		0			€/GJ	-
QC_FC_H2		0			€/GJ	-
ITRUCK_MOTOR_EL		0			€/GJ	-
ITRUCK_ICE_NG		0			€/GJ	-
ITRUCK_ICE_DIE		0			€/GJ	-
ITRUCK_FC_H2		0			€/GJ	-
ITRUCK_ICE_Ammo		0			€/GJ	-
ITRUCK_ICE_MeOH		0			€/GJ	-
REEF_MOTOR_EL		0			€/GJ	-
YC_MOTOR_EL		0			€/GJ	-
YC_ICE_DIE		0			€/GJ	-
YC_FC_H2		0			€/GJ	-
FL_MOTOR_EL		0			€/GJ	-
FL_ICE_NG		0			€/GJ	-
FL_ICE_DIE		0			€/GJ	-
FL_FC_H2		0			€/GJ	-
RS_MOTOR_EL		0			€/GJ	-
RS_ICE_NG		0			€/GJ	-
RS_ICE_DIE		0			€/GJ	-
RS_FC_H2		0			€/GJ	-
ECH_MOTOR_EL		0			€/GJ	-
ECH_ICE_NG		0			€/GJ	-

Table D.3: Technologies Techno-Economic Characterization: Variable Cost.

Code	VARCOST				Units	REF
	2020	2030	2040	2050		
ECH_ICE_DIE		0			€/GJ	-
ECH_FC_H2		0			€/GJ	-
SR_MOTOR_EL		0			€/GJ	-
SR_ICE_DIE		0			€/GJ	-
ETRUCK_MOTOR_EL		0			€/GJ	-
ETRUCK_ICE_NG		0			€/GJ	-
ETRUCK_ICE_DIE		0			€/GJ	-
ETRUCK_FC_H2		0			€/GJ	-
ETRUCK_ICE_Ammo		0			€/GJ	-
ETRUCK_ICE_MeOH		0			€/GJ	-
LOC_MOTOR_EL		0			€/GJ	-
LOC_ICE_DIE		0			€/GJ	-
LOC_FC_H2		0			€/GJ	-
TC_MOTOR_EL		0			€/GJ	-
TC_ICE_DIE		0			€/GJ	-
TC_FC_H2		0			€/GJ	-
TRAIN_MOTOR_EL		0			€/GJ	-
TRAIN_ICE_DIE		0			€/GJ	-
TRAIN_FC_H2		0			€/GJ	-

Table D.4: Technologies Techno-Economic Characterization: Efficiency.

Code	Efficiency				REF
	2020	2030	2040	2050	
NG_Import		100%			[81]
DIE_Import		100%			[81]
EL_Import		100%			NA
Ammo_Import		100%			NA
MeOH_Import		100%			NA
METne_Import		100%			NA
MDO_MGO_Import		100%			NA
HFO_Import		100%			NA
GreenH2_Import		100%			NA
H2_Import		100%			NA
BG_Import		100%			NA
Biomass_Extraction		100%			NA
WS_Extraction		100%			NA
WS_Gasifier		75%			[123]
NG_CHP (Electricity Production)		49%			[60]
NG_CHP (Heat Production)		21%			[60]
BG_CHP (ELE)		59%			[60]
BG_CHP (Heat)		25%			[60]
Biomass_CHP (ELE)		59%			[60]
Biomass_CHP (Heat)		25%			[60]
PV_PP		100%			[81]

Table D.4: Technologies Techno-Economic Characterization: Efficiency.

Code	Efficiency				REF
	2020	2030	2040	2050	
Wave_PP		100%			[124]
Tides_PP		100%			NA
Ocean_Thermal_PP		100%			NA
Wind_PP		100%			[81]
WindOff_PP		100%			[81]
H2_SMR	75%	79%	79%	79%	[80]
H2_PEM	70%	75%	77%	80%	[80] [83]
H2_ALK	67%	68%	69%	70%	[80] [83]
H2_SMR_CCS	64%	70%	70%	70%	[80]
H2_SolidOxy	91%	95%	95%	95%	[83]
E-MeOH_Syn		95%			[82]
MeOH_Gas		75%			NA
E-DIE_Syn		73%			[85]
METne_Gas		75%			NA
E-METne_Syn		77%			[85]
E-Ammo_Syn		95%			[85]
TD_EL		100%			NA
TD_DIE		100%			NA
TD_NG		100%			NA
TD_H2		100%			NA
TD_Ammo		100%			NA
TD_MeOH		100%			NA
TD_MDO_MGO		100%			NA
TD_HFO		100%			NA
TD_Heat		100%			NA
TD_EL_SRD		100%			NA
TD_DIE_SRD		100%			NA
TD_NG_SRD		100%			NA
TD_H2_SRD		100%			NA
TD_EL_OGV		100%			NA
TD_DIE_OGV		100%			NA
TD_NG_OGV		100%			NA
TD_H2_OGV		100%			NA
TD_Ammo_OGV		100%			NA
TD_MeOH_OGV		100%			NA
TD_MDO_MGO_OGV		100%			NA
TD_HFO_OGV		100%			NA
TD_EL_TUG		100%			NA
TD_DIE_TUG		100%			NA
TD_NG_TUG		100%			NA
TD_H2_TUG		100%			NA
TD_Ammo_TUG		100%			NA
TD_MeOH_TUG		100%			NA
TD_EL_PIL		100%			NA
TD_DIE_PIL		100%			NA

Table D.4: Technologies Techno-Economic Characterization: Efficiency.

Code	Efficiency				REF
	2020	2030	2040	2050	
TD_NG_PIL		100%			NA
TD_H2_PIL		100%			NA
TD_Ammo_PIL		100%			NA
TD_MeOH_PIL		100%			NA
TD_EL_BB		100%			NA
TD_DIE_BB		100%			NA
TD_NG_BB		100%			NA
TD_H2_BB		100%			NA
TD_Ammo_BB		100%			NA
TD_MeOH_BB		100%			NA
TD_EL_QC		100%			NA
TD_DIE_QC		100%			NA
TD_H2_QC		100%			NA
TD_EL_ITRUCK		100%			NA
TD_DIE_ITRUCK		100%			NA
TD_NG_ITRUCK		100%			NA
TD_H2_ITRUCK		100%			NA
TD_MeOH_ITRUCK		100%			NA
TD_Ammo_ITRUCK		100%			NA
TD_EL_REEF		100%			NA
TD_EL_YC		100%			NA
TD_DIE_YC		100%			NA
TD_H2_YC		100%			NA
TD_EL_FL		100%			NA
TD_DIE_FL		100%			NA
TD_NG_FL		100%			NA
TD_H2_FL		100%			NA
TD_EL_RS		100%			NA
TD_DIE_RS		100%			NA
TD_NG_RS		100%			NA
TD_H2_RS		100%			NA
TD_EL_ECH		100%			NA
TD_DIE_ECH		100%			NA
TD_NG_ECH		100%			NA
TD_H2_ECH		100%			NA
TD_EL_ETRUCK		100%			NA
TD_DIE_ETRUCK		100%			NA
TD_NG_ETRUCK		100%			NA
TD_H2_ETRUCK		100%			NA
TD_MeOH_ETRUCK		100%			NA
TD_Ammo_ETRUCK		100%			NA
TD_EL_LOC		100%			NA
TD_DIE_LOC		100%			NA
TD_H2_LOC		100%			NA
TD_EL_TC		100%			NA

Table D.4: Technologies Techno-Economic Characterization: Efficiency.

Code	Efficiency				REF
	2020	2030	2040	2050	
TD_DIE_TC		100%			NA
TD_H2_TC		100%			NA
TD_EL_TRAIN		100%			NA
TD_DIE_TRAIN		100%			NA
TD_H2_TRAIN		100%			NA
OGV_OPS_EL		97%			NA
BB_DIE_DIE					NA
BB_NG_DIE					NA
BB_H2_DIE					NA
BB_Ammo_DIE		31%			NA
BB_MeOH_DIE					NA
BB_MGO/MDO_DIE					NA
BB_HFO_DIE					NA
BB_DIE_NG					NA
BB_NG_NG					NA
BB_H2_NG					NA
BB_Ammo_NG		19%			NA
BB_MeOH_NG					NA
BB_MGO/MDO_NG					NA
BB_HFO_NG					NA
BB_DIE_H2					NA
BB_NG_H2					NA
BB_H2_H2					NA
BB_Ammo_H2		54%			NA
BB_MeOH_H2					NA
BB_MGO/MDO_H2					NA
BB_HFO_H2					NA
TUG_MOTOR_EL		92%			NA
TUG_ICE_NG		19%			NA
TUG_ICE_DIE		31%			NA
TUG_FC_H2		54%			[35]
TUG_ICE_Ammo		36%			NA
TUG_ICE_MeOH		43%			NA
PIL_MOTOR_EL		92%			NA
PIL_ICE_NG		19%			NA
PIL_ICE_DIE		31%			NA
PIL_FC_H2		54%			NA
PIL_ICE_Ammo		36%			NA
PIL_ICE_MeOH		43%			NA
QC_MOTOR_EL		92%			NA
QC_ICE_DIE		31%			NA
QC_FC_H2		55%			NA
ITRUCK_MOTOR_EL		9,70 Gtkm/PJ			[81]
ITRUCK_ICE_NG		0,80 Gtkm/PJ			[81]
ITRUCK_ICE_DIE		1,14 Gtkm/PJ			[81]
ITRUCK_FC_H2		9,25 Gtkm/PJ			[81]

Table D.4: Technologies Techno-Economic Characterization: Efficiency.

Code	Efficiency				REF
	2020	2030	2040	2050	
ITRUCK_ICE_Ammo		1,14 Gtkm/PJ			NA
ITRUCK_ICE_MeOH		0,809 Gtkm/PJ			NA
REEF_MOTOR_EL		92%			NA
YC_MOTOR_EL		92%			NA
YC_ICE_DIE		31%			NA
YC_FC_H2		55%			NA
FL_MOTOR_EL		92%			[125]
FL_ICE_NG		19%			NA
FL_ICE_DIE		31%			NA
FL_FC_H2		55%			[80]
RS_MOTOR_EL		92%			NA
RS_ICE_NG		19%			NA
RS_ICE_DIE		31%			NA
RS_FC_H2		55%			NA
ECH_MOTOR_EL		92%			NA
ECH_ICE_NG		19%			NA
ECH_ICE_DIE		31%			NA
ECH_FC_H2		55%			NA
ETRUCK_MOTOR_EL		9,70 Gtkm/PJ			[81]
ETRUCK_ICE_NG		0,809 Gtkm/PJ			[81]
ETRUCK_ICE_DIE		1,14 Gtkm/PJ			[81]
ETRUCK_FC_H2		9,25 Gtkm/PJ			[81]
ETRUCK_ICE_Ammo		1,14 Gtkm/PJ			NA
ETRUCK_ICE_MeOH		0,809 Gtkm/PJ			NA
LOC_MOTOR_EL		95%			[126]
LOC_ICE_DIE		31%			NA
LOC_FC_H2		55%			NA
TC_MOTOR_EL		92%			NA
TC_ICE_DIE		31%			NA
TC_FC_H2		55%			NA
TRAIN_MOTOR_EL		95%			[127]
TRAIN_ICE_DIE		31%			NA
TRAIN_FC_H2		61%			[80]

Table D.5: Technologies Techno-Economic Characterization: Capacity Factor.

Code	Timeslice	Capacity Factor				REF
		2020	2030	2040	2050	
PV_Floating_PP	AD		0,165			[84]
	AN		0			
	SpD		0,223			
	SpN		0			
	SuD		0,247			
	SuN		0			
	WD		0,136			

Table D.5: Technologies Techno-Economic Characterization: Capacity Factor.

Code	Timeslice	Capacity Factor				REF
		2020	2030	2040	2050	
PV_PP	WN		0			[84]
	AD		0,165			
	AN		0			
	SpD		0,223			
	SpN		0			
	SuD		0,247			
	SuN		0			
	WD		0,136			
	WN		0			
Wave_PP	AD		0,250			[124]
	AN		0,250			
	SpD		0,250			
	SpN		0,250			
	SuD		0,250			
	SuN		0,250			
	WD		0,250			
	WN		0,250			
Tides_PP	AD		0,350			[128]
	AN		0,350			
	SpD		0,350			
	SpN		0,350			
	SuD		0,350			
	SuN		0,350			
	WD		0,350			
	WN		0,350			
Ocean_Thermal_PP	AD		0,970			[129]
	AN		0,970			
	SpD		0,970			
	SpN		0,970			
	SuD		0,970			
	SuN		0,970			
	WD		0,970			
	WN		0,970			
Wind_PP	AD		0,311			[84]
	AN		0,267			
	SpD		0,214			
	SpN		0,196			
	SuD		0,194			
	SuN		0,184			
	WD		0,329			
	WN		0,325			
WindOff_PP	AD		0,358			[84]
	AN		0,307			
	SpD		0,338			
	SpN		0,225			
	SuD		0,212			
	SuN		0,223			

Table D.5: Technologies Techno-Economic Characterization: Capacity Factor.

Code	Timeslice	Capacity Factor				REF
		2020	2030	2040	2050	
	WD		0,378			
	WN		0,374			

Table D.6: Technologies Techno-Economic Characterization: Emissions Factor.

Code	CO2e Emissions	NOx Emissions	Units	REF
NG_Import	0,0560		Mton/PJ	[84]
DIE_Import	0,0430		Mton/PJ	[95]
EL_Import PT (Mode 1)	207		gCO2/kWh	[84]
EL_Import (Mode 2)	0		Mton/PJ	[97]
Ammo_Import	0		Mton/PJ	[98]
MeOH_Import	0,110		Mton/PJ	[99]
METne_Import	0,0549		Mton/PJ	[95]
MDO_MGO_Import	0,0740		Mton/PJ	NA
HFO_Import	0,0740		Mton/PJ	NA
GreenH2_Import	0		Mton/PJ	NA
H2_Import	0,0670		Mton/PJ	[100]
BG_Import	0,550		Mton/PJ	[84]
Biomass_Extraction	0,00200		Mton/PJ	[84]
WS_Extraction	0,0920		Mton/PJ	[84]
WS_Gasifier		0,000209	Mton/PJ	[84]
NG_CHP		0,0000890	Mton/PJ	[84]
BG_CHP		0,0000890	Mton/PJ	[84]
Biomass_CHP		0,0000810	Mton/PJ	[84]
PV_Floating_PP		0	Mton/PJ	NA
PV_PP		0	Mton/PJ	[81]
Wave_PP		0	Mton/PJ	NA
Tides_PP		0	Mton/PJ	NA
Ocean_Thermal_PP		0	Mton/PJ	NA
Wind_PP		0	Mton/PJ	[81]
WindOff_PP		0	Mton/PJ	[81]
H2_SMR		0,0000890	Mton/PJ	NA
H2_PEM		0	Mton/PJ	NA
H2_ALK		0	Mton/PJ	NA
H2_SMR_CCS		0	Mton/PJ	[130]
H2_SolidOxy		0	Mton/PJ	NA
E-MeOH_Syn		0	Mton/PJ	NA
MeOH_Gas		0,000209	Mton/PJ	NA
E-DIE_Syn		0	Mton/PJ	NA
METne_Gas		0,000209	Mton/PJ	NA
E-METne_Syn		0	Mton/PJ	NA
E-Ammo_Syn		0	Mton/PJ	NA
TD_EL		0	Mton/PJ	NA
TD_DIE		0	Mton/PJ	NA

Table D.6: Technologies Techno-Economic Characterization: Emissions Factor.

Code	CO2e Emissions	NOx Emissions	Units	REF
TD_NG		0	Mton/PJ	NA
TD_H2		0	Mton/PJ	NA
TD_Ammo		0	Mton/PJ	NA
TD_MeOH		0	Mton/PJ	NA
TD_MDO_MGO		0	Mton/PJ	NA
TD_HFO		0	Mton/PJ	NA
TD_Heat		0	Mton/PJ	NA
TD_EL_SRD		0	Mton/PJ	NA
TD_DIE_SRD		0	Mton/PJ	NA
TD_NG_SRD		0	Mton/PJ	NA
TD_H2_SRD		0	Mton/PJ	NA
TD_EL_OGV		0	Mton/PJ	NA
TD_DIE_OGV		0	Mton/PJ	NA
TD_NG_OGV		0	Mton/PJ	NA
TD_H2_OGV		0	Mton/PJ	NA
TD_Ammo_OGV		0	Mton/PJ	NA
TD_MeOH_OGV		0	Mton/PJ	NA
TD_MDO_MGO_OGV		0	Mton/PJ	NA
TD_HFO_OGV		0	Mton/PJ	NA
TD_EL_TUG		0	Mton/PJ	NA
TD_DIE_TUG		0	Mton/PJ	NA
TD_NG_TUG		0	Mton/PJ	NA
TD_H2_TUG		0	Mton/PJ	NA
TD_Ammo_TUG		0	Mton/PJ	NA
TD_MeOH_TUG		0	Mton/PJ	NA
TD_EL_PIL		0	Mton/PJ	NA
TD_DIE_PIL		0	Mton/PJ	NA
TD_NG_PIL		0	Mton/PJ	NA
TD_H2_PIL		0	Mton/PJ	NA
TD_Ammo_PIL		0	Mton/PJ	NA
TD_MeOH_PIL		0	Mton/PJ	NA
TD_EL_BB		0	Mton/PJ	NA
TD_DIE_BB		0	Mton/PJ	NA
TD_NG_BB		0	Mton/PJ	NA
TD_H2_BB		0	Mton/PJ	NA
TD_Ammo_BB		0	Mton/PJ	NA
TD_MeOH_BB		0	Mton/PJ	NA
TD_EL_QC		0	Mton/PJ	NA
TD_DIE_QC		0	Mton/PJ	NA
TD_H2_QC		0	Mton/PJ	NA
TD_EL_ITRUCK		0	Mton/PJ	NA
TD_DIE_ITRUCK		0	Mton/PJ	NA
TD_NG_ITRUCK		0	Mton/PJ	NA
TD_H2_ITRUCK		0	Mton/PJ	NA
TD_MeOH_ITRUCK		0	Mton/PJ	NA

Table D.6: Technologies Techno-Economic Characterization: Emissions Factor.

Code	CO2e Emissions	NOx Emissions	Units	REF
TD_Ammo_ITRUCK		0	Mton/PJ	NA
TD_EL_REEF		0	Mton/PJ	NA
TD_EL_YC		0	Mton/PJ	NA
TD_DIE_YC		0	Mton/PJ	NA
TD_H2_YC		0	Mton/PJ	NA
TD_EL_FL		0	Mton/PJ	NA
TD_DIE_FL		0	Mton/PJ	NA
TD_NG_FL		0	Mton/PJ	NA
TD_H2_FL		0	Mton/PJ	NA
TD_EL_RS		0	Mton/PJ	NA
TD_DIE_RS		0	Mton/PJ	NA
TD_NG_RS		0	Mton/PJ	NA
TD_H2_RS		0	Mton/PJ	NA
TD_EL_ECH		0	Mton/PJ	NA
TD_DIE_ECH		0	Mton/PJ	NA
TD_NG_ECH		0	Mton/PJ	NA
TD_H2_ECH		0	Mton/PJ	NA
TD_EL_ETRUCK		0	Mton/PJ	NA
TD_DIE_ETRUCK		0	Mton/PJ	NA
TD_NG_ETRUCK		0	Mton/PJ	NA
TD_H2_ETRUCK		0	Mton/PJ	NA
TD_MeOH_ETRUCK		0	Mton/PJ	NA
TD_METne_ETRUCK		0	Mton/PJ	NA
TD_EL_LOC		0	Mton/PJ	NA
TD_DIE_LOC		0	Mton/PJ	NA
TD_H2_LOC		0	Mton/PJ	NA
TD_EL_TC		0	Mton/PJ	NA
TD_DIE_TC		0	Mton/PJ	NA
TD_H2_TC		0	Mton/PJ	NA
TD_EL_TRAIN		0	Mton/PJ	NA
TD_DIE_TRAIN		0	Mton/PJ	NA
TD_H2_TRAIN		0	Mton/PJ	NA
OGV_OPS_EL		0	Mton/PJ	NA
BB_DIE_DIE		4,33	Mton/PJ	NA
BB_NG_DIE		4,33	Mton/PJ	NA
BB_H2_DIE		4,33	Mton/PJ	NA
BB_Ammo_DIE		4,33	Mton/PJ	NA
BB_MeOH_DIE		4,33	Mton/PJ	NA
BB_MGO/MDO_DIE		4,33	Mton/PJ	NA
BB_HFO_DIE		4,33	Mton/PJ	NA
BB_DIE_NG		0,953	Mton/PJ	NA
BB_NG_NG		0,953	Mton/PJ	NA
BB_H2_NG		0,953	Mton/PJ	NA
BB_Ammo_NG		0,953	Mton/PJ	NA
BB_MeOH_NG		0,953	Mton/PJ	NA

Table D.6: Technologies Techno-Economic Characterization: Emissions Factor.

Code	CO2e Emissions	NOx Emissions	Units	REF
BB_MGO/MDO_NG		0,953	Mton/PJ	NA
BB_HFO_NG		0,953	Mton/PJ	NA
BB_DIE_H2		0	Mton/PJ	NA
BB_NG_H2		0	Mton/PJ	NA
BB_H2_H2		0	Mton/PJ	NA
BB_Ammo_H2		0	Mton/PJ	NA
BB_MeOH_H2		0	Mton/PJ	NA
BB_MGO/MDO_H2		0	Mton/PJ	NA
BB_HFO_H2		0	Mton/PJ	NA
TUG_MOTOR_EL		0	Mton/PJ	NA
TUG_ICE_NG		0,953	Mton/PJ	NA
TUG_ICE_DIE		4,33	Mton/PJ	NA
TUG_FC_H2		0	Mton/PJ	NA
TUG_ICE_Ammo		0	Mton/PJ	NA
TUG_ICE_MeOH		0	Mton/PJ	NA
PIL_MOTOR_EL		0	Mton/PJ	NA
PIL_ICE_NG		0,950	Mton/PJ	NA
PIL_ICE_DIE		4,33	Mton/PJ	NA
PIL_FC_H2		0	Mton/PJ	NA
PIL_ICE_Ammo		0	Mton/PJ	NA
PIL_ICE_MeOH		0	Mton/PJ	NA
QC_MOTOR_EL		0	Mton/PJ	NA
QC_ICE_DIE		1,684	Mton/PJ	NA
QC_FC_H2		0	Mton/PJ	NA
ITRUCK_MOTOR_EL		0	Mton/PJ	[81]
ITRUCK_ICE_NG		0,984	Mton/PJ	[81]
ITRUCK_ICE_DIE		0,864	Mton/PJ	[96]
ITRUCK_FC_H2		0	Mton/PJ	[80]
ITRUCK_ICE_Ammo		0	Mton/PJ	NA
ITRUCK_ICE_MeOH		0	Mton/PJ	NA
REEF_MOTOR_EL		0	Mton/PJ	NA
YC_MOTOR_EL		0	Mton/PJ	NA
YC_ICE_DIE		1,684	Mton/PJ	[96]
YC_FC_H2		0	Mton/PJ	NA
FL_MOTOR_EL		0	Mton/PJ	NA
FL_ICE_NG		0,385	Mton/PJ	[96]
FL_ICE_DIE		1,65	Mton/PJ	[96]
FL_FC_H2		0	Mton/PJ	NA
RS_MOTOR_EL		0	Mton/PJ	NA
RS_ICE_NG		0,399	Mton/PJ	NA
RS_ICE_DIE		1,70	Mton/PJ	NA
RS_FC_H2		0	Mton/PJ	NA
ECH_MOTOR_EL		0	Mton/PJ	NA
ECH_ICE_NG		0,399	Mton/PJ	NA
ECH_ICE_DIE		1,70	Mton/PJ	[96]

Table D.6: Technologies Techno-Economic Characterization: Emissions Factor.

Code	CO2e Emissions	NOx Emissions	Units	REF
ECH_FC_H2		0	Mton/PJ	NA
ETRUCK_MOTOR_EL		0	Mton/PJ	[81]
ETRUCK_ICE_NG		0,984	Mton/PJ	[81]
ETRUCK_ICE_DIE		0,864	Mton/PJ	[81]
ETRUCK_FC_H2		0	Mton/PJ	[81]
ETRUCK_ICE_Ammo		0	Mton/PJ	NA
ETRUCK_ICE_MeOH		0	Mton/PJ	NA
LOC_MOTOR_EL		0	Mton/PJ	NA
LOC_ICE_DIE		0,864	Mton/PJ	NA
LOC_FC_H2		0	Mton/PJ	NA
TC_MOTOR_EL		0	Mton/PJ	NA
TC_ICE_DIE		1,68	Mton/PJ	NA
TC_FC_H2		0	Mton/PJ	NA
TRAIN_MOTOR_EL		0	Mton/PJ	NA
TRAIN_ICE_DIE		0,864	Mton/PJ	NA
TRAIN_FC_H2		0	Mton/PJ	[80]

Table D.7: Technologies Techno-Economic Characterization: Availability Factor, Operational Lifetime and Capacity To Activity Unit.

Code	Availability Factor	Operational Lifetime (years)	Capacity To Activity (GW to PJ)	REF
NG_Import	-	30	1	[81]
DIE_Import	-	-	1	[81]
EL_Import	-	30	31,5	[84]
Ammo_Import	-	-	1	NA
MeOH_Import	-	-	1	NA
METne_Import	-	30	1	NA
MDO_MGO_Import	-	-	1	NA
HFO_Import	-	-	1	NA
GreenH2_Import	-	30	1	NA
H2_Import	-	30	1	NA
BG_Import	-	30	1	NA
Biomass_Extraction	-	-	1	NA
WS_Extraction	-	-	1	NA
WS_Gasifier	90%	30	31,5	[84]
NG_CHP		25	31,5	[84]
BG_CHP		25	31,5	[84]
Biomass_CHP		25	31,5	[84]
PV_Floating_PP	-	25	31,5	[131]
PV_PP	-	25	31,5	[81]
Wave_PP	-	20	31,5	NA
Tides_PP	-	20	31,5	[132]
Ocean_Thermal_PP	-	25	31,5	[81]
Wind_PP	-	30	31,5	[81]

Table D.7: Technologies Techno-Economic Characterization: Availability Factor, Operational Lifetime and Capacity To Activity Unit.

Code	Availability Factor	Operational Lifetime (years)	Capacity To Activity (GW to PJ)	REF
WindOff_PP	-	25	31,5	[80]
H2_SMR	90%	20	31,5	[80]
H2_PEM	95%	3	31,5	[80]
H2_ALK	90%	40	31,5	[80]
H2_SMR_CCS	90%	20	31,5	[80]
H2_SolidOxy	95%	10	31,5	[121]
E-MeOH_Syn	95%	25	31,5	[82]
MeOH_Gas	90%	20	31,5	NA
E-DIE_Syn	95%	30	31,5	[85]
METne_Gas	90%	20	31,5	NA
E-METne_Syn	95%	30	31,5	[85]
E-Ammo_Syn	95%	30	31,5	[85]
TD_EL	-	-	1	NA
TD_DIE	-	-	1	NA
TD_NG	-	-	1	NA
TD_H2	-	-	1	NA
TD_Ammo	-	-	1	NA
TD_MeOH	-	-	1	NA
TD_MDO_MGO	-	-	1	NA
TD_HFO	-	-	1	NA
TD_Heat	-	-	1	NA
TD_EL_SRD	-	-	1	NA
TD_DIE_SRD	-	-	1	NA
TD_NG_SRD	-	-	1	NA
TD_H2_SRD	-	-	1	NA
TD_EL_OGV	-	-	1	NA
TD_DIE_OGV	-	-	1	NA
TD_NG_OGV	-	-	1	NA
TD_H2_OGV	-	-	1	NA
TD_Ammo_OGV	-	-	1	NA
TD_MeOH_OGV	-	-	1	NA
TD_MDO_MGO_OGV	-	-	1	NA
TD_HFO_OGV	-	-	1	NA
TD_EL_TUG	-	-	1	NA
TD_DIE_TUG	-	-	1	NA
TD_NG_TUG	-	-	1	NA
TD_H2_TUG	-	-	1	NA
TD_Ammo_TUG	-	-	1	NA
TD_MeOH_TUG	-	-	1	NA
TD_EL_PIL	-	-	1	NA
TD_DIE_PIL	-	-	1	NA
TD_NG_PIL	-	-	1	NA
TD_H2_PIL	-	-	1	NA
TD_Ammo_PIL	-	-	1	NA

Table D.7: Technologies Techno-Economic Characterization: Availability Factor, Operational Lifetime and Capacity To Activity Unit.

Code	Availability Factor	Operational Lifetime (years)	Capacity To Activity (GW to PJ)	REF
TD_MeOH_PIL	-	-	1	NA
TD_EL_BB	-	-	1	NA
TD_DIE_BB	-	-	1	NA
TD_NG_BB	-	-	1	NA
TD_H2_BB	-	-	1	NA
TD_Ammo_BB	-	-	1	NA
TD_MeOH_BB	-	-	1	NA
TD_EL_QC	-	-	1	NA
TD_DIE_QC	-	-	1	NA
TD_H2_QC	-	-	1	NA
TD_EL_ITRUCK	-	-	1	NA
TD_DIE_ITRUCK	-	-	1	NA
TD_NG_ITRUCK	-	-	1	NA
TD_H2_ITRUCK	-	-	1	NA
TD_MeOH_ITRUCK	-	-	1	NA
TD_Ammo_ITRUCK	-	-	1	NA
TD_EL_REEF	-	-	1	NA
TD_EL_YC	-	-	1	NA
TD_DIE_YC	-	-	1	NA
TD_H2_YC	-	-	1	NA
TD_EL_FL	-	-	1	NA
TD_DIE_FL	-	-	1	NA
TD_NG_FL	-	-	1	NA
TD_H2_FL	-	-	1	NA
TD_EL_RS	-	-	1	NA
TD_DIE_RS	-	-	1	NA
TD_NG_RS	-	-	1	NA
TD_H2_RS	-	-	1	NA
TD_EL_ECH	-	-	1	NA
TD_DIE_ECH	-	-	1	NA
TD_NG_ECH	-	-	1	NA
TD_H2_ECH	-	-	1	NA
TD_EL_ETRUCK	-	-	1	NA
TD_DIE_ETRUCK	-	-	1	NA
TD_NG_ETRUCK	-	-	1	NA
TD_H2_ETRUCK	-	-	1	NA
TD_MeOH_ETRUCK	-	-	1	NA
TD_Ammo_ETRUCK	-	-	1	NA
TD_EL_LOC	-	-	1	NA
TD_DIE_LOC	-	-	1	NA
TD_H2_LOC	-	-	1	NA
TD_EL_TC	-	-	1	NA
TD_DIE_TC	-	-	1	NA
TD_H2_TC	-	-	1	NA

Table D.7: Technologies Techno-Economic Characterization: Availability Factor, Operational Lifetime and Capacity To Activity Unit.

Code	Availability Factor	Operational Lifetime (years)	Capacity To Activity (GW to PJ)	REF
TD_EL_TRAIN	-	-	1	NA
TD_DIE_TRAIN	-	-	1	NA
TD_H2_TRAIN	-	-	1	NA
OGV_OPS_EL	-	25	31,5	NA
BB_DIE_DIE	-	20	31,5	NA
BB_NG_DIE	-		31,5	NA
BB_H2_DIE	-		31,5	NA
BB_Ammo_DIE	-		31,5	NA
BB_MeOH_DIE	-		31,5	NA
BB_MGO/MDO_DIE	-		31,5	NA
BB_HFO_DIE	-		31,5	NA
BB_DIE_NG	-		31,5	NA
BB_NG_NG	-		31,5	NA
BB_H2_NG	-		31,5	NA
BB_Ammo_NG	-	20	31,5	NA
BB_MeOH_NG	-		31,5	NA
BB_MGO/MDO_NG	-		31,5	NA
BB_HFO_NG	-		31,5	NA
BB_DIE_H2	-		31,5	NA
BB_NG_H2	-		31,5	NA
BB_H2_H2	-		31,5	NA
BB_Ammo_H2	-		31,5	NA
BB_MeOH_H2	-		31,5	NA
BB_MGO/MDO_H2	-		31,5	NA
BB_HFO_H2	-		31,5	NA
TUG_MOTOR_EL	-	20	31,5	[114]
TUG_ICE_NG	-	20	31,5	[114]
TUG_ICE_DIE	-	20	31,5	[114]
TUG_FC_H2	-	20	31,5	[35]
TUG_ICE_Ammo	-	20	31,5	NA
TUG_ICE_MeOH	-	20	31,5	NA
PIL_MOTOR_EL	-	20	31,5	NA
PIL_ICE_NG	-	20	31,5	NA
PIL_ICE_DIE	-	20	31,5	NA
PIL_FC_H2	-	20	31,5	NA
PIL_ICE_Ammo	-	20	31,5	NA
PIL_ICE_MeOH	-	20	31,5	NA
QC_MOTOR_EL	-	10	31,5	NA
QC_ICE_DIE	-	10	31,5	NA
QC_FC_H2	-	10	31,5	NA
ITRUCK_MOTOR_EL	-	25	1	[81]
ITRUCK_ICE_NG	-	25	1	[81]
ITRUCK_ICE_DIE	-	25	1	[81]
ITRUCK_FC_H2	-	15	1	[80]
ITRUCK_ICE_Ammo	-	25	1	NA

Table D.7: Technologies Techno-Economic Characterization: Availability Factor, Operational Lifetime and Capacity To Activity Unit.

Code	Availability Factor	Operational Lifetime (years)	Capacity To Activity (GW to PJ)	REF
ITRUCK_ICE_MeOH	-	25	1	NA
REEF_MOTOR_EL	-	10	31,5	NA
YC_MOTOR_EL	-	10	31,5	NA
YC_ICE_DIE	-	10	31,5	[40]
YC_FC_H2	-	10	31,5	NA
FL_MOTOR_EL	-	10	31,5	NA
FL_ICE_NG	-	10	31,5	NA
FL_ICE_DIE	-	10	31,5	NA
FL_FC_H2	-	10	31,5	[80]
RS_MOTOR_EL	-	10	31,5	[133]
RS_ICE_NG	-	10	31,5	NA
RS_ICE_DIE	-	10	31,5	NA
RS_FC_H2	-	10	31,5	NA
ECH_MOTOR_EL	-	10	31,5	NA
ECH_ICE_NG	-	10	31,5	NA
ECH_ICE_DIE	-	10	31,5	NA
ECH_FC_H2	-	10	31,5	NA
ETRUCK_MOTOR_EL	-	25	1	[81]
ETRUCK_ICE_NG	-	25	1	[81]
ETRUCK_ICE_DIE	-	25	1	[81]
ETRUCK_FC_H2	-	15	1	[81]
ETRUCK_ICE_Ammo	-	25	1	NA
ETRUCK_ICE_MeOH	-	25	1	NA
LOC_MOTOR_EL	-	30	31,5	[134]
LOC_ICE_DIE	-	30	31,5	[134]
LOC_FC_H2	-	20	31,5	NA
TC_MOTOR_EL	-	10	31,5	NA
TC_ICE_DIE	-	10	31,5	NA
TC_FC_H2	-	10	31,5	NA
TRAIN_MOTOR_EL	-	30	31,5	NA
TRAIN_ICE_DIE	-	30	31,5	NA
TRAIN_FC_H2	-	20	31,5	[126]

Appendix E

Demand Evolution

The energy demand evolution, from 2030 to 2050, is presented in Tables E.1 and E.2.

Table E.1: Demand evolution from 2030 until 2040.

Year	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Demand Growth Indicator	2,8	3	3,2	3,4	3,6	3,8	3,9	4	4,1	4,2	4,3
Final Energy	6,70	7,20	7,70	8,20	8,60	9,10	9,40	9,60	9,80	10,1	10,3
OGV MDO [PJ]	533	571	609	647	685	723	742	761	780	799	818
OGV HFO [PJ]											
Tugboats [PJ]	0,0143	0,0153	0,0164	0,0174	0,0184	0,0194	0,0200	0,0205	0,0210	0,0215	0,0220
Useful Energy											
Pilot Vessels [PJ]	0,0122	0,0134	0,0143	0,0152	0,0161	0,0170	0,0174	0,0178	0,0183	0,0187	0,0192
Quay Cranes [PJ]	0,077	0,082	0,088	0,093	0,099	0,104	0,107	0,110	0,112	0,115	0,118
Yard Cranes [PJ]	0,0357	0,0382	0,0408	0,0433	0,0459	0,0484	0,0497	0,0510	0,0522	0,0535	0,0548
Reefers [PJ]	0,512	0,548	0,585	0,621	0,658	0,694	0,712	0,731	0,749	0,767	0,786
Internal Trucks [Gtkm]	0,0820	0,0879	0,0938	0,0996	0,105	0,111	0,114	0,117	0,120	0,123	0,126
Train Terminal Cranes [PJ]	0,00231	0,00248	0,00265	0,00281	0,00298	0,00314	0,00322	0,00331	0,00339	0,00347	0,00356

Table E.2: Demand evolution from 2040 until 2050.

Year	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Demand Growth Indicator											
Final Energy	4,3	4,4	4,5	4,6	4,6	4,73	4,73	4,73	4,73	4,73	4,73
OGV MDO [PJ]	10,3	10,6	10,8	11,0	11,0	11,4	11,4	11,4	11,4	11,4	11,4
OGV HFO [PJ]	818	837	856	875	875	900	900	900	900	900	900
Tugboats [PJ]	0,0220	0,0225	0,0230	0,0235	0,0235	0,0242	0,0242	0,0242	0,0242	0,0242	0,0242
Pilot Vessels [PJ]	0,0192	0,0196	0,0201	0,0205	0,0205	0,0211	0,0211	0,0211	0,0211	0,0211	0,0211
Quay Cranes [PJ]	0,118	0,121	0,123	0,126	0,126	0,130	0,130	0,130	0,130	0,130	0,130
Yard Cranes [PJ]	0,0548	0,0561	0,0573	0,0586	0,0586	0,0603	0,0603	0,0603	0,0603	0,0603	0,0603
Reefers [PJ]	0,786	0,804	0,822	0,840	0,840	0,864	0,864	0,864	0,864	0,864	0,864
Internal Trucks [Gtkm]	0,126	0,129	0,132	0,135	0,135	0,139	0,139	0,139	0,139	0,139	0,139
Train Terminal Cranes [PJ]	0,00356	0,00364	0,00372	0,00380	0,00380	0,00391	0,00391	0,00391	0,00391	0,00391	0,00391