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Master Thesis in Mechanical Engineering Submitted To Faculdade De Engenharia Da Universidade Do Porto

Developing an Energy System Model for Ports: A Sustainable Approach

Author:
Pedro Miguel Madeira Barbosa

Under the supervision of:
Professora Zenaida Mourão from FEUP

Under the co-supervision of:
Researcher Adrian Galvez from INESC TEC

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"Think, think, think."

Winnie The Pooh

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Abstract

Maritime transportation and the industrial sector have played pivotal roles in facilitating commerce and trade for countless centuries. With the continuous expansion of globalization, it becomes imperative to undertake a comprehensive examination of the pivotal connection between the maritime realm and terrestrial territories, specifically focusing on ports. This Master's Thesis in Mechanical Engineering is dedicated to the development of an energy model capable of meticulously delineating the energy consumption patterns and carbon emissions generated within the port facilities. Consequently, this research endeavor is motivated by the need to mitigate carbon emissions by charting the existing energy consumption and juxtaposing it with potential future scenarios achieved through the adoption of cleaner technologies and energy sources. It is only through the joint efforts of all industrial sectors, including ports, that humankind can effectively combat the pressing issues of climate change and global warming, with the ultimate aim of keeping the temperature rise since pre-industrial levels below the critical threshold of 2°C.

The model and its methodology represent a robust foundation for guiding decision-makers within the context of port management. This research endeavor involved an exhaustive examination of various facets of energy consumption within ports, with a particular emphasis on assessing emissions resulting from shipping activities and cargo handling equipment, given their relatively constrained utilization to ports. Several methodologies for calculating emissions were subjected to evaluation and critical analysis.

Furthermore, the primary objective of this study is to construct a succinct methodology that facilitates the process of accessing precise information that is often dispersed and fragmented across various sources. The model has been structured into five distinct areas, namely: Operations, Support & Maintenance, Buildings, General, and Energy Supply.

The methodology delineated for port operations was implemented at the port of Sines to illustrate its practical validity. This application not only serves the purpose of unveiling current constraints but also delves into prospects for enhancing the model. To comprehensively assess the model's capabilities, several decarbonization scenarios were conceptualized. By implementing pertinent measures, it was possible to achieve a notorious reduction of up to 90% in emissions within the Operations sector. This accomplishment underscores the robustness and relevance of this analytical tool.

Keywords - Maritime Ports, Sustainability, Energy Model, Carbon Emissions, Green Ports, Energy Efficiency, Electrification.

Resumo

O transporte marítimo e o setor industrial têm desempenhado papéis fundamentais na facilitação do comércio e das trocas comerciais ao longo de inúmeros séculos. Com a contínua expansão da globalização, torna-se imperativo efetuar uma análise abrangente da ligação fundamental entre o domínio marítimo e os territórios terrestres, com especial incidência nos portos. Esta tese de mestrado em Engenharia Mecânica é dedicada ao desenvolvimento de um modelo energético capaz de delinear meticulosamente os padrões de consumo de energia e as emissões de carbono geradas nas instalações portuárias. Consequentemente, este esforço de investigação é motivado pela necessidade de mitigar as emissões de carbono através do mapeamento do consumo de energia existente e justapondo-o com potenciais cenários futuros alcançados através da adoção de tecnologias e fontes de energia mais limpas. É apenas através dos esforços conjuntos de todos os setores industriais, incluindo os portos, que a humanidade pode combater eficazmente as questões prementes das alterações climáticas e do aquecimento global, com o objetivo final de manter o aumento da temperatura desde os níveis pré-industriais abaixo do limiar crítico de 2°C.

O modelo e a sua metodologia representam uma base sólida para orientar os decisores no contexto da gestão portuária. Este trabalho de investigação envolveu uma análise exaustiva das várias facetas do consumo de energia nos portos, com particular ênfase na avaliação das emissões resultantes das actividades de navegação e dos equipamentos de movimentação de carga, dada a sua utilização relativamente limitada aos portos. Várias metodologias de cálculo das emissões foram objeto de avaliação e análise crítica.

Além disso, o principal objetivo deste estudo é construir uma metodologia sucinta que facilite o processo de acesso a informação precisa, muitas vezes dispersa e fragmentada em várias fontes. O modelo foi estruturado em cinco áreas distintas, nomeadamente: Operações, Apoio & Manutenção, Edifícios, Geral e Fornecimento de Energia.

A metodologia delineada para as operações portuárias foi implementada no porto de Sines para ilustrar a sua validade prática. Esta aplicação não só serve o propósito de revelar os constrangimentos actuais, mas também de aprofundar as perspetivas de melhoria do modelo. Para avaliar de forma abrangente as capacidades do modelo, foram conceptualizados vários cenários de descarbonização. Através da implementação de medidas pertinentes, foi possível alcançar uma redução notória de até 90% nas emissões no setor das Operações. Essa conquista ressalta a robustez e a relevância dessa ferramenta analítica.

Palavras-Chave - Portos Marítimos, Sustentabilidade, Modelo Energético, Emissões de Carbono, Portos Verdes, Eficiência Energética, Eletrificação.

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List of Acronyms

AE	Auxiliary Engine
AGV	Automatic Guided Vehicles
ALV	Automated Lifting Vehicles
ASC	Automatic Straddle Carriers
CHE	Cargo Handling Equipment
CHP	Combined Heat and Power
COP	Coefficient Of Performance
DTC	Dual-Trolley Cranes
EC	European Commission
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Index
EMAS	Eco-Management and Audit Scheme
EMPs	Environmental Management Plans
EMS	Environmental Management System
EnBs	Energy Baselines
EnMS	Energy Management System
EnPIs	Energy Performance Indicators
ESF	Electricity Specific Factor
ESPO	European Sea Ports Organisation
EU	European Union
FEU	Fourty-foot Equivalent Unit
GHG	Greenhouse Gas
GT	Gross Tonnage
HC	Harbour Craft
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
ISO	International Standards Organization
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
MDO	Marine Diesel Oil
ME	Main Engine
NGOs	Non Govermental Organizations
OBC	Overhead Bridge cranes
OGV	Ocean Going Vessels
OPS	Onshore Power Supply
PA	Port Authority
PDCA	Plan-Do-Check-Act
PERS	Port Environmental Review System
PM	Particulate Matter
QC	Quay Cranes
RES	Renewable Energy Source
RMG	Rail Mounted Gantry
RO	Residual Oil

RoPax	Combination of RoRo and ferry for people
RoRo	Roll-on Roll-off
RSZ	Reduction Speed Zone
RTG	Rubber Tired Gantries
SC	Straddle Carriers
SDGs	Sustainable Development Goals
SEUs	Significant Energy Uses
STC	Single-Trolley Cranes
TEU	Twenty-foot Equivalent Unit
TT	Terminal Trucks
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development
WEF	World Economic Forum
YT	Yard Trucks

List of Symbols

AS	Actual Speed	[knots] or [km/h]
C	Average consumption	[L/km or move] or [kWh/km or move]
CH_4	Methane	[-]
CO	Carbon monoxide	[-]
CO_2	Carbon dioxide	[-]
CO_{2e}	Carbon dioxide equivalent	[-]
E	Electricity consumed	[kWh]
EF	Emission Factor	[kg/kWh]
H_2O	Water	[-]
h_v	Heating value	[MJ/kg]
HFC_s	Hydrofluorocarbons	[-]
LF	Load Factor	[-]
MS	Maximum Speed	[knots] or [km/h]
N_2O	Nitrous oxide	[-]
P	Power	[kW] or [hp]
PFC_s	Perfluorocarbons	[-]
S	Number of containers	[-]
SF_6	Sulfur hexafluoride	[-]
SO_x	Sulfur oxide	[-]
t	Time	[h]
V	Liters consumed	[L]
ρ	volumic mass	[kg/L]
η	efficiency	[-]

Chapter 1

Introduction

This work will consist of the study and development of a new tool to calculate and reduce carbon dioxide (CO_2) emissions in order to achieve carbon neutrality in maritime ports by 2050. For this purpose, it is necessary to model the energy uses in a port and propose solutions for this objective.

1.1 Background and context: sustainability concerns in ports

Maritime trade represents more than 80% of global trade [1]. The tendency is that the amount of volume of trade keeps increasing as globalization and international trade grow even bigger [2]. The transportation of cargo or passengers nowadays results in huge amounts of Greenhouse Gas (GHG) emissions due to the technologies used [3].

Although maritime trade represents this high volume of trading around the world, it only represents 2.3% of global emissions of CO_2 (800 to 850 million tons). However, for sulfur emissions (SO_x), ocean-going vessels represent 5-8% of emissions worldwide [4]. It is a problem that has to be addressed by competent authorities such as IMO (International Maritime Organization), ports' management and governments [5]. To fight global warming and meet the United Nations (UN) Sustainable Development Goals (SDGs) it is necessary to be a joint effort around the globe [6].

The point that connects the maritime routes with posterior routes (can be maritime as well, river, trains or trucks) are the ports. Ports have existed for many centuries and are characterized by being a transit point for goods and people [7]. Since maritime transports impact many people's lives, it is mandatory to study the door to the mainland, the ports [8]. As ports serve as a connecting point in global trade, they have a pivotal role to serve when speaking about the sustainability of the maritime sector [9].

The modern port is not only a structure where boats come to unload their goods or people but it is becoming a fulcrum point in technology development, industry and logistics right in the center of the supply chain [10, 11].

1.2 Relevance of energy system modeling in ports

For the reason given in the previous subsection, many studies have been conducted in recent years in order to achieve higher energy efficiency and incorporate higher energy management [12]. The common goal is to achieve the decarbonization of every sector by 2050, in this case, the ports [13]. In the Declaration on Zero Emission Shipping by 2050, held in Glasgow in 2021 by the UN, several countries emphasize the fact that emissions from international shipping must be reduced significantly during the next decades, reaching 0 by 2050 in order to maintain the temperature goals set in the Paris Agreement [14]. The principal goal is to maintain the temperature with an increase up to 2 °C and make an effort to keep it under 1.5 °C compared with pre-industrial levels. Figure 1.1 shows the possible trends of temperature. In one evolution with stronger measures, the temperature increase can be reduced significantly. This implicates the decarbonization by 2050, as mentioned above. On the contrary, if the target is global decarbonization in 2100, the rise in temperature is kept and with this comes intangible consequences.

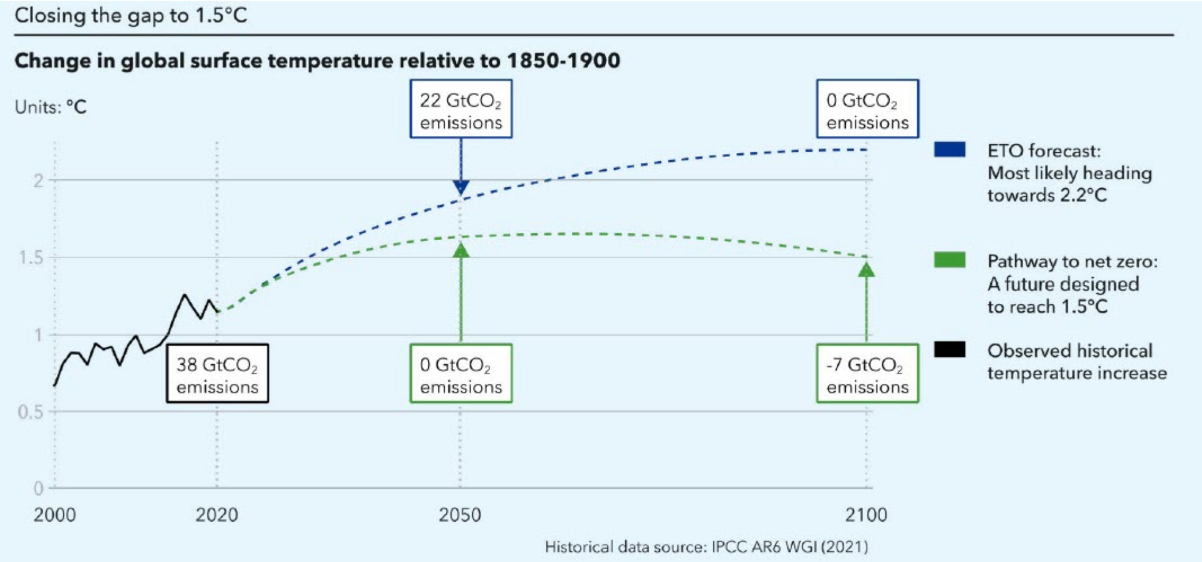

Figure 1.1: Evolution of global surface temperature [15].

To achieve this goal of having green ports [1] it is necessary to conduct exhaustive research on which are the sources of energy and then create a model with which is possible to preview future scenarios of energy consumption and greenhouse gas emissions. This, in turn, can help port authorities and policymakers identify opportunities for improving energy efficiency and promoting the transition towards more sustainable and low-carbon port operations.

1.3 Research questions and objectives

The main objective of this study is to develop and apply an energy system model for ports that enables the assessment of current and future energy use and the evaluation of different

[1] Green ports are characterized by being both environmentally and economically efficient. There are three main ways of becoming a green port. It can be through stakeholder engagement, green policies, and scientific monitoring [16].

decarbonization scenarios, with the aim of identifying opportunities for improving energy efficiency and promoting sustainable port operations. To achieve this goal, the study addresses the following research questions:

- How can an energy system model be developed to effectively represent and analyze the current and future energy use in ports, considering the disaggregated demand into final end uses for different activities or areas within ports?
- What are the potential impacts of different decarbonization scenarios on the energy consumption and greenhouse gas emissions in ports from the reference year (e.g., 2019) up to 2050?
- How can the developed energy system model help identify opportunities for improving energy efficiency and supporting the transition towards more sustainable and low-carbon port operations?

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

- Design a comprehensive energy system model for ports that accurately represents the full energy conversion chain from supply to demand, considering the disaggregated demand into final end uses for different activities or areas within ports.
- Characterize the current energy system in ports using available energy and logistics data, and establish a baseline for evaluating future energy use and decarbonization scenarios.
- Develop and analyze various decarbonization scenarios that consider different levels of ambition in reducing greenhouse gas emissions and improving energy efficiency within port operations.
- Evaluate the impacts of the decarbonization scenarios on the energy consumption, greenhouse gas emissions, and sustainability performance of the ports from the reference year (e.g., 2019) up to 2050.
- Identify opportunities and strategies for improving energy efficiency and promoting the transition towards more sustainable and low-carbon port operations based on the findings of the energy system model.
- Develop a model that is accessible to anyone for free and at the same time reliable and easy to work.
- Compile the data gathered from various sources of information about technologies used in ports (powers, load factors, specific emissions, fuels used, etc).

1.4 Structure of the Thesis

This master's thesis is organized into several interconnected chapters. The organization of the work is the following:

The present chapter (section 1) provides an introduction to the problem and explains the importance of this work presenting the background, context, and research questions related to sustainability concerns and energy system modeling in ports.

Section 2 provides an overview of existing models and identified research gaps that inform the proposed research questions.

In the next section (chapter 3), it is elaborated on the process of how the model was built. The technologies and methods used in the different operations at the ports are reviewed. It is also a chapter in which the tools to calculate GHG emissions are mentioned as well as evaluated and examined.

After this, section 3.3 shows how the data was obtained. The implementation of the tool is also shown in the present section.

In section 4, are made some predictions about the future and given some solutions for the next decades in order to achieve the climate goals.

In section 5, it is made a summary of the main findings, implications for port operations and policies, limitations and challenges.

Finally, in section 6 are addressed the gaps in the model and how it can be improved in future work.

Chapter 2

State of Art

This chapter presents a literature review that explores various topics relevant to the work and models 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. Additionally, the chapter examines the current energy use in ports and the supporting equipment and systems that facilitate their operation. This is the basis for designing port specific measures for energy efficiency improvement, energy policies and decarbonisation roadmaps for ports. Thus, an analysis of the existing sources of energy, from primary to final and useful energy, is also crucial to understand the connection of the overall energy use in ports to the operations and services these support.

The review is organized into several sections aligned with the overall aims stated above. First, a brief description of the methodology used for the literature review is presented. This is followed by a section on the importance of ports and their links to energy supply and demand - both within and beyond their geographical limits. Subsequently, the different energy and GHG emissions reporting models and methodology for ports are discussed, followed by a brief overview of the international standards for environmental and energy management. Finally, the last section of this chapter summarizes the main gaps identified in the literature and highlights the novel contribution of this work, linking these clearly to the objectives and research questions addressed in this thesis.

2.1 State of Art: the methodology

A comprehensive literature review was carried out on the topics associated with port energy systems, mapping GHG emissions and the different conversion systems and equipment supporting operations in ports. In order to ensure that the research is comprehensive, several databases of journals in relevant topics were consulted. The list of keywords and databases used are shown in table 2.1. The languages that were chosen were: English, Portuguese and Spanish.

Table 2.1: Literature Review: Data Bases and set of Keywords used in the research

Data Bases	Keywords
Scopus Science Direct Google Scholar	"Ports", "Ports and Harbours", "Ports and Harbours" AND "energy", "Ports and Harbours" AND "energy model", "Port emissions", "Ports and Harbours" AND "sustainability", "Shipping emissions", "Cargo Handling equipment emissions"

In addition to search for papers within the databases presented above, reports from different institutions were also analysed to get a better understanding of the general picture of maritime ports. These included reports from ports worldwide, for example, Hamburg Port, European Union (EU) plans or reports, United Nations Conference on Trade and Development (UNCTAD), the World Economic Forum (WEF) and books about this subject.

2.2 Maritime Trade and Importance of Ports

Ports, as critical hubs in international trade, are positioned uniquely within global energy dynamics due to their geographic concentration, high energy demand and supply activities [17]. This stems from their proximity to cities and power production facilities and their crucial role in the transportation of raw materials. With their growing significance in today's global economy and their potential as hubs for future low-carbon vectors, it is important to study and develop an energy system model capable of describing energy use at the port level, that can also serve as support to the definition of port decarbonisation pathways and energy policies at different levels.

Research on the shipping sector shows that emissions originate from both vessels and ports, with a significant portion contributed by the first. Extensive studies on strategies to decrease emissions from vessels have been carried out, for example in [12] and [18]. However, less focus has been placed on harbours' and ports' efforts to reduce their emissions. Ports are an essential part of the shipping industry's transportation network and have a significant impact on trade demand and the expansion of marine freight. The expanding capacity of the ports as transport nodes is essential for the expansion of the freight industry thus also economic growth in general [19, 20].

Forecasts indicate that maritime transportation will continue to grow in the coming decades, in tandem with expected population growth and global trade expansion [1, 21]. Hence, sustained efforts to increase the sustainability and resilience of the sector must be made at the EU and global levels [22]. The shipping industry is especially vulnerable to the impacts of global warming, such as rising sea levels, flooding, and extreme weather events, making adjustments to port infrastructure and shipping operations necessary. In addition to these problems, there are concerns regarding health issues affecting local communities living in the vicinity of ports, such as respiratory problems and lung cancer [23, 24]. Studies suggest that the pressure on the industry to deal with these issues are likely to intensify unless effective mitigation measures are implemented [19, 25].

According to the International Maritime Organization's (IMO) 2020 forecast, the shipping industry's GHG emissions were projected to increase by 90% in 2018 relative to 2008, and 90-130% by 2050, relative to 2008. Although these projections did not account for the COVID-19 pandemic, which could slow the growth of the maritime sector for several years, such an increase in emissions is incompatible with the European Union's 2050 goal of achieving climate neutrality [25].

Given these challenges, the EU has implemented several legislations to protect the marine ecosystem, such as the Habitats Directive, the Water Framework Directive, and the Marine Strategy Framework Directive. The major objectives of these regulations is to reduce air and other forms of pollution in ports and coastal communities while upholding high environmental standards. Further initiatives, including those proposed in REPowerEU and EU Green Deal, aim to decrease GHG emissions and foster innovative solutions [26, 25].

The European Sea Ports Organisation (ESPO) provides updates on the top 10 priorities for port authorities regularly, offering crucial insights for policymakers about which are the focus of ports in environmental issues. Figure 2.1 shows the increasing emphasis on climate change as a major priority throughout the years, having reached the top priority for European Ports in the latest edition of the list. This, combined with the other top priorities of air quality and energy efficiency, underscore the importance of developing a model capable of evaluating measures to improve energy use, efficiency and emissions in ports [27].

	1996	2009	2013	2018	2019	2020	2021	2022
1	Port development (water)	Noise	Air quality	Air quality	Air quality	Air quality	Air quality	Climate change
2	Water quality	Air quality	Garbage/ Port waste	Energy consumption	Energy consumption	Climate change	Climate change	Air quality
3	Dredging disposal	Garbage/ Port waste	Energy consumption	Noise	Climate change	Energy efficiency	Energy efficiency	Energy efficiency
4	Dredging operations	Dredging operations	Noise	Relationship with the local community	Noise	Noise	Noise	Noise
5	Dust	Dredging disposal	Ship waste	Ship waste	Relationship with the local community	Relationship with the local community	Relationship with the local community	Water quality
6	Port development (land related)	Relationship with the local community	Relationship with the local community	Port development (land related)	Ship waste	Ship waste	Water quality	Relationship with the local community
7	Contaminated land	Energy consumption	Dredging operations	Climate change	Garbage/ Port waste	Water quality	Ship waste	Ship waste
8	Habitat loss/ degradation	Dust	Dust	Water quality	Port development (land related)	Garbage/ Port waste	Dredging operations	Garbage/ Port waste
9	Traffic volume	Port development (water)	Port development (land related)	Dredging operations	Dredging operations	Dredging operations	Port development (land related)	Port development (land related)
10	Industrial effluent	Port development (land related)	Water quality	Garbage/ Port waste	Water quality	Port development (land related)	Garbage/ Port waste	Dredging operations

Figure 2.1: Top 10 priorities of European Ports over the last years [27].

In 2021, the European Union announced its plan to implement a new package of proposals termed ‘Fit for 55’. This initiative targets a substantial reduction in net GHG emissions of at least 55% by 2030, compared to emission levels of 1990, therefore establishing Europe as the first climate-neutral continent by 2050 [28].

While such measures and packages might target large geographical areas, such as the entirety of the EU, the responsibility for implementation and exploration of optimal solutions for achieving the targets at the port level lies with port authorities and port stakeholders [29, 30]. Thus, a thorough understanding of the energy use and needs at the port level is essential to implement these goals. The development of an energy system capable of simulating the current energy system as well as the future energy needs, subject to specific targets, would therefore allow port authorities and stakeholders to explore pathways with the best cost-benefits.

2.3 Overview of existing energy system models for ports

Ports are complex systems with different areas of study and interest. Many existing studies focus on ship emissions as maritime shipping is the primary mode for transporting goods internationally between ports. However, other activities within the ports related to the movement of cargo also have a major impact on energy use and emissions, especially at the local scale. Figure 2.2, shows an image of one of the biggest ports in the world located in Shenzhen, China (fourth in the volume of trade in container ports, with 28.77 million Twenty-foot Equivalent Units (TEU) in 2021) [31]. The image shows the complexity and size of a port as well as its proximity to urban areas. This is representative of many other ports in the world, with differences mainly in the scale of operation.

Figure 2.2: Photography of the port of Shenzhen, China [32].

As illustrated in figure 2.3, the port has various zones on the mainland. Vessels enter the harbour and when they berth, in the quayside, their goods are unloaded. Vehicles then transport these goods to an intermediary zone (the yard side) to be stored before being sent by train or truck to their final destination in the hinterland or loaded to other maritime vessels.

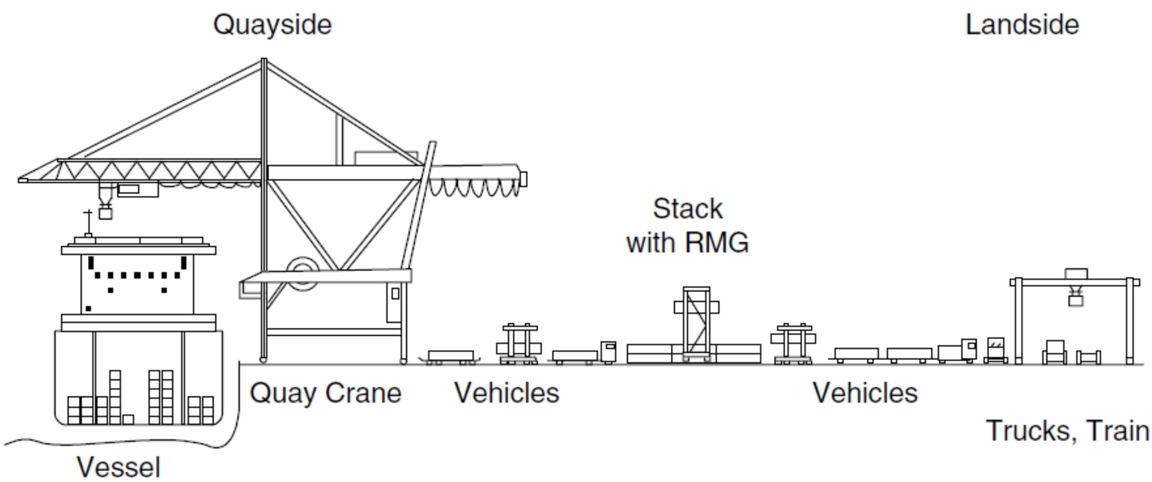

Figure 2.3: Representation of different areas and operations of a port (not in scale) [33].

Figure 2.4 presents an overview of the operations and transport routes within a port, as it was explained previously. It also illustrated the interconnection between the three key areas of a port. Notably, the yard side is where more operations take place due to its connection with the other areas.

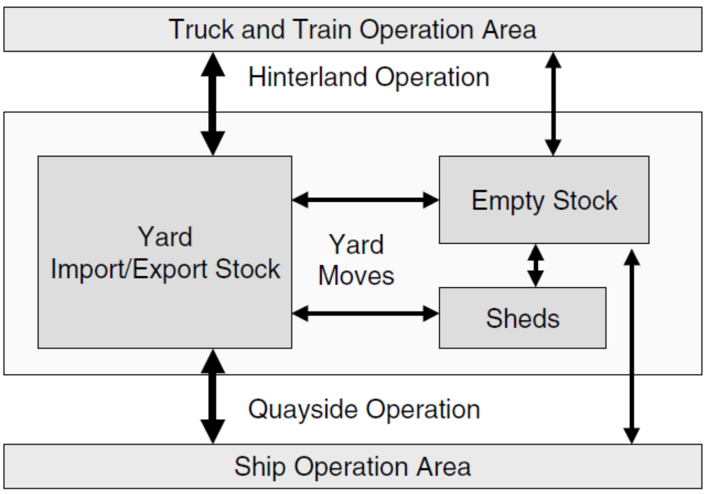

Figure 2.4: Operation in a port (simplified) [33].

There are various models existing in the literature that calculate the emissions and energy consumption in ports at different levels of detail. Some allow the calculation of emissions or energy consumption produced by vessels - both for the entirety of the trip between ports and specifically during their time within the port area, with the former being the most studied aspect of these types of models. Other models focus on container port and its uses (land-based), even examining specific cranes or comparing different cranes. Some models aim to provide comprehensive inventories of energy consumption and sources of emissions in a port, including land-based emissions and those from vessels in the port area. Examples of these different categories of models can be found in the literature and are presented in table 2.2.

Table 2.2: Models for different sectors in ports and shipping

Sector of model	Area/timeframe	Reference
Ship emission	Porto, Portugal, 2023	[4]
	Portugal, 2016	[34]
Ship emissions at the port	Southeast Asia, 2022	[35]
	Mexican ports, 2021	[36]
	Split, Croatia, 2020	[37]
	Port of Gothenburg, Sweden, 2015	[12]
	Las Palmas Port, Spain, 2015	[38]
	Barcelona, Spain, 2011	[39]
Land-based emissions	Roterdam, Netherlands 2011	[40]
	Ambarlı Port, Turkey, 2021	[41]
Specific Cranes	Saudi Arabia, 2022	[42]
	Indonesia, 2021	[43]
	Port of Felixstowe, England, 2017	[44]
	Port of Felixstowe, England, 2017	[45]
	Port of Kaohsiung, Taiwan, 2013	[46]
Port's Emissions (all combined)	Shenzhen Port, China, 2023	[19]
	Ambarlı Port, Turkey, 2023	[47]
	Vigo, Spain, 2023	[48]
	Barcelona, Spain, 2021	[49]
	Valencia, Spain, 2020	[50]
	Los Angeles, USA, 2020	[51]
	South Korea, 2018	[52]

This work aims to explore the latter category - models capable of mapping the whole energy system of a port. However, it is also essential to map the various subsystems which constitute a port, representing the energy use and related emissions of vessels within the port, buildings or any other equipment [53]. The reason for this is that ports are responsible not only for the land-based emissions but also for shipping emissions within a given radious of the port [54].

The following sections deal with energy use and related emissions from ports into two major groups, given the particularities of the systems involved: Ships and Land-based systems [39].

2.3.1 Shipping emissions

In the analysis of maritime port emissions, it is important to distinguish between different types of vessels: the ones that leave the port continuing their maritime journey, Ocean-Going Vessels (OGV), and the ones that operate within the port, which include Harbour Craft (HC), and inland waterway vessels. This division, along with a detailed methodology, will be discussed later in this thesis.

Table 2.3 presents several type of OGV that can enter in a port. Each vessel's emissions must be evaluated within the geographical scope of any port, defined by the respective port or authority analysing the port emissions.

Table 2.3: Types of Ocean Going Vessels

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

Dry Bulk carriers transport essential raw dry materials for the global economy. They carry a wide diversity of products, but the most common cargos are iron ore (a key material for steel production), coal, and grain. Other products like rice and sugar are transported by these carriers [55]. Loading and unloading of goods typically use a conveyor belt and chute system [56].

In contrast to Dry Bulk carriers, tankers have the task of carrying liquid cargoes in bulk. The category of tanker will change depending on the cargo they transport. Tankers can be divided in several sub-types: Chemical Tankers, Oil Tankers, Liquified Gas Tankers and Other Liquids Tankers [56, 57].

Oil tankers transport crude oil and refined petroleum products to where they are required. For this reason, oil tankers play a vital role in global economy and in energy supply chains around the globe [57].

Chemical tankers transport a variety of industrial chemicals, many of which are hazardous. Due to the risks associated with their cargo, these vessels have tight construction and operation regulations. Some examples include caustic soda or sulphuric acid [57, 58].

Gas carriers can transport Liquified Petroleum Gas (LPG) or Liquified Natural Gas (LNG), which are used in many applications, including at ports [57]. Recent technological advances in hydrogen production, climate goals, and international politics, have prompted a growing interest in Liquid Hydrogen tankers which are under development in many countries [59].

Any other type of liquid cargo, such as water and alcohol, falls under the category of other liquid tankers. Tankers, in general, play a crucial role in global trade and energy security as they are responsible for moving essential commodoties such as gas and petroleum.

Containerships transport the vast majority of manufactured goods and products. These vessels usually transport two standardizes container sizes: 20 or 40-feet equivalent units, known as TEUs and FEUs respectively [60].

In the era of globalization, consumers are accustomed to having access to a wide variety of fruits, vegetables and meats all year round. This is only possible due to cold supply chains, particularly refrigerated vessels. These vessels transport perishable goods (food, vaccines, pharmaceutical products, etc.) that would otherwise spoil on regular ships or containers [61, 62]. The cargo can be stored in pallets or in bulk. Alternatively, these goods can also be transported in reefers (refrigerated containers) on a containership. Reefers are usually made of steel with insulation [63].

Ferries transport people, vehicles and cargo from one ferry terminal to another. The ferry RoPax, which combines a cruise ship with a Roll-On Roll-Off Vessel (RoRo), can transport both passengers and vehicles. RoRos allow quick loading, or boarding, and unloading, or exit, from the vessel [64, 65].

Cruise ships are seagoing vessels where passengers stay on board for at least one night, usually with more than 100 people onboard [66]. They typically offer various forms of entertainment and are usually associated with tourism activities [67].

Finally, tugboats assist larger vessels in maneuvering when near or inside a port [68, 69]. Despite their relatively small size, tugboats have disproportionately large power, which they use for short periods while towing or pushing other floating platforms [70].

For HC, the different types of vessels are depicted in table 2.4. It should be noted that model specifications can vary, leading to fluctuation in the type or designation given to a specific group of vessels. In tables 2.3 and 2.4 are sorted the most common categories of ships found in literature. The data was mainly retrieved from [56] and [71], being completed from other sources.

Table 2.4: Types of Harbour Craft

Harbour Craft
Assist Tugboats
Towboats and Push boats
Government Vessels
Local Ferries
Excursion Vessels
Crew Boats
Work Boats
Pleasure Craft

Emission evaluation methodologies in maritime transport can differ significantly depending on the focus of the study. Some models choose to evaluate emissions from 3 or 4 types of vessel, others evaluate only one type, and some evaluate all vessels simultaneously. This usually occurs due to the aim of the assessment, which may be focusing on emissions specific sets of vessels, e.g., transporting certain types of cargo, as explained above, or may be focusing on studying specific types of terminals, such as those for containers or dry bulk.

The available literature tends to focus on OGV emissions since these represent a larger percentage of global emissions [72, 73]. Nevertheless, some studies address the emissions of HC as they contribute significantly in the emissions within ports, accounting for up to 23% of CO_{2e} emissions in some cases [74]. Moreover, in many ports, the number of harbour vessels exceeds that of ocean-going vessels, leading to a higher impact on humans and the environment due to their activities taking place in closer proximity to the port [72].

Ship emissions can be calculated using two main methods: one is fuel-based (top-down) and the other is activity-based (bottom-up) [75]. The top-down method uses total fuel consumption and specific fuel emission factors (quantity and type of fuel are important) [36]. This approach is mainly used when there is no detailed information about the ship traffic [76]. Despite apparent simplicity of this method, it has several drawbacks. For example, calculating fuel consumption can be complex, leading to potential errors in the calculation of fuel emissions [35, 77].

The bottom-up method is mostly used to estimate emissions from vessels. It uses detailed information about the vessels' specifications, for example its type, dimensions, type of main and auxiliary engines, fuel type, and operation data such as time spent in every phase (hotelling, anchoring, maneuvering, cruising, etc.), travel distances and maximum speed [35, 36, 75, 76]. In this type of method, total emissions are calculated for each vessel according to its activity and are then aggregated with the rest of the fleet [76, 78]. Consequently, in comparison to the top-down method, the bottom-up approach tends to be more accurate.

Despite its advantages, the bottom-up method raises some challenges, particularly for large-scale models intended for use in different ports across various countries. The biggest challenge is the use of average input values for engines load factors, fuel consumption rate, and emissions factors that depend on the specific vessel due to different size, age, fuel type, and ship type. All these factors can introduce significant uncertainties in the overall emissions estimates [75, 76].

Some studies use a combination of both methodologies, depending on data availability [76]. While the top-down method might be less reliable due to its dependence on fuel sales data, the bottom-up method often over-estimates emissions [75, 77]. Table 2.5 presents a few studies and the method used for emissions calculation.

Table 2.5: Methodology used in the shipping models for ports from table 2.2

Area/timeframe	Shipping Sector	Methodology	Ref.
Port of Gothenburg, Sweden, 2015	OGV	BOTTOM-UP method	[12]
Barcelona, 2011	OGV	BOTTOM-UP method	[39]
Oslo, 2017	OGV and HC	BOTTOM-UP method	[74]
Las Palmas Port, Spain, 2015	OGV	Full BOTTOM-UP approach	[38]
Southeast Asia, 2022	OGV	BOTTOM-UP method	[35]
Mexican Ports, 2021	Container, RoRo, Tanker and Bulk Carrier	BOTTOM-UP method, incorporating information on typology and vessel as well as emission factors.	[36]
Split, Croatia, 2020	Passenger Vessels and Cargo	BOTTOM-UP method, using the EMEP/EEA air pollutant emission inventory guidebook (Tier 3 method) Manoeuvring and Hotteling	[37]

2.3.2 Land Based emissions

This subsection covers a broad range of topics concerning land-based emisions in ports. To fully comprehend the land-based emissions, it is necessary to consider a variety of sources such as buildings, lighting, cargo handling equipment, and others.

These emissions are categorized into two broad sections. The first, which is often associated with ports, is Cargo Handling Equipment (CHE). In the literature, various studies focus either on a specific type of crane, others on sets of different equipment, or on a comparative analysis between different cranes and other equipment. The second category includes analysis of emissions from buildings, generation of heat/electricity, lighting, among others.

Emissions from CHE operations, can be estimated using fuel consumption (top-down approach), or by determining the average consumption of specific equipment and multiplying by the number of kilometers or hours spent in utilization and waiting (bottom-up approach). These calculations include emissions from equipment used for operations related to the quay loading and unloading, quay-to-storage transportation, and storage/hinterland operations. The CHE is shown in the table 2.6 below. It is worth noting that these emission sources are specific to maritime ports, hence the emphasis on shipping emissions and Cargo Handling Equipment in the present section 2.

Table 2.6: Cargo Handling Equipment

Cargo Handling Equiment	
Quay Cranes	Single-trolley Cranes
	Dual-trolley Cranes
Stack Cranes	Rail Mounted Gantry Cranes
	Rubber Tired Gantries
	Overhead Bridge Cranes
Transport Vehicles	Automatic Guided Vehicles
	Automatic Straddle Carrier
	Automated Lifting Vehicles
	Straddle Carrier
	Intelligent Automatic Vehicles
	Yard Trucks
Light Container Movement	Forklifts
	Reachstackers

2.4 Measures to achieve decarbonization in ports

This section covers the measures identified in the literature that analyze the strategies that ports are following to achieve full decarbonization of their operations by 2050. The measures can be grouped into three types:

1. Changing or adapting the conversion devices. This involves changing the technology used for a given activity. It can be a change in equipment or energy vector used.

   Onshore Power Supply (OPS) or cold ironing is one of the first policies to be suggested to be implemented to promote decarbonization at ports. This measure is simply about plugging the vessel into the dock so it can have energy in the form of electricity to perform all the activities necessary during berth. Ports and calls with a higher ship handling time, which means a higher time spent at a port, have a greater potential of reducing emissions through OPS. This technology faces some challenges, for example, finding the correct voltage, the most proper connection type, or grid capacity [79]. Not only emissions but also noise is reduced through the implementation of OPS [80].

   Electrification of cranes and terminal trucks is a measure with an immense potential depending on the electricity mix used to power this equipment [79, 80]. Electrification needs to be supported by cleaner electricity so that emissions can be truly reduced. If for example, the electricity was produced by burning coal, emissions could in fact rise. As it was seen in the previous chapter, this policy can reduce the emissions of CHE in a great percentage, using an average value of ESF = 447 gCO_{2eq}/kWh [81]. If the electricity is in fact green, it can reduce the emissions by 100%. The increase in the use of electricity at ports needs to be followed by the increase in electricity production at a local scope.

   In many ports, the current fleet is obsolete. This means that the emissions produced by these ships, for example, tugboats or pilot vessels are higher than emissions produced by newer vessels. When the substitution occurs, there will be immediately a reduction in emissions and energy consumption.

Alternative Fuels (LNG, methanol, hydrogen) as energy storage technologies and their implementation for vehicles, vessels, and harbour craft and also cargo handling equipment [19, 79, 80].

Hydrogen production (green hydrogen) and Carbon Capture are measures that are viewed with great potential to help decarbonization [19, 79, 80].

For ports with high traffic of people due to cruises and ships, investing in greener means of transportation as hydrogen-powered buses can reduce significantly emissions and energy use. Other alternatives are electricity, natural gas or biofuels, for instance. These fuels joined with the fact that people are using public transport instead of particular vehicles can help the ports with cruise and ferry terminals reduce their emissions.

2. Improving the efficiency of the activities. This is not related to changing or improving the efficiency of the equipment used at ports. It is related to the way vessels and equipment operate within ports.

   The creation of a Reduction Speed Zone (RSZ) has the goal of reducing the speed of cruising and can be a very impactful measure. This is an optional measure for many ports and regions and can commonly been found in the USA. To aid with their more extensive diffusion into other regions, localities are giving economic incentives to the ships that do it. This measure not only is better in terms of emissions but also better for the local ecosystem. In many regions of the globe, in particular California, this measure is applied due to the fact there are many whales in those waters. For mammals, it is beneficial to reduce the speed and Load Factor of the boat, since it subsequently reduces its noise emissions (therefore, impacting less the aquatic animals) and also since the danger of collision between marine life and vessels is considerably decreased [82].

   Improving shipping schedule means less time waiting to berth and unload/load the goods. Better routes are also a point where shipping companies can make efforts, although this is more related to shipping emissions and not only port emissions. Nevertheless, it is important to consider straighter movements in the port zone (fewer emissions from Cruising and Manoeuvring). Schedule and optimization increase the terminal efficiency and as a consequence reduce the time a ship is berthed and spending energy, being this fuel or electricity from OPS [19].

   Real time monitoring would permit that the equipment is only turned on when it is needed. By reducing the waiting time, there is also a reduction in energy consumption. Real time monitoring is also an impactful measure to populate the current model with more accurate data. In turn, this can help the decision-makers to opt for solutions based on better and more real information [19].

3. Measures that are taken on a higher scale (can be taken outside the port) and affect the port. They do not have a direct relation with the equipment used or the efficiency. Nevertheless, they can belong to the port.

   Renewables (solar on top of buildings (Los Angeles), wind (ports of Antwerp and Rotterdam, for example), waves and tides (Leixões), and geothermal) are the future in electricity production at ports [19]. Local generation of electricity creates independence from the grid but also permits lowering the Electricity Specif Factor as renewables are considered to have an emission factor of 0 $kgCO_2/kWh$. Many ports have advantageous conditions in terms of possibility of harvesting renewable energy from various sources. One is the proximity to the ocean. This symbiosis can be achieved with the employment of wave energy facilities in wave breakers in ports or with technology that serves as buoys to indicate the path vessels should follow at night or during foggy conditions and also a technology that generates electricity with wave or tides oscillation [80].

2.5 Sustainability indicators and approaches in port energy systems

This subsection covers the literature which addresses the indicators that better assess a port's environmental performance. There are a lot of different sustainability indicators and approaches in port energy systems. Here will be explained only the most relevant ones.

The most commonly used indicator is undoubtedly pollutant emissions. In many studies, the emissions accounted are the GHG ones (There are 6 main gases: water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).) and also SO_x, CO (carbon monoxide) and PM (particulate matter) emissions [51, 83]. In the studies that incorporate emissions, there is one that is more present than the rest, CO_2 [40, 47, 48] . The ones that follow in more studies are nitrous oxide (N_2O), and methane (CH_4). Some studies take also into account emissions of these important gases as is the case in [38, 35, 49, 51].

Another indicator that is usually found in the literature available is energy efficiency. As it is known, energy efficiency is the quotient between the power output and the power input. Energy efficiency is oftentimes related to the portion of total energy input that is used and not wasted. Therefore it is deeply related to waste and not using the resources at 100% [84]. So, naturally, it is an indicator that is worth looking into. When talking about sustainability it is also important to talk about the efficiency of processes and technologies as it serves as a way to reduce emissions and ensure that every bit of possible primary energy is put to use [85].

For ship emissions, the IMO has proposed two indicators for this efficiency evaluation. They are the Energy Efficiency Design Index, known as EEDI, for new vessels and the Energy Efficiency Operational Index, known as EEOI, for operating vessels [18]. These indexes are defined as the ratio of the mass of CO_2 emitted per unit of transport work (grams per nautical mile, for example) [86]. The EEOI is used in some studies [18, 71]. For landside emissions, the energy efficiency indicator can be shown in liters or kWh per TEU depending on the power input (fuel or electricity) [50].

Another sustainability indicator of relevant importance is local air quality. As mentioned in this section, as ports are often close to big concentrations of populations, it is important to control the air quality by evaluating constantly the air contents [2, 87].

Then, there are also less used indicators, for example, noise pollution, water quality, amount and description of accidental spills on inner port waters, creation of sludge from dredging, and alteration of the sea floor. These are some of the potential indicators that allow to analyze how a port is working towards sustainability [88, 89, 90].

The reason for the great variety of indicators used by different ports is the fact that every port has its own requirements due to social and topographic conditions [90]. This, combined with the ambition of port authority results in a different model with different indicators to represent the port energy uses and its efforts to become more sustainable [91].

The same thing occurs with the different approaches identified. To tackle the various environmental issues found in ports, port authorities have been working to establish a proper management system. There is no solution that can be applied to every and each port [92]. It requires an investment of money and time in order to achieve the goals proposed. These systems are capable of satisfying the priorities established in subsection 2.2.

In this subsection, the main strategies, policies and standards considered to be the most effective in addressing energy consumption and contribute to a better energy port management will be presented.

2.5.1 Energy Management Plans

Energy Management Plans contribute to the better functioning of the energy systems present in a given organization. This starts with improving the efficiency of the technologies and processes involved leading to the lowering of emissions. The most know ones are the standards ISO 50001 and EN 16001.

2.5.1.1 ISO 50001

First introduced in 2011 by the International Standards Organization (ISO), the ISO 50001 standard serves as a valuable instrument in assisting energy managers in achieving their objectives of reducing energy consumption [93]. This standard follows the well-established Plan-Do-Check-Act (PDCA) improvement cycle, which encompasses the following stages:

1. **Plan**: To comprehend the organizational context effectively, it is crucial to establish an energy policy and an energy management team. Additionally, careful consideration must be employed to address both the risks and opportunities of a potential action. This involves conducting a thorough energy review to identify Significant Energy Uses (SEUs) and establish key Energy Performance Indicators (EnPIs), Energy Baselines (EnBs), objectives, and energy targets. Furthermore, action plans must be formulated to facilitate the achievement of desired outcomes that align with the organization's energy policy, ultimately leading to improved energy performance.

2. **Do**: The implementation phase of the energy management system entails executing the predetermined action plans, establishing operational and maintenance controls, and fostering effective communication throughout the organization. It is vital to ensure the competence of personnel involved in energy management activities. Additionally, energy performance considerations should be incorporated into the design and procurement processes, taking into account relevant factors to optimize energy efficiency and sustainability.

3. **Check**: The monitoring and evaluation stage of the energy management system involves the systematic monitoring, measurement, analysis, and evaluation of energy performance and the overall effectiveness of the Energy Management System (EnMS). This includes conducting regular audits and periodic management reviews to assess the progress and compliance with established energy performance objectives and targets.

4. **Act**: Following the identification of nonconformities, it is imperative to take appropriate actions to address them within the energy management system (EnMS). These actions

should be aimed at rectifying any deviations from established standards, procedures, or regulations. Furthermore, a continuous improvement approach must be adopted to enhance both energy performance and the effectiveness of the EnMS over time. This entails identifying areas for improvement, implementing necessary changes, and monitoring the outcomes to ensure sustained progress in energy efficiency and overall system performance [94].

The ISO 50001 energy management system standards promote the establishment of organizational systems and processes aimed at incremental enhancements in energy efficiency and the quantification of energy consumption. However, it is noteworthy that only a select few ports, including the Hamburg Port Authority in Germany, the Port of Antwerp in Belgium, the Port of Felixstowe in the United Kingdom, the Port of Arica in Chile, the Baltic Container Terminal in Poland, and the Noatum Container Terminal Valencia in Spain, have obtained certification under the ISO 50001 standard [79].

2.5.1.2 EN 16001

EN 16001 is said to be the predecessor to ISO 50001 [95]. This European Standard was introduced in 2009 [93]. These two standards have a lot of similarities, for example the PDCA, explained in the last subsection. However, there are some differences between them. ISO 50001 introduced 3 new concepts that were not previously mentioned in the European Norm.

The first aspect pertains to management responsibility, particularly the pivotal role played by top management. Top management defines the energy policy and key objectives, allocates available resources, and establishes operational roles. To assist top management, an energy management team must be established in accordance with ISO 50001, led by a management representative.

The second concept focuses on the "PLAN" phase, providing detailed guidelines for the energy review process. This process aims to establish a solid baseline for monitoring energy performance using appropriate indicators.

The third distinction lies in the "DO" phase, where ISO 50001 places greater emphasis on the design of processes, systems, and equipment that may impact energy aspects. It highlights the necessity of outlining the energy policy within any new contracts or communications with energy suppliers.

And also there are some aspects mentioned in EN 16001 that are not mentioned in ISO 50001 are:

1. The prioritization of energy aspects enables the identification of areas that necessitate a more comprehensive examination.
2. The identification of the workforce within the company who potentially exhibit higher energy consumption behavior.
3. The aspect of cost reduction pertains to the potential upgrades aimed at reducing energy consumption within their entity.

2.5.2 Environmental Management Plans

When the focus is not only becoming more energy efficient but also reducing the environmental impacts of a given business/organization, Environmental Management Plans (EMPs) can be put to place. In general, the implementation of an Environmental Management System (EMS) contributes to the promotion of cleaner production by facilitating systematic reviews of production processes and procedures [96]. The great majority of ports are using environmental measures through EMPs to identify solutions that enhance efficiency and mitigate environmental impacts [97].

There are three primary internationally recognized EMS standards: ISO 14001, the Ecoports Port Environmental Review System (PERS), and Eco-Management and Audit Scheme (EMAS) [27]. In figure 2.5 can be seen the share of usage of these three major EMS, noting that commonly more than one is used at the same time.

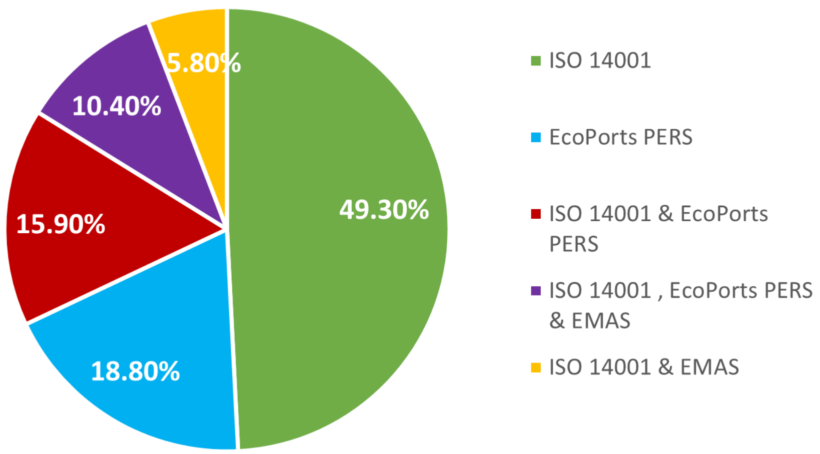

Figure 2.5: Breakdown in percentage of the Environmental Management Systems certificates (inspired in [27]).

With figure 2.5, it can be concluded that around 80% of ports use systems based on ISO 14001 and 70% of ports use a system based only in one EMP. It also indicates that ISO 14001 and PERS are the most commonly used standards [27].

2.5.2.1 ISO 14001

The objective of this international standard is to provide organizations with a framework for safeguarding the environment and effectively responding to evolving environmental conditions while considering socio-economic needs. It establishes the requirements that enable an organization to attain the desired outcomes it sets for its system of environmental management [98].

Adopting a systematic approach to environmental management can equip port management with valuable information to achieve long-term success and contribute to sustainable development by:

1. Safeguarding the environment through the prevention or mitigation of adverse environmental impacts.
2. Mitigating the potential negative effects of environmental conditions on the organization.
3. Assisting the organization in meeting its compliance obligations.
4. Enhancing environmental performance.
5. Exerting control or influence over the design, manufacturing, distribution, consumption, and disposal of the organization's products and services. This is accomplished by adopting a life cycle perspective that prevents unintended environmental impacts from being shifted elsewhere within the life cycle.
6. Realizing financial and operational benefits resulting from the implementation of environmentally sound alternatives that strengthen the organization's market position.
7. Communicating environmental information to relevant stakeholders and interested parties.

As it happens with ISO 50001, ISO 14001 relies its foundation on the concept of Plan-Do-Check-Act (PDCA):

1. **Plan**: determine and establish the environmental priorities and define objectives and solutions to achieve those goals.
2. **Do**: Impletement the solutions previously thougth.
3. **Check**: Monitor and evaluate the solutions confronting against the objectives, analysing also the results obtained.
4. **Act**: Do not stop to improve the measures taken [98, 99].

ISO 14001 brings environmental management to the forefront of an organization, complementing business strategy and facilitating ongoing improvements in environmental performance. By integrating the latest environmental perspectives, including a lifecycle approach, it contributes to greater environmental protection. ISO 14001 serves as a framework that addresses the growing expectations of customers, stakeholders, and regulatory requirements [90].

While ISO 14001 includes an obligation to comply with relevant environmental legislation, it does not encompass the implementation process. In contrast, the EMAS regulation mandates EMAS-registered organizations to provide evidence of legal compliance, including permits, as part of the environmental verifier's on-site inspection and the evaluation conducted by the competent body during the registration process [90].

2.5.2.2 Eco-Management and Audit Scheme

The European Commission (EC) developed the EMAS as a non-mandatory management tool for evaluating, reporting, and improving environmental performance, as well as transmiting environmental achievements. EMAS was enacted in June 1993.

The Eco-Management and Audit Scheme is an European regulation that establishes a recognized and sustainable legal framework for fulfilling administrative and social obligations. It serves as the most credible and robust environmental management tool, incorporating additional elements beyond the requirements of the international standard ISO 14001. Since EMAS incorporates the complete text of the ISO 14001 management system, any port authority can take additional steps towards achieving environmental performance, credibility, and transparency [90]. EMAS is an EMP that was inspired by the previously mentioned international standard EMS to achieve the stricter environmental management requirements imposed in Europe [100].

EMAS enjoys greater popularity in countries with a more adaptable environmental regulatory framework that imposes less stringent requirements on organizations. Consequently, organizations may choose to adopt EMAS as a means to assume responsibility for environmental matters, thereby avoiding the expenses associated with traditional control mechanisms [101]. It is mostly applied in countries like Germany or Italy [102].

EMAS entails the regular publication of annual environmental statements, which include a description of the EMS and a summary of environmental performance data. These statements must be validated by an environmental verifier, made accessible to the public, and updated annually. The objective of EMAS is to recognize and reward organizations that surpass legal compliance and continually improve their environmental performance. Unlike ISO 14001 certification, EMAS certification requires organizations to demonstrate legal compliance with environmental legislation, including permits. This enhances the environmental performance and cultivates a 'green' image through transparent and validated reporting, while helping organizations save resources, reduce costs, and meet environmental requirements.

With the implementation of ISO 14001, enterprises will be able to continuously improve environmental protection while adhering to legal compliance requirements. While EMAS concentrates on ongoing improvements to environmental performance, it places more emphasis on the management system. The organization needs to assess the environmental programs, goals, metrics, and targets that are currently in place. EMAS and ISO 14001 may cover different topics and have different scopes. However, a complete regulatory compliance audit is not part of the ISO 14001 implementation process. EMAS regulation, on the other hand, requires EMAS-registered organizations to present proof of compliance with environmental laws, including permits.

Among other requirements, employee involvement at all levels and participation in the process of continuous environmental improvement are crucial in EMAS. All organizations with EMAS certification must demonstrate the identification and addressing of significant environmental aspects associated with procurement procedures within the EMAS framework [90].

2.5.2.3 Ecoports Port Environmental Review System

Developed by ports themselves, the Port Environmental Review System (PERS) has firmly established its status as the sole internationally recognized environmental management standard specific to the port sector. PERS certification is voluntary and serves as evidence of compliance, which is subject to independent audits conducted by Lloyd's Register. Approximately one-third of EcoPorts members have obtained PERS certification for their ports [27, 100].

PERS is flexible and easily adaptable to future changes in regulations and goals. The Port Environmental Review System (PERS) has been specifically designed to support ports in implementing an environmental management program that aligns with the recommendations outlined by the European Sea Ports Organization (ESPO). The ESPO Environmental Code of Practice (2004) presents a series of key directives for ports, including:

1. Assisting in the creation of a sustainable supply chain.
2. Encouraging extensive consultation, communication, and collaboration with pertinent local stakeholders, including port users, the general public, and Non-Governmental Organizations (NGOs).
3. Generating new knowledge, technology, and sustainable methods that successfully combine cost effectiveness and environmental efficacy.
4. Facilitating communication and cooperation among port authorities in order to exchange experiences and put best practices into effect.
5. Creating publicly accessible environmental policies to promote the incorporation of sustainable development concepts and improve awareness of environmental issues.
6. Develop suitable environmental impact studies for both port projects and port development plans.
7. Fostering continuous and further development of the port's environmental management procedures.
8. Promote the use of monitoring techniques based on environmental performance indicators to systematically track improvements in environmental practices inside ports.
9. Advocating for environmental reporting as a means of effectively communicating environmentally sound behavior to stakeholders.
10. Strengthening communication efforts to spread information about environmental improvements made by ports [103].

2.6 Research gaps and basis for the proposed research questions

The more recent studies aiming to assess port emissions have been developing tools using the 3 Scopes approach, idealized in the GHG Protocol [104, 105]. The 3 scopes can be seen in figure 2.6.

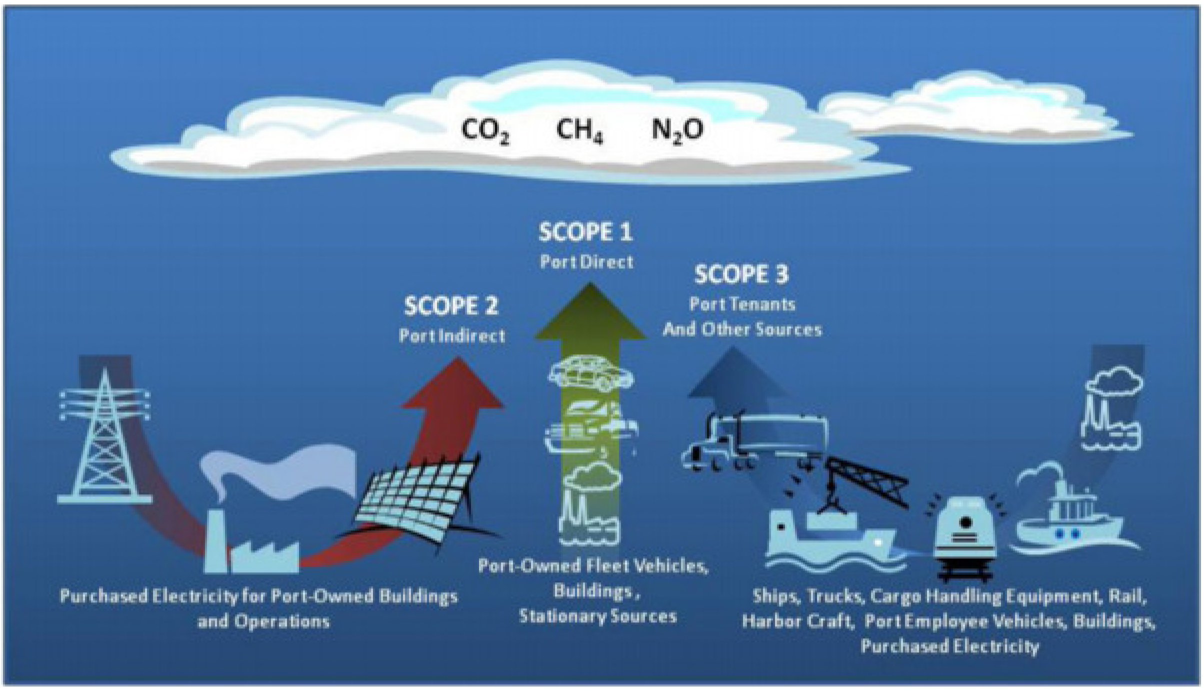

Figure 2.6: 3 Scopes used to calculate port emissions [49].

Scope 1 refers to port direct sources, which encompass emissions sources directly controlled and operated by the port administration entity. These sources include vehicles owned by the port, vehicles owned or leased by the port administration, boilers and furnaces in port buildings, cargo handling equipment owned and operated by the port, and any other emissions sources owned and operated by the port administrative authority [106].

On the other hand, Scope 2 pertains to port indirect sources, specifically the purchased electricity utilized for port administration buildings and operations. However, it does not include power and energy purchases made by tenants [106].

Lastly, Scope 3 encompasses other indirect sources associated with tenant operations. These sources comprise ships, trucks, cargo handling equipment, rail locomotives, harbor craft, tenant buildings, tenant-purchased electricity, and port employee vehicles. In ports with a substantial number of tenants, Scope 3 is likely to be the largest contributor to greenhouse gas emissions [106].

The organization of the emissions in 3 Scopes is the best solution when the tool is going to be used by port authorities to address their emissions and the emissions of the consumers/tenants in a port separately. By doing this, it is possible to get insight into if the emissions and energy consumption come from sources that can be targeted by the port itself (PA) or if it is not the port authority's direct responsibility.

Despite this being a great solution in some works, in the scope of this master thesis, the objective is to consider the port as one. That means that every consumption that occurs in a port with services provided directly to the port itself is considered as one. This will simplify the division in scopes and allow the port to work together to reduce emissions in order to fight global climate change.

Another liability found in many studies online is that the model itself is not available online for the public. Some are not free, others require permissions and a few more have out-dated versions that are not suitable for today's software. The goal is that the model presented in this thesis is made available for users in various areas, especially at ports.

The majority of the articles that elaborate on models lack the definition of basic information about technology. This work serves also as an opportunity to gather information for future works about ports and harbours, creating a more concise and dense font of information. The information about technologies is spread around different articles and reports.

From what was found in the different search databases, many of the models don't allow to make previsions for the next year. Within this thesis, this possibility is developed, giving the chance to the user to create future scenarios of emissions, taking into account developments in technologies, electrification and a higher volume of electricity produced by renewables, for instance.

In the following chapter, the methodology applied to the construction and development of the described model are depicted.

Chapter 3

Methodology

This chapter describes the methodology used in this work to develop the energy model of a port. The assumptions, the division in different categories of energy use and emission sources, and an explanation of the most relevant technologies are provided. Additionally, this section also describes the data collection and the procedure followed by other authors in work that was used as the basis for the energy model develop in this dissertation. The most relevant information that resulted from the data collection and analysis is partly shown in the last two sub-sections.

3.1 Overview of the energy system modeling approach

The main aim of modeling the energy system of a port is first and foremost to map the energy consumption and emissions of different port assets, and to identify measures that could improve the energy and environmental impact of port activities. As ports have a key role as energy and transport hubs, the first step of this work consisted in identifying any existing approaches for managing and modeling the energy use in ports. As presented in the previous chapter, this is already carried out to some degree in the GHG emissions inventories of some ports and also to implement specific norms related to energy management. Given the state of the art (as presented in Chapter 2) the starting point for the development the model was the ISO 50001, which has been covered in more detail in the previous chapter.

The energy technologies supporting final energy uses and energy services in ports can be grouped into specific areas, as shown in figure 3.1. This categorization is based mainly on three studies ([53, 107, 108]) and complemented with additional categories that were considered to be relevant to the development of a comprehensive energy model for a port, as per the literature review carried out and presented in the state of the art.

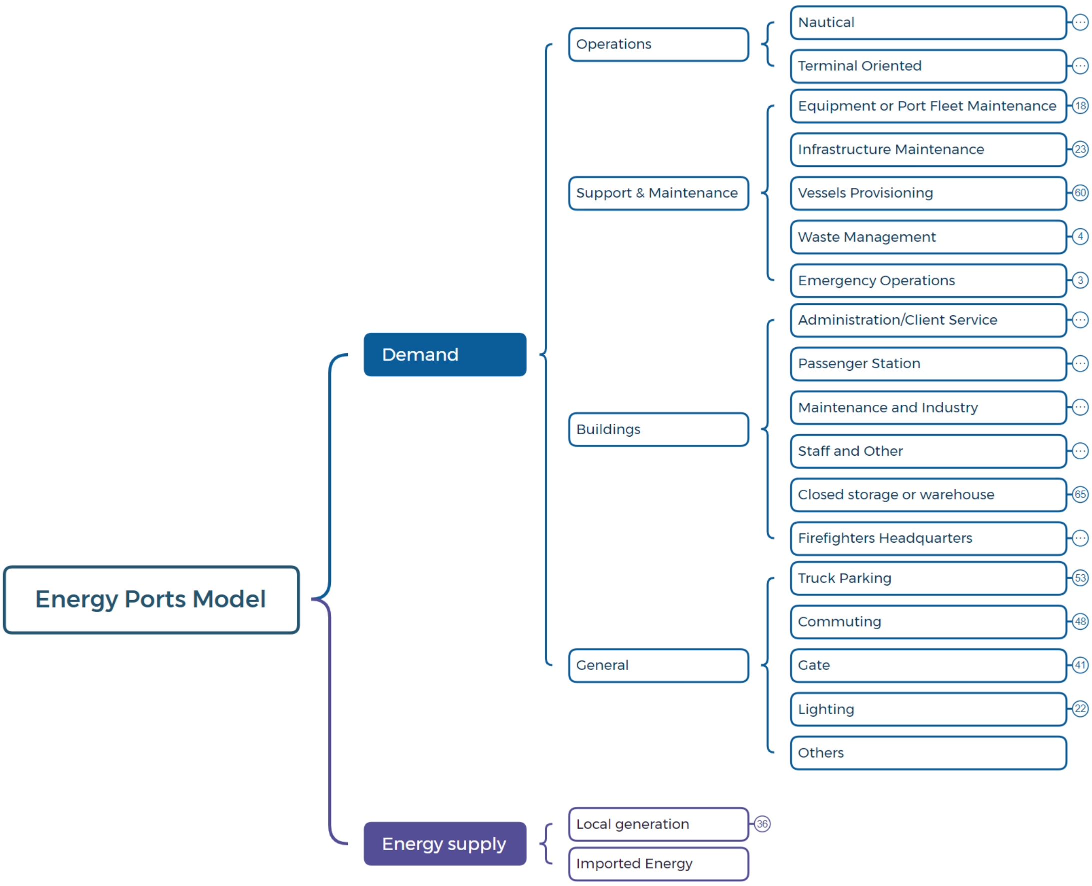

Figure 3.1: Final uses of energy in terms of areas and sub-areas (based on [107] and [53]).

The model is divided in the first level into Demand and Energy Supply that will aggregate other sub-categories relevant to the operations of the port. The Demand is category aggregates all end uses and technologies related with the direct use of energy. Energy supply includes the processes that are used locally to produce energy vectors (e.g., electricity, heat, hydrogen) and imported energy (e.g., electricity) that is used inside the port. The approach implemented in this section builds on the ISO 50001 international standard, as presented in chapter 2, where the emissions were split into ship based and land based.

Figure 3.1 shows the categories considered within Demand, with the Operations and Support & Maintenance representing areas are more specific to the activities carried out in ports. The other categories - Buildings, General and Energy Supply, have already been modeled in some detail in the existing literature and emissions at the level of the different devices, systems and equipment that support the different end uses are available. Additionally, modeling of energy use in sectors such as for different industries or commercial sub-sectors can also serve as an inspiration and be adapted to the specific context of ports, due to the logistics activities taking place there. For the energy demand of different types of buildings within the port, commuting or other general activities, such as lighting, information can be retrieved from literature where these uses have been thoroughly addressed (for example [109]). In the case of the activities considered within Support & Maintenance category, it must be highlighted that only the sub-activity "Vessels Provisioning" is exclusive of ports. Again, approaches can be found in the literature addressing the energy and emission modeling of maintenance and waste management activities (see, for instance, [110]). Considering all these elements, it was decided to mainly focus the work of this dissertation on the assessment of the Operations category by further analyzing the sub-activities related to Nautical and Terminal Oriented operations.

To ensure that the model covers all the relevant energy use related with port activities, a comprehensive analysis was performed to identify the variety of processes that may be present in the geographical boundaries of ports, including the characterization of a wide set of technologies related with the different activities in terms of their energy consumption and emissions. The following sections will present each category represented in the above diagram in detail, including the approach followed to identify the relevant energy uses, the associated technologies, the models used for the assessment of the energy use, and the data that needs and availability to support further modeling of port energy systems.

3.1.1 Operations

The Operations category is further divided in two sub-categories covering Nautical and Terminal oriented activities. Nautical activities deal with the maneuvering of vessels within the territorial area of the port. Terminal oriented activities include all operations supporting the movement of cargo in land. The main separation between these two categories is mainly based on the spatial location of the vessel. Namely, once the vessels have safely berthed, cargo handling operations begin, removing/placing cargo in the vessels, storing it within the yard or sending it to the final consumers. For this process, some equipment is required, for example, the CHE. For loading the ships, the same equipment is used. Figure 3.2 shows these two sub-areas, which are then subdivided into different categories of activities supporting terminal operations, which will be linked to specific technologies and energy vectors.

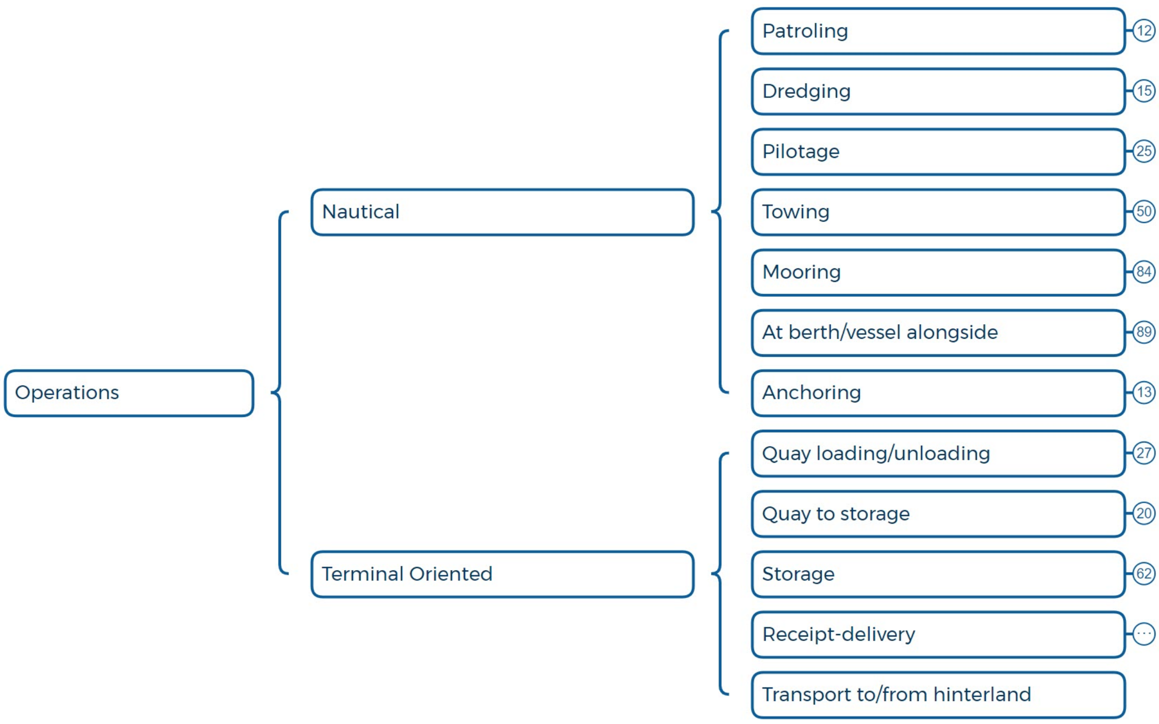

Figure 3.2: Sub-areas and activities of area Operations.

As presented in figure 3.2 the Nautical category mainly encompasses activities related to the safe movement of vessels within the port areas, including all the activities needed to perform the moooring, maneouvering and berthing of the ships. This category includes the activities related to the use of the Ocean Going Vessels (OGVs) and the Harbour Crafts (HCs). Activities, and related systems, included in this category include those performed by bigger vessels entering and leaving the port which may need assistance to safely unload and load cargo. This maneuver are supported by the HCs, which perform activities such as piloting, towage and mooring. Patrol and dredging are also the supported by the HCs.

3.1.2 Support & Maintenance

Support & Maintenance includes activities responsible for supporting the logistics operations and guaranteeing everything runs smoothly within the port. This category is divided into five sub-categories that cover several important activities taking place in ports: Equipment or port fleet maintenance, Infrastructure maintenance, Vessel provisioning, Waste management and Emergency operations, as presented in figure 3.3.

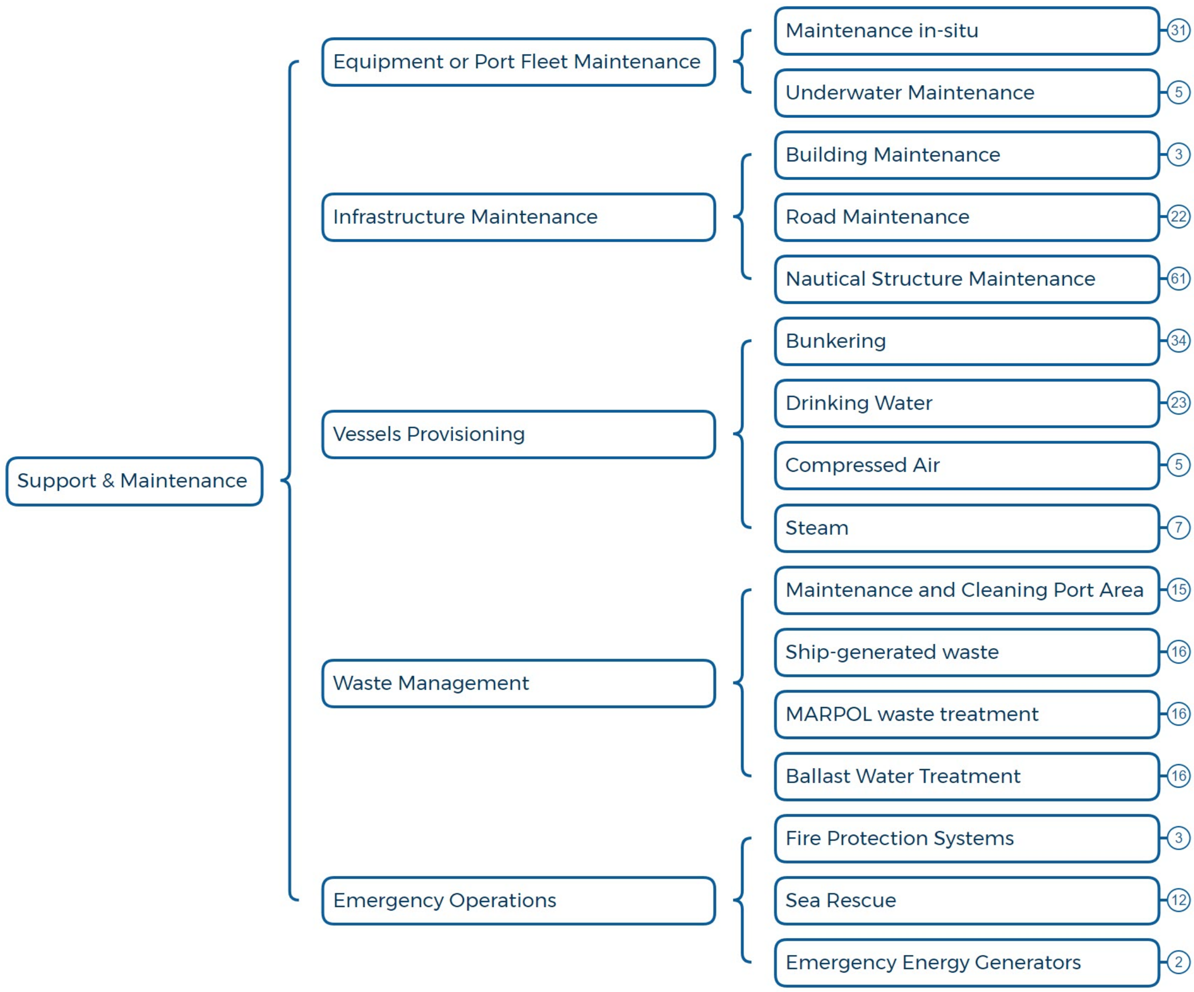

Figure 3.3: Sub-areas and activities of area Support & Maintenance.

Vessel provisioning covers all the the basic needs of vessels, such as supply of water, provisioning of compressed air or steam, which are fundamental for the normal operation of the ships.

The Waste Management sub-area is responsible for cleaning and collecting the waste and litter a ship may produce. This sub-category also includes "Emergency Operations", such as facilities supporting firefighting or other emergency assistance to vessels. Finally, the "Maintenance" activities cover Equipment or Port fleet Maintenance, on ground, water and underwater and maintenance of port infrastructure and buildings.

3.1.3 Buildings

Buildings support a myriad of core activities in ports, such as administrative, storage or supporting passenger and freight activities, although typically not the major energy user in ports, can non-the-less be responsible for a relevant share of energy consumption and emissions within ports. Some ports may have cruise and/or ferry terminals, with offices, museums or restaurants. Similarly, all ports have buildings with dedicated staff areas, administration, emergency or firefighters headquarters and storage. Additionally, some ports include buildings dedicated to maintenance or industrial operations, e.g., assembly of offshore turbines or shipyards. Considering these activities within and functions of buildings in ports, the Buildings category is grouped into several sub-categories as shown in figure 3.4.

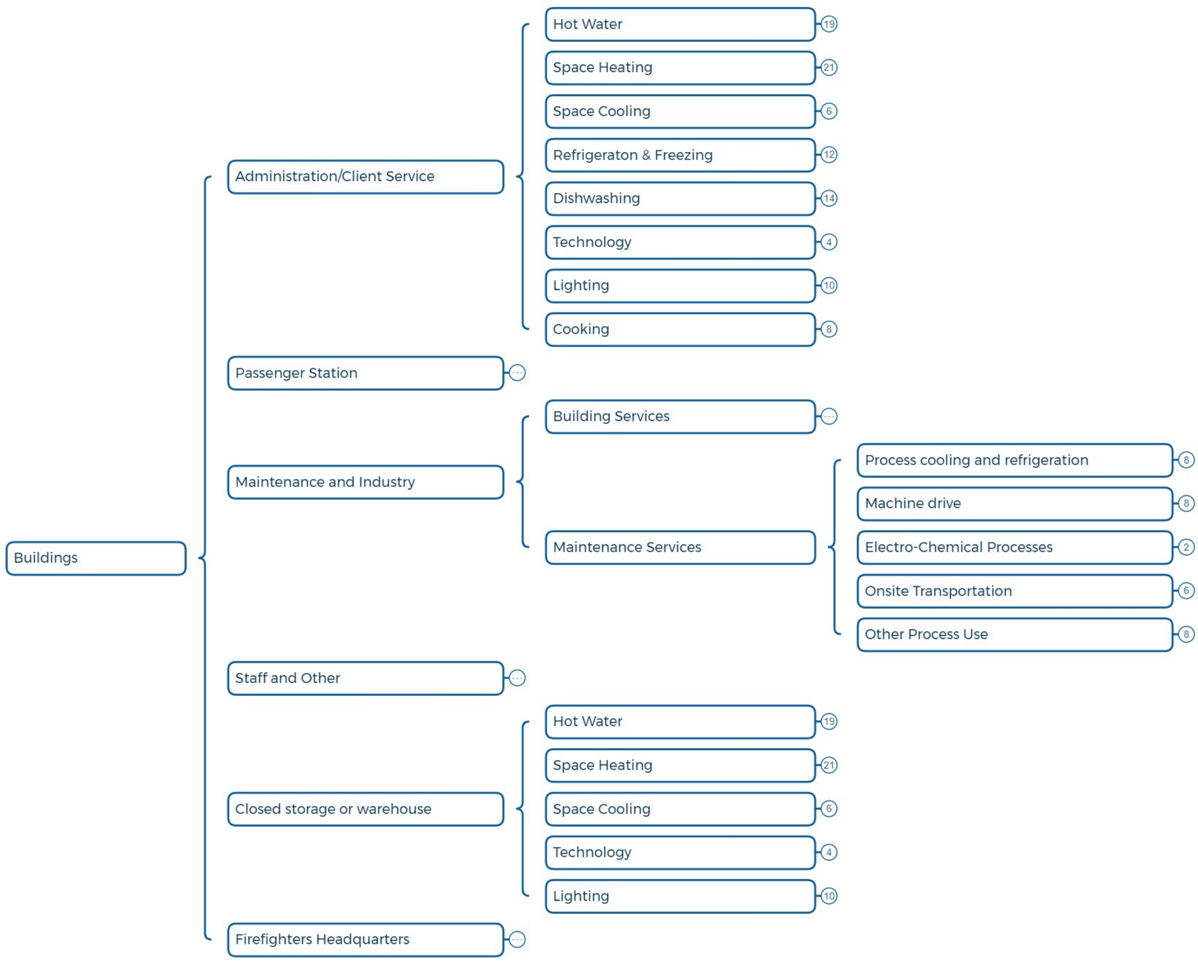

Figure 3.4: Sub-areas and activities of area Buildings.

Although many of the energy end-uses and technologies associated with the proposed sub-categories of buildings are similar, their overall characteristics (lifetime, efficiencies, rated power, costs and time of use) are particular to the activities they support. As an example the end-uses considered in the "Administration/Client Service" are presented in figure 3.4 and are based on the models described in the state of the art. These same end uses are considered for "Passenger Station", "Building Services" inside "Maintenance and industry", "Staff and Other" and "Firefighters Headquarters".

3.1.4 General

The last sub-category, General, includes the remaining energy end-uses and associated technologies, supporting activities that are not included in the other sub-categories. These activities include parking facilities for freight and staff vehicles, street lighting within the port, and other operations servicing the outdoor spaces and movement of people and goods within the port limits.

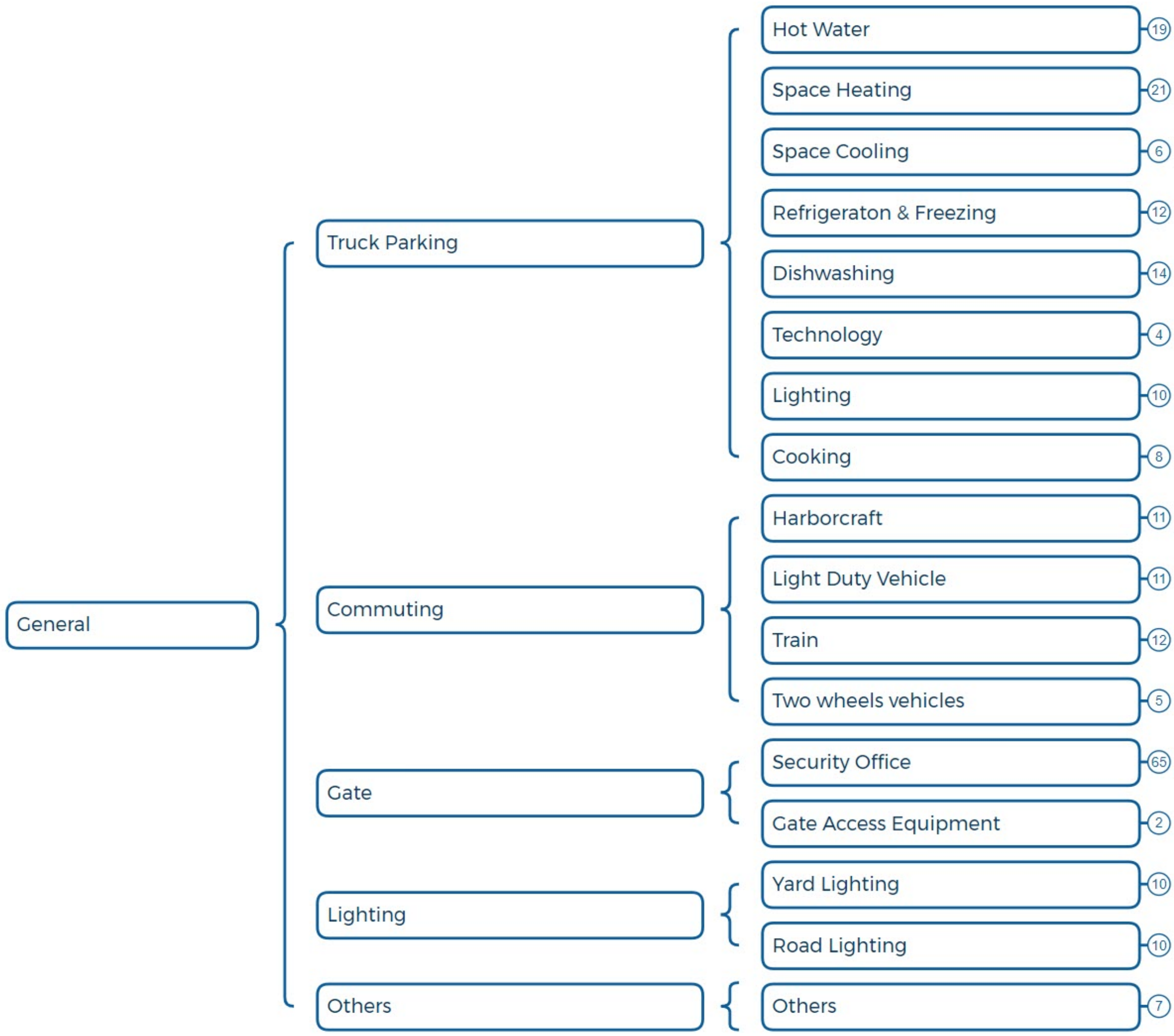

Figure 3.5: Sub-areas and activities of area General.

3.1.5 Energy Supply

The energy demand within ports can be met by both endogenous production - e.g., renewable electricity generation from solar or wind, or through import of energy, e.g., electricity from the grid, or Natural Gas supplied by pipelines. This is at the basis of the sub-categories considered for the grouping of energy supply and energy vectors used in support of port activities, i.e., Local Generation and Imported Energy.

As energy hubs, ports are key infrastructure in the import and export of fossil energy sources such as crude oil, coal and natural gas, and are expected to support the future trade of renewable based energy commodities, such as hydrogen, green ammonia or (bio)methanol. Thus the subdivision of this category considers the local generation of renewable energy, the import of energy and the supporting role of ports in the production, storage and trade of low-carbon vectors. The division in sub-areas and activities is represented in figure 3.6.

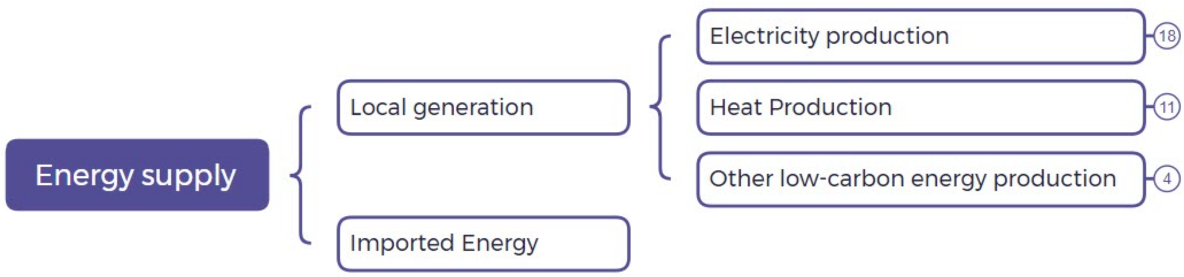

Figure 3.6: Sub-areas and activities of area Energy Supply.

The following sections describe in more detail the technologies and end-uses associated with the sub-categories described in section 3.1.

3.2 Disaggregating demand into final end uses for different activities or areas within ports

Any representation of an energy system for ports needs to consider the specific activities taking place therein. This section describes the methodology used to break down energy demand, including the classification of activities, the allocation of energy consumption to specific end uses, and the estimation of future energy demand based on projected growth in port activities. The disaggregated energy demand enables a more detailed and accurate analysis of energy consumption patterns, which is essential for identifying opportunities for improving energy efficiency and reducing emissions. A specific example of the methodology and resulting structure will be shown for a particular sub-category of the energy system with further information for other categories shown in the Appendix A.

3.2.1 Operations

Firstly, as mentioned before, Operations includes any energy use use and technology supporting maneuvering of vessels and any land-based equipment used in the operations, and activities related to loading/unloading and movement of cargo through the port. This sub-sections describes in more detail this sub-category.

3.2.1.1 Nautical Operations

The activities included in Operations (figure 3.2) are mainly related to suport to maneouvering of OGVs. The categories of vessels were described in the previous chapter, principally in table 2.3. These vessels usually require assistance from port authorities to safely carry out port calls, in entering or exiting the port. These activities are mainly represented by the Piloting, Towage, Mooring, Patrol, and Dredging end-uses which are carried out by Harbour Crafts, also mentioned in chapter 2. The vessels responsible for each activity are included in table 2.4. Note that mooring is also assisted by land vehicles which help the vessel maneuver into the right position for loading and unloading, much like the airplanes that are tugged and pushed after landing and ahead of takeoff.

In order to fully characterize the energy uses and technologies related to the activities that take place when OGVs call at different ports, it is essential to have access to vessel specific information. A significant part of the data and OGV specific information used in this dissertation was collected from the Fourth IMO GHG Study published in 2020 [71], which considers several types of vessels, the sizes and the power of engines during the different activities. The vessels can be powered by different fuels during the different stages that take place during port calls, which are shown in table 3.1.

Table 3.1: Fuels used for ships (based on [71])

Fuel used	**Comment**
HFO (Heavy Fuel Oil)	The most commonly used residual fuel in marine ships
MDO (Marine Diesel Oil)	Distilled fuel
LNG (Liquified Natural Gas)	An alternative fuel to reduce emissions [111]
Coal	A cheaper option than the previous ones
Nuclear Fuel	Most vessels are icebreakers with high power demand, so they do not exist in every port
Methanol	One of the newest and with higher potential technology [112]
Hydrogen	Recent technology and is being studied to increase its use [112]
Ammonia	Can be blended with diesel fuel in dual fuel mode to start combustion. Ammonia only engines are still being study [112, 113].

The fuels presented in table 3.1 are the most commonly used, especially HFO and MDO. As stated in the table above, nuclear fuel is only used for special purposes. The bottom three fuels include energy sources that are expected to grow substantially in the coming decades, to replace the current use of fossil fuels. Nevertheless, they are still at early commercial or lower TRL stages. The evolution of methanol, hydrogen and ammonia generation and storage will likely be essential to their uptake in the shipping industry [112].

Battery-powered vessels are a viable, and already available, option for shorter routes or in-port operations. Depending on the electricity mix available at the port, this alternative can be an important contribution to reducing emissions associated with port activities [114].

For the activity "Patroling", figure 3.7 shows the technologies and associated energy vectors.

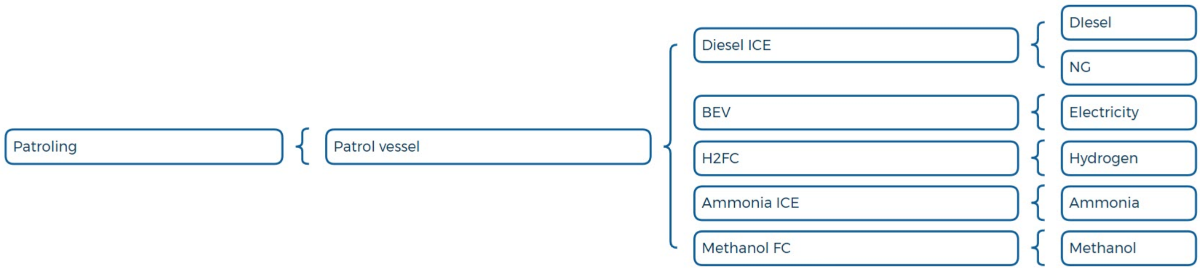

Figure 3.7: Disaggregation of Activity "Patroling".

The locks, lighthouse, buoy and beacon many times are not considered because of their low intervention in these operations. Nonetheless, they are relevant participants in port operations and help in a significant way the easy path of vessels to their position. For beacons and buoys, activities involving energy use and mostly related to lighting. The locks and lighthouse can be more complex, but is mostly consisting of lighting end-uses as well. Thus these activities are mostly powered by electricity.

3.2.1.2 Terminal Oriented Operations

The activities included in the sub-category of the Terminal Oriented Operations are mostly related to cargo handling which are supported by a variety of equipment, including cranes, vehicles, forklifts or reachstackers. For quay loading and unloading, Quay Cranes (QC) are used. Recall that the division of these cranes into different types can be found in section 2.2. There are Single-Trolley Cranes (STC) and Dual-Trolley Cranes (DTC). The disaggregation in technologies and vectors used can be seen in figure 3.8.

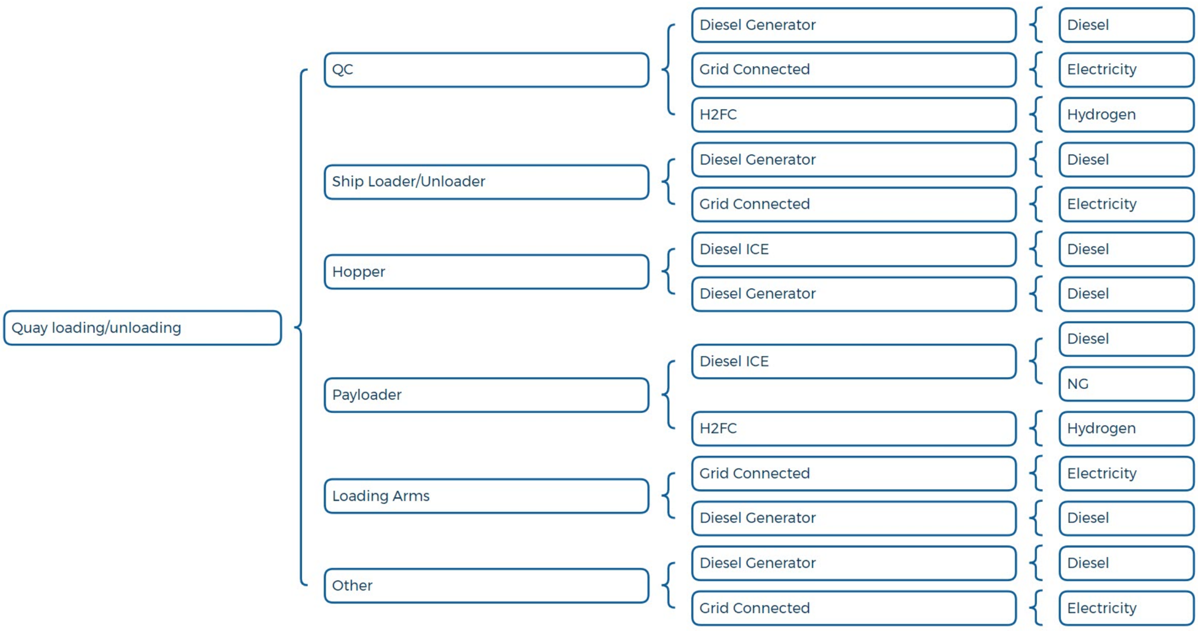

Figure 3.8: Disaggregation of Activity "Quay loading/unloading".

For quay to storage, Yard Trucks (YTs) and Automatic Guided Vehicles (AGV) are used to transport containers. On the yardside, where the storage is done, there are several other equipment to consider such as the yard cranes, composed by Rail Mounted Gantry (RMG) cranes, Rubber Tired Gantries (RTG) and Overhead Bridge Cranes (OBC). The yard vehicles are the Straddle Carriers (SC), Automatic Straddle Carriers (ASC) and the Automated Lifting Vehicles (ALV). In this area of the port, forklifts and reach stackers are also present. Empty containers are moved by forklifts and reach stackers. Reefers, the containers with refrigeration and a major energy user in many ports, can also be stored there and need to be considered as part of storage. This equipment was previously described and presented in table 2.6.

The sub-category of Receipt-delivery includes the activities and end-uses related to the transport of cargo to the sections of the port where these are transferred to the hinterland, via trucks, trains, or inland waterways in barges (e.g., tow and tugboats). In the transport to/from hinterland, the goods are delivered to the final consumer or to the port.

3.2.2 Support & Maintenance

For the Support & Maintenance activities, the first sub-area "Equipment or Port Fleet Maintenance" is disaggregated into "Maintenance in situ" and "Underwater Maintenance". Figure 3.9 illustrates the technologies and vectors that associated with these activities.

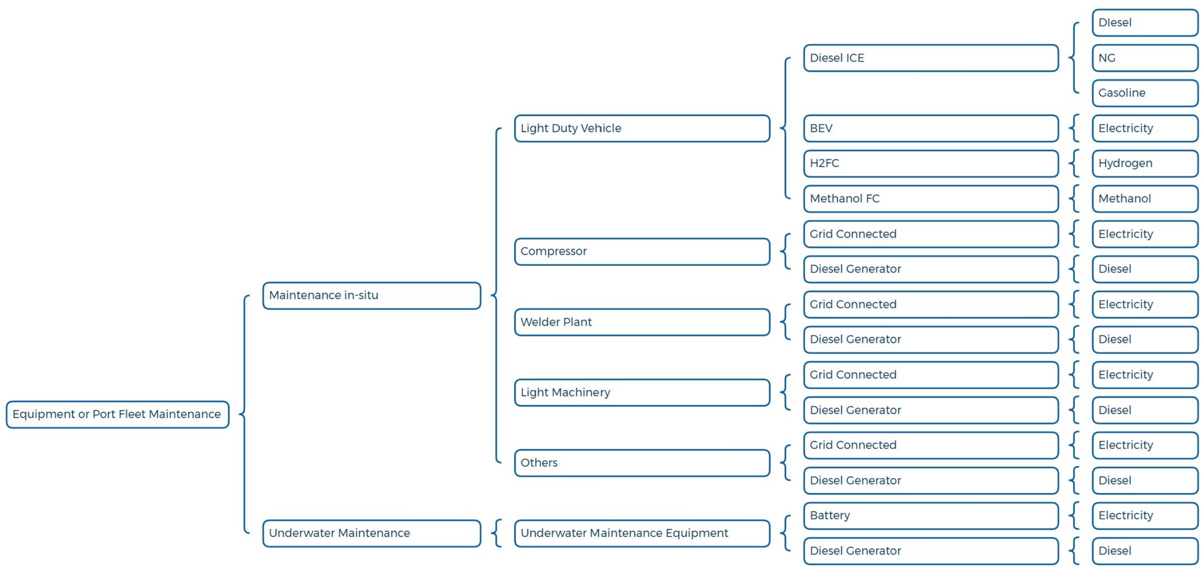

Figure 3.9: Disaggregation of Activity "Equipment or Port Fleet Maintenace".

Further details for other sub-categories are presented in the Appendix A.

3.2.3 Buildings

For Buildings, the main basis for dissagregation into end-uses and technologies is that of [109]. The technologies and energy vectors used are shown in figure 3.10, with a specific example presented for "Hot Water" is done. The rest is compiled in the Appendix A.

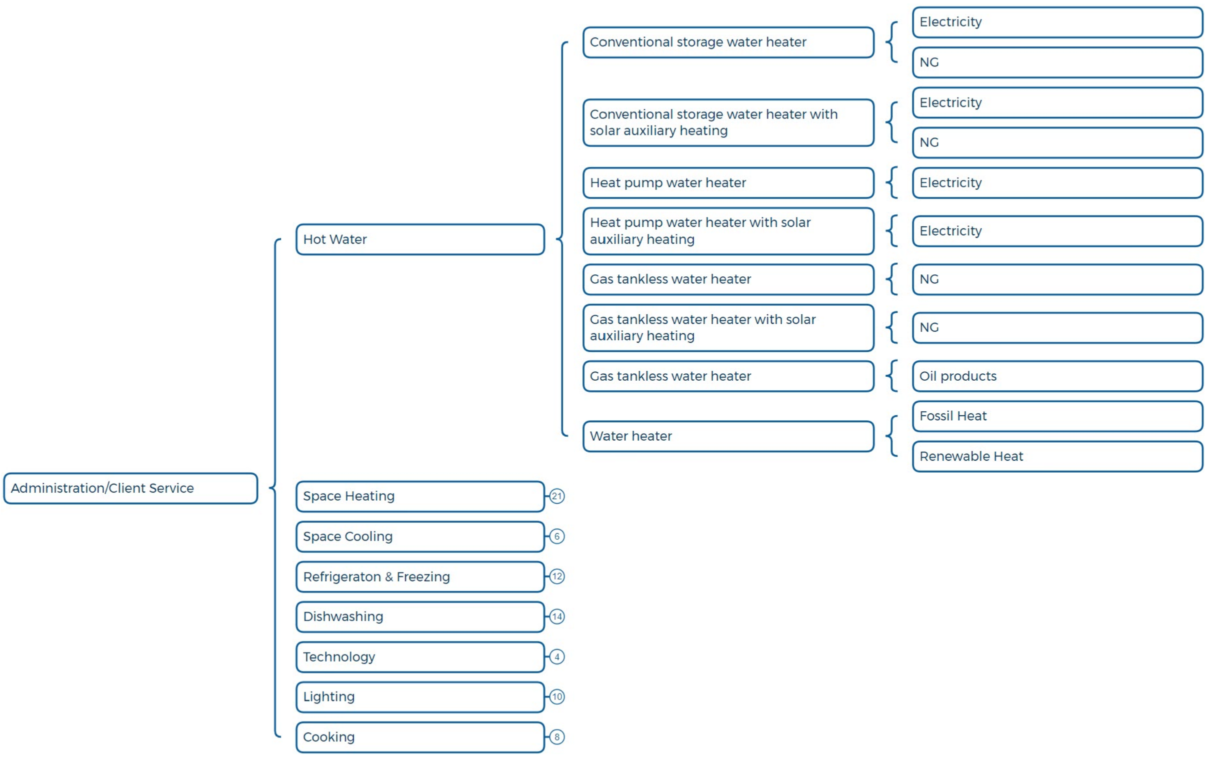

Figure 3.10: Disaggregation of Activity "Administration Buildings".

3.2.4 General

As previously stated, this area fits all the activities that do not belong to any of the other. This includes lighting, i.e., street and traffic lighting. The lighting has various sources/technologies available, as presented in figure 3.11.

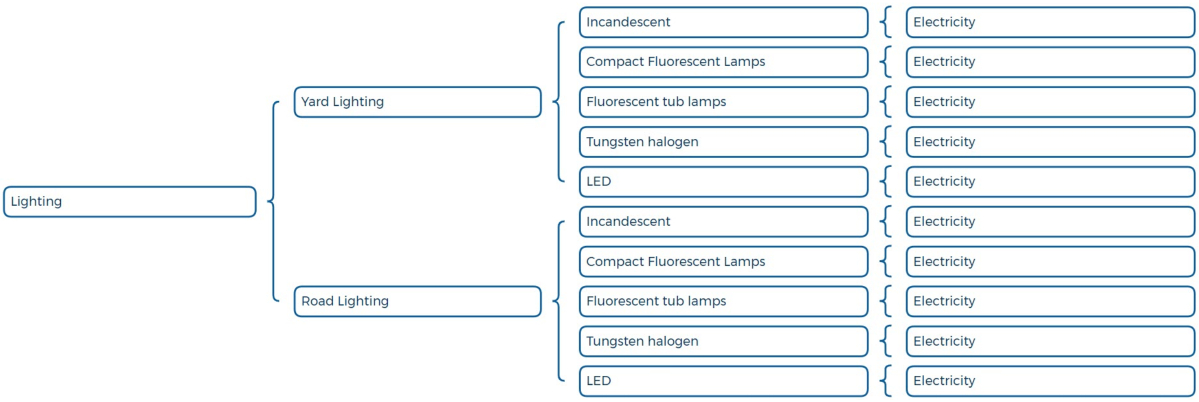

Figure 3.11: Disaggregation of Activity "Lighting".

The truck parking supports different activities, with the main end uses considered as lighting and space cooling or heating. To achieve better logistics of the port, oftentimes automatic machines, in which the truck or train driver inserts a ticket that is automatically read by the machine, are utilized, and powered by electricity. The gate itself is also powered by electricity, but there are other energy uses, such as those associated with the operation of surveillance cameras and alarms. Additionally, the surveillance at the gate may be supported by port staff within a small building which may include energy use for cooling, heating, a computer, and other technologies.

The commute of the personnel of the port is also accounted for in this area. In this category, the rest of the activities that do not belong to any of the rest are also included in "Other". With this area, the "Demand" division is done.

3.2.5 Energy Supply

The sub-category is "Energy supply" which, as mentioned before, is divided into "Local Generation" and is the one which corresponds to figure 3.12. The other subdivisions of this sub-category are are presented in Appendix A.

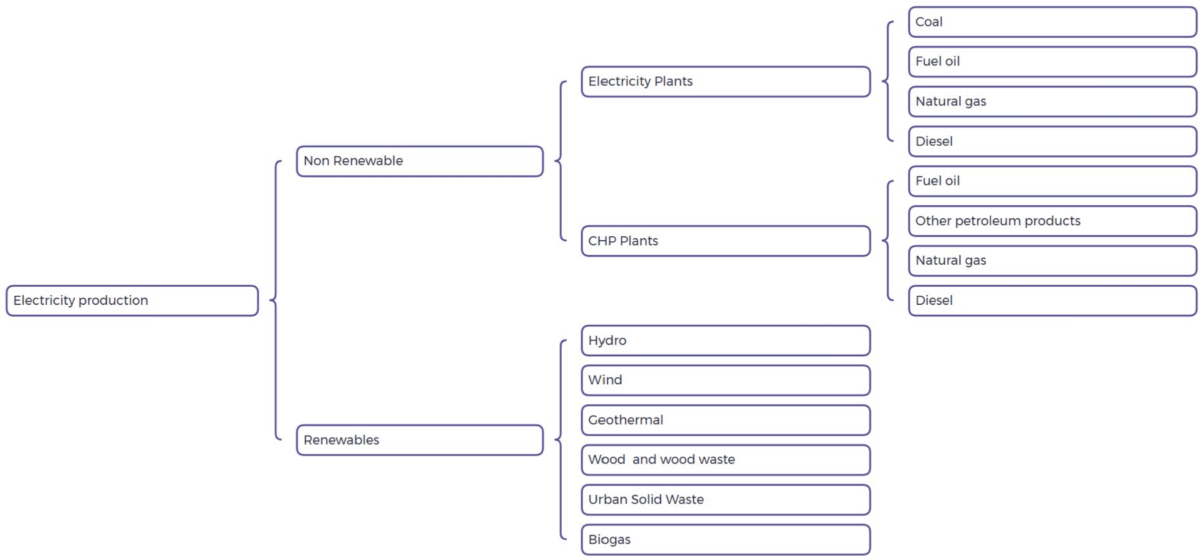

Figure 3.12: Disaggregation of Activity "Electricity Production".

The energy mix supporting the "Imported Energy" is not considered in detail in the model of the port is is produced outside the port boundaries. Nevertheless, it is necessary to have knowledge of, for instance, the electricity emission factors in order to understand the emissions produced inside the port.

3.3 Data collection

This section outlines the data collection process, including the sources of data, data quality and consistency checks, and the handling of missing or incomplete data. Evidently, the category division remains the same as presented in section 3.1.

3.3.1 Energy data

In order to fully caracterize the port energ system, several sources of data and type of information was collected, ecompassing the existing information on energy consumption, local energy generation, energy conversion efficiencies, and emissions factors for different energy vectors, technologies, and activities associated with the energy use, that mainly support the logistics operations of ports. The following sections describe in detail the identification of sources and data collection.

3.3.1.1 Operations

Vessels emissions

As part of the implementation of this dissertation work, the plan included obtaining data on logistics activities and characterization of port infrastructure and CHE directly from the port, specifically as part of ongoing research projects with the Port of Sines. However, the data was not obtained in time to be included in this work, and thus an alternative methodology for data collection, characterization of port infrastructure and activities and estimation of associated energy use and emissions had to be adopted. This mainly consisted in using data from literature, and publicly available information from the Port of Sines.

For example, for vessels, the process of calculating the emissions inside a port follows a bottom-up methodology. The emission for an individual ship is equal to equation 3.1:

$$E_{ship} = P \times t \times LF \times EF \text{ [71]} \tag{3.1}$$

where P is the nominal power of the engine (kW) and t is the time spent in a given operation (h). The EF is the emission factor (g/kWh) and LF is the load factor which is the quotient between the power used and the power of the engine.

For the sum of every emission produced by ships, the following equation (equation 3.2) is used:

$$E_{TotalShip} = \sum_{i=1}^{N} \sum_{j=1}^{M} P_{i,j} \times t_{i,j} \times EF_{i,j} \times LF_{i,j}, \tag{3.2}$$

where i is an index related to a particular vessel and N being the total number of vessels considered. The index j is related to the operation within port boundaries (cruising, manoeuvering, and berthing). M is the total of the number of operations performed by OGVs. In fact, the previous equation is equal to equation 3.3:

$$E_{TotalShip} = E_{Cruising} + E_{Manouevring} + E_{Berthing}, \tag{3.3}$$

and each of these terms is equal to equation 3.4:

$$\begin{aligned} E_{cruise} &= t_{cruise} \times (P_{ME} \times EF_{ME} \times LF_{cruiseME} + P_{AE} \times EF_{AE} \times LF_{cruiseAE}) \\ E_{man} &= t_{man} \times (P_{ME} \times EF_{ME} \times LF_{manME} + P_{AE} \times EF_{AE} \times LF_{manAE} \\ E_{berth} &= t_{berth} \times (P_{ME} \times EF_{ME} \times LF_{berthME} + P_{AE} \times EF_{AE} \times LF_{berthAE}) \end{aligned} \tag{3.4}$$

where *cruise* corresponds to cruising, *man* to manouevring and *berth* to berthing. It should be noted that, in the case of the OGVs, it is considered that the time required in cruising and maneouvering operations when entering is the same as when leaving the port. We introduce ME to indicate the Main Engine and AE for the Auxiliary Engine.

There are different processes to obtain the data related to the previous equations. The power of the main engine can be known by accessing a database with information about the vessels. Another way, if only the Gross Tonnage (GT) is known, is to use the information detailed in table B.1 in Appendix B. In this table, one can find a non-linear regression model estimating the installed ME power for each type of OGV. Inserting the GT in the equation results in a respective ME Power.

For auxiliary engine power, there are also data otained in the literature (table B.2) that give a ratio between the power of the ME and the power of AE. This way, there is solely the need of multiplying the power obtained previously for the ME by the ratio that relates to the type of OGV and the AE power is obtained.

The time t is calculated using equation 3.5:

$$t\ [h] = \frac{DistanceTravelled\ [km]}{AverageSpeed\ [km/h]} \tag{3.5}$$

For obtaining the load factor of ships when sailing, equation 3.6 (Propeller law) can be utilized:

$$LF = \left(\frac{AS}{MS}\right)^3 \tag{3.6}$$

where AS is the actual speed and MS is the maximum speed [115]. If this information is unknown, it is common to use values present in the literature (example in [75, 116, 117, 51, 118]).

In this study, one of the LF used to simulate the emissions was computed using the equation 3.6 (Load Factor of ME cruising) and the other values was retrieved from the literature. See table B.5 in Appendix B.

The second parameter needed to calculate the emissions of shipping is the Emission Factor. This can be taken from the literature as there are numerous studies with this information. It is necessary to know the fuel and engine type of the vessel, as it is related to the EF.

For the activities of Piloting, Towage, Mooring and Patrol, the same methodology of calculation is applied. The values for the LFs and EFs of the vessels that participate in these activities are obtained in the same way (propeller law). The logistics data is explained in the next subsection. For these activities, as the vessels are always in the port geographical area, it is possible to use the fuel consumption as well.

Terminal oriented activities emissions

For the terminal oriented activities, the emission can be calculated in different ways. It is possible to have an understanding of the average consumption per container moved, for instance, and then the emissions released for the cranes involved in handling the cargo is equal to (equation 3.7):

$$E_{crane} = C \times S \times EF, \tag{3.7}$$

where C is the average consumption per container [kWh/container], S is the number of containers moved (loaded or unloaded) by a specific crane and then EF is the same as above [g/kWh]. Evidently, the emissions resulting from these activities depend on the fuel used in each operation. If the vector used is electricity it is necessary to evaluate the electricity mix. This will be detailed in the subsubsection Electricity, Heat and Vector Generation. In other cases, the consumption is given in [L/container] and it is necessary to know the heating value [MJ/kg] and volumetric mass [kg/L]. These values can be obtained from studies such as [49]. The conversion is equal to equation 3.8:

$$C\ [kWh/container] = C_{fuel}\ [L/container] \times hv\ [MJ/kg] \times \rho\ [kg/L] \times \frac{1}{3.6}\ [1/h] \tag{3.8}$$

The consumption, mostly the consumption of vehicles involved in the horizontal movement of cargo, is given in [kWh/km]. However it is hard to estimate the total distance covered by vehicles, in the absence of direct measurements. One estimate that can be done is assuming an average distance for every piece of equipment. Another method consists in using the record of distance traveled for each vehicle, provided this type of metric is estimated by operators and is available. A third solution is to know how many liters of fuel or kWh of electricity are supplied to each equipment or vehicle.

3.3.1.2 Support & Maintenance

The Support and Maintenance activities are extremely diverse in nature. In this case, highly detailed energy consumption models can be very difficult to obtain. As a feasible approach, historical data about energy consumption can be considered for the sub-areas: Equipment or Port Fleet Maintenance, Infrastructure Maintenance and Emergency Operations. Whereas for the sub-areas: Vessel Provisioning and Waste Management, a combination of historical energy consumption and forecasted vessel calls should be considered, since the level of activity in these sub-areas is directly related with the number and characteristics of the vessels calling to the port.

3.3.1.3 Buildings

For Buildings, as mentioned previously, the model was based on [109]. For the categories considered for each sub-area, the technologies' efficiency can be retrieved from the same model, although there are now several models available from the EC for the EU energy system and end-uses which can be used to further describe the technical of different energy technologies linked to the end-uses and activities in ports.

3.3.1.4 General

For the activities of operations that include lighting the emission calculation is given by equation 3.9:

$$E_{lighting} = \frac{P \times t \times ESF}{\eta}, \tag{3.9}$$

where P [kW] is the power installed, t [h] is the time of use of the lighting technology, ESF is the Electricity Specific Factor [g/kWh] and η [-] is the efficiency of the technology. To obtain the total emissions [g] of a specific activity or technology is necessary to sum the emissions related to every light.

The power is provided by the manufacturer or by the Port Authority. This value can also be estimated by knowing the area of the port and the area a specific type of lighting technology covers. This is the process for outdoor lighting.

When looking into commuting , it is important to know the share of utilization of each, in terms of technology use. This is important because for each fuel or energy vector there is an Emission Factor associated. Equation 3.10 can be used:

$$E_{vehicle} = C \times hv \times \rho \times EF \times d \times \frac{1}{3.6}, \tag{3.10}$$

the variable d is the distance traveled using a specific vehicle in kilometers. Another way of obtaining the emissions related to vehicles for people's transportation is the fuel consumption records. If the vehicle is powered by human force, for example, a bicycle, the EF is equal to 0 [g/kWh]. The emission factor for each type of vehicle can be found in the literature. In this case, the EF were retrieved from the same model [109].

As covered in the previous subsection, the activities that are conducted at the gate are lighting, scanner use, climatization and electronic equipment. The lighting has the same methodology as the one covered for outdoor lighting but this time is for indoor lighting. What changes is exclusively the technology. The scanner use and some of the electronic equipment used (for example, the system that makes the door open) are proportional to the times that the gate has to let some vehicles in or out. Depending on the environmental conditions on the outside of the room of the small building where a person responsible for the security of the gate sits, it can be necessary to heat or cool down the space. For this, there is the possibility of both options, with of course, different technologies. These technologies emit a certain quantity of emissions given by equation 3.11:

$$E_{climatization} = \sum \frac{P \times t \times EF}{\eta}, \tag{3.11}$$

the variables are the same but the Power P is the power needed to cool or heat the room and η is the efficiency or COP (Coefficient of Performance) for a heat pump.

As for reefer containers, they can be responsible up to 40% of emissions of a terminal [119]. In the literature, some values of energy consumption regarding reefers can be found, for example in [120]. Another way of knowing the emissions produced by reefers is to monitor the electricity consumption of the containers. As previously mentioned, the electricity mix will influence the emissions.

3.3.1.5 Energy Supply

To evaluate the Electricity Specific Factor (ESF) it is necessary to know how is the electricity mix composed. For that, it is essential to establish what are the Emission Factors for every technology that produces electricity. It is known that the facilities that produce electricity using Renewable Energy Sources have an EF equal to 0. The technologies, that use resources such as wind power, wave or tides power or sun (these are the most common at ports, are helpful in reducing the ESF and therefore the emissions at a port [79].

The production of electricity using RES can be one of the sources of electricity at a port. However, it is not the only one yet. There is still a need to burn fossil fuels, like coal or LNG. If the electricity production inside the port is not enough for the necessities of the port, there is a need to import electricity. In this process, usually, it is considered that the ESF of this electricity can be the one of the country [121]. This can be considered to depend only on the country of the port or it can depend on the region [121]. In some cases, it can also be dependent on the electricity supplier company [116].

The data for the EF for each one of the technologies is retrieved from [109] and compared with the ones of [121], for example.

The result is given by equation 3.12:

$$ESF = \frac{\sum(Ele_{ElePlant} \times EF) + \sum(Ele_{CHP} \times \frac{Ele_{CHP}}{Ele_{CHP}+Heat_{CHP}} \times EF) + Ele_{imports} \times EF_{grid}}{Ele_{Total@port} + Ele_{imported}}, \tag{3.12}$$

where ESF is the Electricity Specific Factor [g/kWh], EF is the emission factor for each source of electricity [g/kWh] and then Ele is the total amount of electricity produced or imported. This amount is related to the index adjacent to the respective "Ele". "ElePlants" is Electricity Plants and CHP means Combined Heat and Power. The electricity values can be collected in any unit, but there must be a posterior care to convert them all to the same one, for example, toe (tonnes of equivalent oil).

The reason for the fact that electricity produced using RES does not appear in the equation 3.12 is that the $EF = 0$, as seen before. However, this amount of electricity enters in the $Ele_{Total@port}$. In this case, if the percentage of renewable energy is increased, the ESF decreases as the required electricity to be produced by non-renewable electricity plants, Combined Heat and Power plants and imported electricity is reduced. This way, it is possible to reduce the emissions of the technologies using electricity at ports, making them much more attractive for utilization.

This electricity will be used in every area of the Port. No matter if it is Operations or General, every area has specific technologies that need electricity. Thus, it is of extreme importance to correctly map the imports and productions in order to evaluate the mix. The records of imports can be easily accessed, resorting, for instance, to the information of the national grid and what enters a certain area (port area). Despite this, for the electricity production inside the port, only the Port Authority knows what is being produced during a year. The results can be estimated in a first approach but for more correct data, it is imperative that this information is provided by the Port Authority itself.

For heat production, the technologies used can be renewable CHP plants or non-renewable

CHP plants. These technologies not only produce electricity but also heat that can be used in industry processes, for example.

The generation and storage of energy vectors represents a major new commercial opportunity for ports. The emissions produced by these activities have to be considered. The energy needs of these sources are significant as the vectors many times need to be stored in a low temperature and high pressure. The values used in the generation and storage are found in the literature and have different values for various technologies and vectors.

3.3.2 Logistics data

In addition to energy data, the energy system model requires logistics data related to port activities, operations, and infrastructure. This section describes the data collection process for logistics data, discussing the sources of information, data validation, and the integration of logistics data into the energy system model. Logistics data may include information on cargo throughput, passenger volumes, vessel movements, and port infrastructure, which are essential for understanding the energy demand patterns and potential efficiency improvements within the port.

3.3.2.1 Operations

The power of engines can be given by the PA, retrieved from databases knowing which vessels have entered the port and then researching the engine power or looking into some studies that present some average values for a category or group of vessels. Due to the fact that real information from a port is unavailable, the solution is to start calculating using average values obtained in [71].

The time, t, can be also determined using an estimation found in the literature. There are studies that highlight the duration for each operation inside a port, for example, [34]. One can also ask the Port Authority for the time spent in any of the operations making an estimate knowing the number of calls and an average value or using the true number of hours. It is worth noting that is challenging to determine where one activity ends and the next begins. Knowing this, another option used to estimate this value is dividing the distance [km] traveled during a certain operation and the average velocity [km/h] of the same operation.

For the activities of Piloting it is known that for every vessel approaching the port, another one is necessary to guide the OGV inside and to its place. Therefore, the number of calls corresponds to the number of vessels that enter or exit the port. The distance is a value that depends on a specific port.

Towage depends on the tonnage of the inbound vessels and also on the tugboats available to use. The company that supplies the service of towage does not have every type of vessel. In this case, the number of vessels used depends on the experience of the operators of the port and the technology available. Nevertheless, there is some data in the literature that presents the number of tugboats needed depending on the size and tonnage of the boat [122].

For Mooring operations, the amount of vessels and vehicles depends on the size of the ship. Patrolling depends on the average actuation of these vessels, i.e., on the use and need of patrol vessels.

When looking into the QC and the vehicles responsible for the transport of containers from the quay to storage and the yard cranes and vehicles, it is crucial to account for the number of containers moved by each. This information, for instance, the number of quay cranes necessary to unload or load a ship is also available in the literature. This information can be used when the one provided by Port Authority is lacking. For the yard vehicles, it is necessary to consider the movements between the spaces in the storage space (the yard) and not only the movement to the hinterland where the movement in trains and trucks takes place.

For this set of equipment, it is necessary to know the number of containers that are moved in the port (import and export) as well as the operating cranes and vehicles. For some vehicles, it can also be necessary to know the distance traveled when moving the containers.

For trucks and trains, there are some studies, for example, in [116] that consider that the emission produced by these two means of transportation are responsability of the port. This study calculates their emission based on an average trip of a train or truck with goods in Spain. Within the scope of this work, the regarded emissions are produced in the geographical boundaries of ports. It is necessary to define with the Port Authority or the user what these boundaries are. For the simplest case, it is when a vehicle crosses the gates of the port but it can also be established a x kilometers radius from the port.

Regarding reefers, one should know the quantity of each type (TEU or FEU) in a port at a given moment. It can be easier if the reefers are dealt as groups , being possible to determine the energy consumption of a given group depending on the time they stayed at the port and the composition of the group (for example 50 TEU and 20 FEU).

3.3.2.2 Support & Maintenance

This data can be provided by the Port Authority and tenants that use and supply these services. In each of the sub-areas and respective activities, it is possible to account for the energy spent in a couple of ways. One is to know how much time a given machine/technology works during a certain time interval and then, with the specific power, it is possible to know the fuel or electricity consumption. Another way, a more direct approach, is to know the specific amount of fuel or electricity spent on a certain technology or group of technologies.

Despite the second alternative being more direct, the lack of information in many activities regarding fuel or electricity consumption creates a big challenge. The first option is also linked with certain difficulties. The number of equipment, the time of operation, and the specific consumption are all parameters that influence the final energy consumption. It is challenging to assess these values, so it becomes difficult to retrieve data with no deviation from the supposed real values.

3.3.2.3 Buildings

The buildings' data can be retrieved by analyzing with PA and tenants the several activities and the technologies used in the present. This corresponds to laborious work due to the number of possible sources inside buildings at a port. As for every category, the values can fluctuate considerably from port to port due to the different existing infrastructures. A typical procedure to estimate the energy use of buildings is to simulate a random day with an equally random, yet adequate, usage of technologies for a single day. The activities of all sub-areas except for "Maintenance and Industry" are the same, but the consumption profiles and equipment are particular to the different activities.

3.3.2.4 General

The estimation of energy use and emissions related with lighting uses, it is essential to have information of the time of day and duration of use, although an estimate can be made based on the are that is supported by the lighting system and by considering that lights are on during nighttime. Around the year that value can be around 10 hours, considering that it is possible to see without artificial light for one hour after the sun sets and one hour before the sun rises.

For traffic lighting, the technology is on 24 hours per hour. Despite the longer utilization time-wise, the number of traffic lights is smaller than the that of street lighting.

For commuting related energy and emissions, data on the utilization of the different vehicles by port staff is necessary. This data can be supplied by the Port Authority (number of employees and average distance traveled during a work day at the port) and the company responsible for the Cruise ship and Ferry Terminal, which knows the number of passengers using each type of vehicle. As the port serves as an energy vector generation and storage hub, it is safe to assume that Port employees and people arriving by cruise or ferry can travel using alternative fuels/vectors as the main option. Regular bicycles and electric bicycles can be major travel modes as well. These assumptions of a green port can lead us to the data used.

3.3.2.5 Energy Supply

Regarding local production, the values can be obtained by asking the tenants that produce electricity or heat or other vectors. They can supply the values of goods produced and energy spent during these processes. An alternative approach is to have knowledge of the values of a typical process and of the final product of a certain technology, thereby reaching the emissions related to it.

Information regarding imported energy can be retrieved from a national energy database or information of the municipality regarding energy trade.

3.4 Application of the model: Preparation for the case study

With the purpose of trying to demonstrate how the model works and test the approach within a practical case, a case study based on the Port of Sines was implemented. Port of Sines is the main port at the Atlantic front of the Iberian Peninsula. It is a recent port (1978) with a lot of space for expansion and an entry point for goods from the Atlantic, in particular Africa and America. It is the biggest entry point for energy primary resources in Portugal (crude, natural gas, and refined products) in Portugal and an important port in maritime trade [123]. Figure 3.13 shows the geographical location of Port of Sines.

Figure 3.13: Geographical location of Port of Sines in Portugal and Iberian Peninsula [124].

Due to the difficulty of obtaining real data for all areas addressed throughout the present chapter 3, this model application was conducted for the sub-category of Operations only. The main objective of implementing this case study is to demonstrate a real application of the model developed for the sources of emissions that are specific to ports. Whereas vessels and CHE are mainly found at ports, buildings, lighting, and other services are present in many other sectors and previously developed models.

This case study is implemented by considering a restricted number of container ships and their movements within the port. This study measures the emissions of these vessels, the HC that help the OGV enter the port and berth, and the equipment responsible for the container's movement. It is worth mentioning that this analysis was performed for a container terminal only, not considering liquid bulk or dry bulk transport, for example.

All the simplifications and assumptions made are clarified, allowing the estimation of values for energy consumption and emissions for several technologies, even when real data on the equipment is not available. Another aspect is the use of different technologies that are not considered during the case study. In the next section, an explanation of how the model developed was populated and how this case study was developed. The process of calculation of relevant values is made explicit, allowing the user to understand how a future user can apply it to their specific case.

Chapter 4

Results and Discussion

This section presents the results of the implementation of the energy system model decribed in the previous sections for the a case study related to the energy used in the operations related to port calls by 4 vessels for a given reference year (e.g., 2019). This estimate and case study includes only vessel operations and the activities performed in a container terminal.

The analysis includes a detailed breakdown of energy consumption by energy vector, technology, and activity or final end use, as well as the assessment of greenhouse gas emissions associated with port operations. The discussion highlights key trends, patterns, and potential inefficiencies in the current energy system, which serve as a baseline for evaluating future energy use and decarbonization scenarios.

4.1 Application of the model: Case study

As mentioned in the previous chapter, this analysis is performed for the Operations area, which includes the nautical operations and the terminal oriented ones. The two sub-categories are related with the container transport inside the port's geographical borders.

The case-study consists with mapping the energy consumption related to the operation within a container terminal. All the assumptions throughout this study are properly justified and supported by data or publications. The following sections present the case study, determines energy uses and emissions.

4.1.1 Nautical Operations

Beginning with the activities performed by Ocean Going Vessels, in this case, containerships, first is necessary to evaluate the calls during a given week. Table 4.1 shows the day of the week a vessel enters the port, the name of the vessel, the gross tonnage and year of construction of the specific vessel. This data can be extracted from databases such as *MarineTraffic* [125].

Table 4.1: Information about the calls and the vessels [125]

Call	Arrival Week Day	Vessel	Vessel Tonnage [t]	YEAR
1	1	WEC Van Goh	9408	2004
2	1	Maersk Serangoon	108306	2007
3	3	MSC Manya	43093	2003
4	4	MSC Mumbai VIII	108106	2005

From the table 4.1, it is possible to verify that the four vessels have different gross tonnages, with the second ship being extremely similar. Despite this, table 4.2 illustrates that the vessels transport different amounts of cargo, in this case, containers imported and exported.

Table 4.2: Information about the container through put

Call	Vessel	Import Container	Export Container	Total
1	WEC Van Goh	80	80	160
2	Maersk Serangoon	653	340	993
3	MSC Manya	125	200	325
4	MSC Mumbai VIII	890	1200	2090

The number of containers loaded/exported and unloaded/imported for each vessel, may not correspond to the reality as the values are chosen to create different scenarios.

As the principal characteristics of the call (except the entrance and exit of the port) are defined, the information related to the emissions can be collected. The first unknown is the ME power. It is obtained using equation 4.1 from table B.1 in the Appendix B:

$$P_{ME} = 2.9165 \times GT^{0.8719} \tag{4.1}$$

From the application equation 4.1 to all the ships, table 4.3 is obtained:

Table 4.3: Main Engine Power

Call	Vessel	Vessel Tonnage [t]	Power ME [kW]
1	WEC Van Goh	9408	8499
2	Maersk Serangoon	108306	71544
3	MSC Manya	43093	32033
4	MSC Mumbai VIII	108106	71429

Knowing the value and that the ratio between the power of auxiliary engine and power of main engine for containerships is 0.25 (from table B.2), the power of the AE is obtained and presented in table 4.4.

Table 4.4: Auxiliary Engine Power

Call	Vessel	Power AE [kW]
1	WEC Van Goh	2125
2	Maersk Serangoon	17886
3	MSC Manya	8008
4	MSC Mumbai VIII	17857

As the powers of both engines of the ship are known, the next step is to know the time of each operation. For the cruising and manoeuvring operations, it is possible to determine the time spent in operation dividing the distance by an average speed during the specific operation. It comes across a question related to where the jurisdiction of the port starts. This is a difficult question to work around, so it is up to the user to define what is the scope of the model. For this case, it was considered that the manoeuvring starts around 9260 meters (or approximately 5 nautical miles) from shore and cruising is done for more 27780 meters (or nearly 15 nautical miles).

The other term missing is the average speed. From table B.3 in Appendix B, it is possible to say that the average cruising speed for a containership is around 20 knots. Substituting the values in equation 3.5, it is obtained the time spent during cruising. Considering the same average speed and distance for every boat, the time spent in cruising is given by equation 4.2:

$$t = \frac{2 \times 27780/1000}{20 \times 1.854} = 1.5\ h \tag{4.2}$$

It is worth mentioning again that both the cruising and maneuvering have to be counted two times because there is the distance travelled when going in the direction of the port and existing the port. It is also necessary to convert meters into kilometers and knots into kilometers per hour.

The same methodology is applied to manoeuvring. However, this time the speed is 11 knots. The time spent in manoeuvring is 0.91 h.

For the berthing time, the scenario is a little bit more complicated. It is necessary to look at the terminal efficiency. One characteristic of this specific container terminal is that the average efficiency of the installed QCs is 45 containers/hour moved. This will be the factor that makes the time of berth change. It is also known that there are operations that take place with the ship already in position, thereby also increasing the total time of loading and unloading of the ship. All this leads to an equation (equation 4.3) that defines the berthing time when one QC is committed, where two additional hours have been considered:

$$t = \frac{S}{45} + 2, \tag{4.3}$$

with S being the total number of containers, explicit in table 4.2. Applying this equation to the values of the previously mentioned table, it results that the times of berthing per vessel corresponds to those in table 4.5:

Table 4.5: Times of berthing per vessel

Call	Vessel	Time [h]
1	WEC Van Goh	5.6
2	Maersk Serangoon	24.1
3	MSC Manya	9.2
4	MSC Mumbai VIII	48.4

When looking at table 4.5, it is easily seen that the time for two of the four vessels is higher than one complete day, even two for the fourth call. This is not a desirable turnaround time for the incoming ships. Considering this, the value of the terminal's efficiency is doubled in the second call and tripled in the fourth vessel, by committing additional QCs. This is made to correspond better to reality, as the global average of the time of berthing of containerships is around 14 hours (from table B.4 in the Appendix B). With this assumption results in a new table with the times (table 4.6):

Table 4.6: Times of berthing per vessel adjusting the terminal efficiency

Call	Vessel	Time [h]	Average time [h]
1	WEC Van Goh	5.6	11.3
2	Maersk Serangoon	13	
3	MSC Manya	9.2	
4	MSC Mumbai VIII	17.5	

The next step is to understand what are the load factors. For the LF of the main engine is possible to apply the propeller law given by equation 3.6. For the other engines and operations, the LF can be retrieved from the literature. The actual speed of cruising is known and it is equal to 20 knots. It is missing the maximum speed or the design speed. As it happens for the other one, there are no real data considering each specific vessel. So, the design speed is found in the literature and is about 20 to 25 knots, being the most common value around 24 knots [126]. Using the values of 20 for the AS and 24 for the MS, the Load Factor is equal to 0.59. The value obtained from the literature is 0.8. Comparing the two values, the value used in this study is a bit more conservative. In table 4.7, the Load Factors for each engine functioning in each operation are compiled, joining the information of table B.5 in the Appendix B.

Table 4.7: Load Factors for the two engines depending on the operation

Operational Mode	ME load (%)	AE load (%)
Cruising	59	30
Manoeuvring	20	50
Berthing	20	40

Knowing the engines' power, the time spent in each operation and the respective load factors, it is possible to calculate the energy used in each operation for each engine per vessel. This information is determined using equation 4.4 [2]:

[2]This step is optional. One can automatically calculate the Emissions, knowing the EF. The extra step is

$$Energy = P \times t \times LF \tag{4.4}$$

The energy for each combination during cruising is provided in table 4.8.

Table 4.8: Energy used by ME and AE for cruising

Cruising			
Call	**Vessel**	**Energy ME [kWh]**	**Energy AE [kWh]**
1	WEC Van Goh	7377.4	956.1
2	Maersk Serangoon	62104.5	8048.7
3	MSC Manya	27806.7	3603.7
4	MSC Mumbai VIII	62004.5	8035.8

The energy for each combination during manoeuvring is presented in table 4.9.

Table 4.9: Energy used by ME and AE for manoeuvring

Manoeuvring			
Call	**Vessel**	**Energy ME [kWh]**	**Energy AE [kWh]**
1	WEC Van Goh	1545.2	965.8
2	Maersk Serangoon	13008.1	8130.0
3	MSC Manya	5824.2	3640.1
4	MSC Mumbai VIII	12987.1	8117.0

The energy for each combination during berthing is shown in table 4.10.

Table 4.10: Energy used by ME and AE at berth

Berthing			
Call	**Vessel**	**Energy ME [kWh]**	**Energy AE [kWh]**
1	WEC Van Goh	9443	4722
2	Maersk Serangoon	186492	93246
3	MSC Manya	59084	29542
4	MSC Mumbai VIII	249738	124869

In table 4.11, the total energy consumption, total energy consumption per activity and per engine are given.

used to comparate the energy used in each activity, which will be useful afterwards, for the OPS.

Table 4.11: Energy used in each activity and ME and AE

Activity	Energy ME [kWh]	Energy AE [kWh]	Energy per activity
Cruising	159293	20644	179937
Manoeuvring	33365	20853	54218
At berth	504757	252378	757135
TOTAL	697414	293876	991290

Only one unknown is missing, which is the Emission Factor (EF). The emission factor is related to the type of engine and the fuel used. This information is present in table B.6 and can be retrieved knowing solely the fuel used for each vessel. For all ships, there is a principal combination of fuel and type of engine used. Regarding the fuel, this information depends on the type of ship and is shown in table B.7.

The engine type not only depends on the type of vessel but also on the gross tonnage of the vessel. This information is presented in table B.8. The combination of engine and fuel is compiled in table 4.12 for the main engine and in table 4.13 for the auxiliary engine. For each type of OGV there is information about the percentage of ships worldwide using a combination of fuel and a specific engine (present in table B.9).

Table 4.12: Main Engine Fuel and Engine for each vessel

Call	Vessel	Fuel	Engine
1	WEC Van Goh	HFO	MSD
2	Maersk Serangoon	HFO	SSD
3	MSC Manya	HFO	SSD
4	MSC Mumbai VIII	HFO	SSD

Table 4.13: Auxiliary Engine Fuel and Engine for each vessel

Call	Vessel	Fuel	Engine
1	WEC Van Goh	HFO	MSD
2	Maersk Serangoon	HFO	MSD
3	MSC Manya	HFO	MSD
4	MSC Mumbai VIII	HFO	MSD

With the most usual combinations of fuel and engine for the ME and AE, it is possible to take the EF for each one of the pollutants from table B.6. There are only 3 combinations used for the EF. However, there is a distinction for Cruising and Manoeuvring and while At Berth, which leads to two more combinations. The HFO used is 2.70% Sulphur and the MDO is 1.0% Sulphur. This is important for the calculation of some Emission Factors [127]. As the information is available for ships, it is possible to calculate also the emissions of several pollutant other than CO_2. Obviously, the uncertainty in the estimated emissions can be significantly reduced with access to the specific characteristic of the installed engines and the mix of bunker used by each ship.

The emissions produced by OGV in the port boundaries depend on the scenario evaluated.

This means the fuel used, the speed of the vessels and the usage of OPS. The calculation will be addressed in the next section.

After having calculated the total emissions of OGV inside the port's boundaries, the second step is to analyze the emissions of HC. This includes piloting and towing emissions. In this case, he mooring operations have not been included since there was no reliable data available on the installed equipment and the emissions released during this phase are not comparable with those emitted by the OGVs and HCs during the other operations considered.

For piloting the intervenient is the pilot boat. The same approach as the one done for OGV is performed here. In terms of power, it is given by the data accessible through the port and databases. The pilot boat's power is equal to 1000 kW.

In order to determine the time and the Load Factor it is vital to collect information about the average speed. From literature data, it is possible to hypothesise the average speed being equal to 16 knots. This is a suitable velocity considering the speeds for cruising and manoeuvring for OGV.

The average distance travelled for a pilot vessel is considered to be 9260 meters per trip. The distance accounts the distance the pilot vessel has to travel to reach the ship while the incoming vessel is approaching the port and then when it is piloting the ship off the port. Note that, for each call, the pilot vessel has to travel this distance twice, one time when the OGV is entering and another when it is leaving the port.

The time spent in activity by the piloting vessel per call is equal to equation 4.5:

$$t = \frac{2 \times 2 \times 9260/1000}{16 \times 1.854} = 1.25\ h \tag{4.5}$$

For the LF, it is used the Propeller law (equation 3.6). The actual speed is the same as the average speed and the maximum speed takes the value of 20 knots. This way, the LF is equal to 0.512.

Considering the same distance and average speed during the piloting the same for each call, the total energy consumption for the pilot vessel is equal to equation 4.6:

$$E = 4 \times P \times t \times LF = 1909\ [kWh] \tag{4.6}$$

Taking in consideration that the fuel used is HFO and the engine is MSD, the Emission Factors can be extracted from table B.6. From now on, the emissions are only calculated for CO_2, which is the pollutant with more information in the literature.

With all the information regarding the pilotage activity, the emissions of CO_2 are calculated. The emissions of pilot vessels are equal to 1.29 tonnes of CO_2.

To account the emissions of the main sources in nautical operations in a port, it is only missing the tugboats' activity. The tugboats have a more complex action: they need to deslocate to the incoming ship (a cruising operation) and then a manoeuvring operation where they guide the ship towards the berth place, where the ship is unloaded/loaded.

As for the other two categories, this process starts in assessing the activity of the ships in question. There are four calls, that means four operations to the tugboats. Then, the next step is to know what is the power of the engine.

For tugboats, there is a rule for the power required as well as the number of tugs required as a function of the tonnage of the vessel that is being towed. This information is shown in table B.11 in the Appendix B .

From this table, based in the information of table 4.1, the power of tugs is collected and can be scounsulted in table 4.14.

Table 4.14: Required Power for the set of tugboats depending on the vessel

Call	Vessel	Vessel Tonnage [t]	Power [hp]	Number of Tugboats
1	WEC Van Goh	9408	2400	1
2	Maersk Serangoon	108306	12000	3
3	MSC Manya	43093	6400	2
4	MSC Mumbai VIII	108106	12000	3

Considering the the cruising speed of the tugboat 16 knots and the average distance of a trip equal to 3500 meters, the time of this operation is 0.12 hours. The LF for the same operation, following the Propeller law, is equal to 0.512.

Combining the retrieved data, it yields that the energy spent by tugs during the cruising operation is given by equation 4.7:

$$E\ [kWh] = P\ [hp] \times 0.7457\ [kW/hp] \times t\ [h] \times LF \tag{4.7}$$

The energy consumed by tugboats in each call is presented in table 4.15.

Table 4.15: Energy consumed by tugboats depending on the call and total energy consumed by tugboats

Call	Power [hp]	Number of Tugboats	Energy [kWh]
1	2400	1	286
2	12000	3	1432
3	6400	2	764
4	12000	3	1432
		E_T	3913

For the tugboats, the fuel considered was the MDO, as it is the most common to use in this type of HC [128]. With this information and table B.6, it is possible to find the EF for CO_2 for the ME during cruising.

The emissions produced by the tugboats are the following (table 4.16):

Table 4.16: Emissions produced by tugboats when cruising

Call	Emissions during cruising [kgCO_2]
1	1.85E+02
2	9.23E+02
3	4.93E+02
4	9.23E+02
Total	2.52E+03

For the other activity performed by tugboats, i.e., manoeuvring, there are some steps that are already done. The Power is already known. For the time of operation, it was assumed that bigger vessels would take more time during the actual berth. In this case, the times for each call are present in table 4.17.

Table 4.17: Times of berth-in operation in hours for each call

Call	Time of berth-in [h]
1	0.80
2	1.3
3	1
4	1.3

The Load Factor is taken from the literature and a value of 0.60 was assumed during this operation [128].

With this information, it is possible to calculate the Energy consumed during the operation. The table 4.18 contains the energy consumption per call.

Table 4.18: Energy consumed during berth-in operation for each call and total

<table>
<tr><th>Call</th><th>Time of berth-in [h]</th><th>Load Factor</th><th>Energy [kWh]</th></tr>
<tr><td>1</td><td>0.80</td><td rowspan="4">0.6</td><td>859.1</td></tr>
<tr><td>2</td><td>1.3</td><td>6979.8</td></tr>
<tr><td>3</td><td>1</td><td>2863.5</td></tr>
<tr><td>4</td><td>1.3</td><td>6979.8</td></tr>
<tr><td></td><td></td><td>E_T</td><td>17682.0</td></tr>
</table>

The CO_2 emissions resulting from this activity are shown in table 4.19.

Table 4.19: CO_2 emissions during berth-in operation for each call and total

Call	Emissions during berth-in [$kgCO_2$]
1	6.10E+02
2	4.96E+03
3	2.03E+03
4	4.96E+03
Total	1.26E+04

In table 4.20 are compiled the emissions for tugboats.

Table 4.20: CO_2 emissions for tugboats

	Emissions [tCO_2]
Cruising	2.5
Berth-in	12.6
Total	15.1

Figure 4.1 represents the percentage of total emissions corresponding to the emissions of pilot vessels and tugboats.

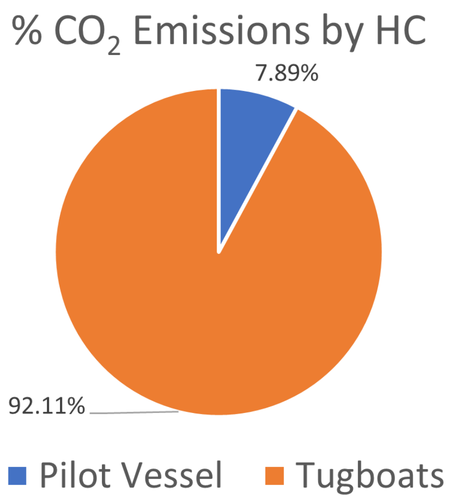

Figure 4.1: Percentage of Emissions of CO_2 of total emissions by each type of HC.

The lighting and other vessels (emergency vessels, for example) were not considered during the elaboration of this study because the use of these sources varies a lot from port to port and there is no true relevant information that could be used to illustrate the model. Its applications follow the same principles when talking about vessels and for lighting it is only necessary to follow the methodology presented during the present chapter 3.

4.1.2 Terminal Oriented Operations

When the OGV is put in position by the tugboats, the ship is ready to be loaded/unloaded. For this procedure are necessary the Quay Cranes.

A QC is defined by its consumption and its efficiency. This case considers two QCs, one fueled with diesel and the other powered by electricity. The consumption is presented in table D.1 in the Appendix D. The efficiency, meaning the number of containers moved per hour, is the same for both cranes. In table 4.21, this information is presented. If instead of knowing the consumption of each CHE, one knew the power, it would be necessary to know the LF and time spent in operation. The information related to the Load Factor is presented in table D.2 in the Appendix D.

Table 4.21: Information about the Quay Cranes

	Energy Vector	**Consumption**	**Efficiency [move/h]**
1	Diesel	2.77 L/move	60
2	Electricity	6 kWh/move	

With this information, it is possible to calculate the energy needs in terms of liters of diesel and kWh of electricity necessary to load and unload each ship and in total. The fuel/electricity needed are given by equation 4.8:

$$E\ [kWh] = C\ [kWh/move] \times S\ \vee\ V\ [L] = C\ [L/move] \times S \tag{4.8}$$

To better simulate what occurs in a real terminal, there is also a level of energy consumption when the equipment is waiting. As it was covered previously, the quay cranes efficiency (containers loaded or unloaded per hour) is higher than the one of the terminal. This means that the QC are waiting and still spending energy. However, the emission is undoubtedly smaller than when working. For this reason, the waiting consumption for the diesel crane was considered to be 0.277 L/h. For the electricity one, a value of 0.015 kWh/h was chosen. Depending on how much time the QCs are performing an idle activity, consumption will increase.

The total consumption while waiting is given by equation 4.9:

$$E\ \vee\ V = \frac{S}{45} \times (60 - 45) \times C \tag{4.9}$$

Being S the number of containers unloaded plus the number of containers loaded (table 4.2), the total consumption values may be calculated. The results are compiled in table 4.22.

Table 4.22: Consumption of Quay Cranes

Call	S	Diesel [L]	Electricity [kWh]
1	160	443.4	960.0
2	993	2752.1	5958.1
3	325	900.8	1950
4	2090	5792.5	12540.2
	Total	9888.9	21408.0

After knowing how many liters are required to power the QCs fueled with diesel and how many kWh are needed for the QCs powered by electricity, one can estimate the emissions of these two situations. For the first situation it is necessary to know the heating value, the volumic mass and the CO_2 emission factor in energy base. Other alternative is to have information of the CO_2 emission factor in a liquid base. This value is obtained by multiplying all the variables described above [40, 49]. It comes in equation 4.10 that:

$$2.6765\ kg\ CO_2/L = \frac{43}{10^6}\ [TJ/kg] \times 0.84\ [kg/L] \times 74000\ [kg\ CO_2/TJ] \tag{4.10}$$

Note that, since the amount of liters is known, a simple multplication is left to do.

For the electricity, it is necessary to evaluate the ESF. For a first approach, this value can be the one of the Residual mix. This is the result of the ESF after the electricity produced in Portugal is sold to specific consumers, that have contracts for buying electricity from certain sources, in particular RES, which have an ESF = 0. For Portugal, this residual mix has an ESF corresponding to 0.28106 $kgCO_2/kWh$. The production mix, which is the mix after production and before this specific electricity is sold to any consumer, has an ESF equal to 0.16418 $kgCO_2/kWh$. This data is obtained from [121]. In this first approach, it is not considered any production of electricity inside the port.

With the data of the EF for the two energy vectors, it is possible to evaluate the emissions for each case. This results are depicted in table 4.23.

Table 4.23: Emissions of Quay Cranes

	Emissions [$kgCO_2$]	
	Diesel	**Electricity**
Total	2.65E+04	6.02E+03

In alternative, there can be also a utilization of both technologies at the same time. This is, a port can decide to use ,for instance, 50% of the cranes powered by diesel and the rest 50% powered by electricity. This will result in table 4.24.

Table 4.24: Emissions of Quay Cranes combining both technologies

Usage % of each technology		**Emissions [kgCO_2]**		
Diesel	**Electricity**	**Diesel**	**Electricity**	**Total**
100	0	2.65E+04	0	2.65E+04
80	20	2.12E+04	1.20E+03	2.24E+04
50	50	1.32E+04	3.01E+03	1.62E+04
20	80	5.29E+03	4.81E+03	1.01E+04
0	100	0	6.02E+03	6.02E+03

The previous results are presented in a graphic manner in figure 4.2.

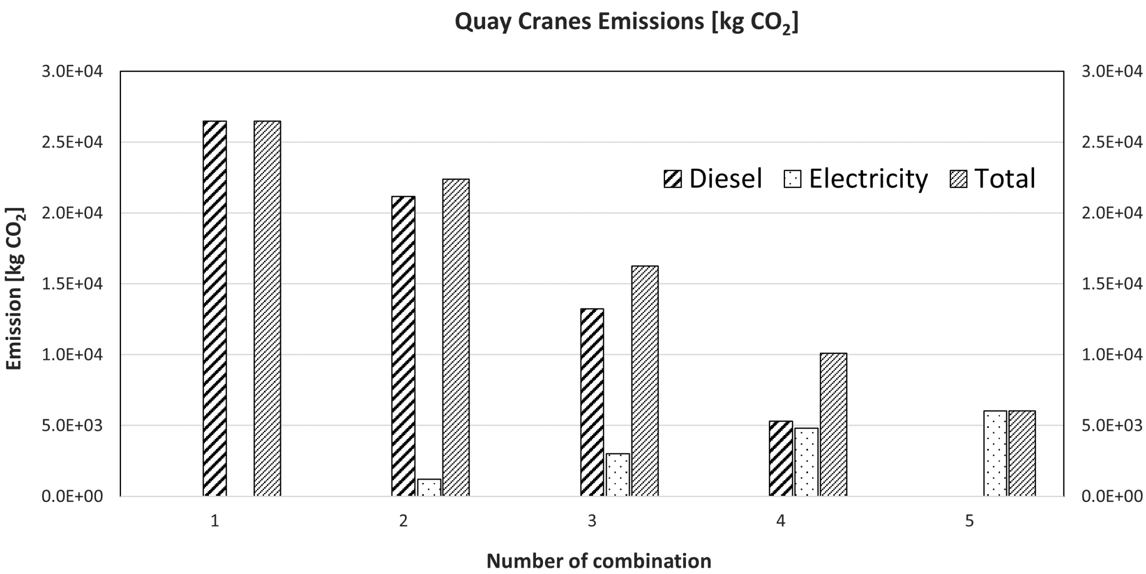

Figure 4.2: Graphical representation of results of table 4.24.

The next step in terminal-oriented operations is to move the containers from the quayside to the yardside (storage). For these operations, the terminal trucks are put in place.

The distance traveled for each trip for the Internal Trucks (IT) is measured using Google Earth (figure 4.3) and estimating an average route for ITs [124]. The average trip has a distance of 700 meters.

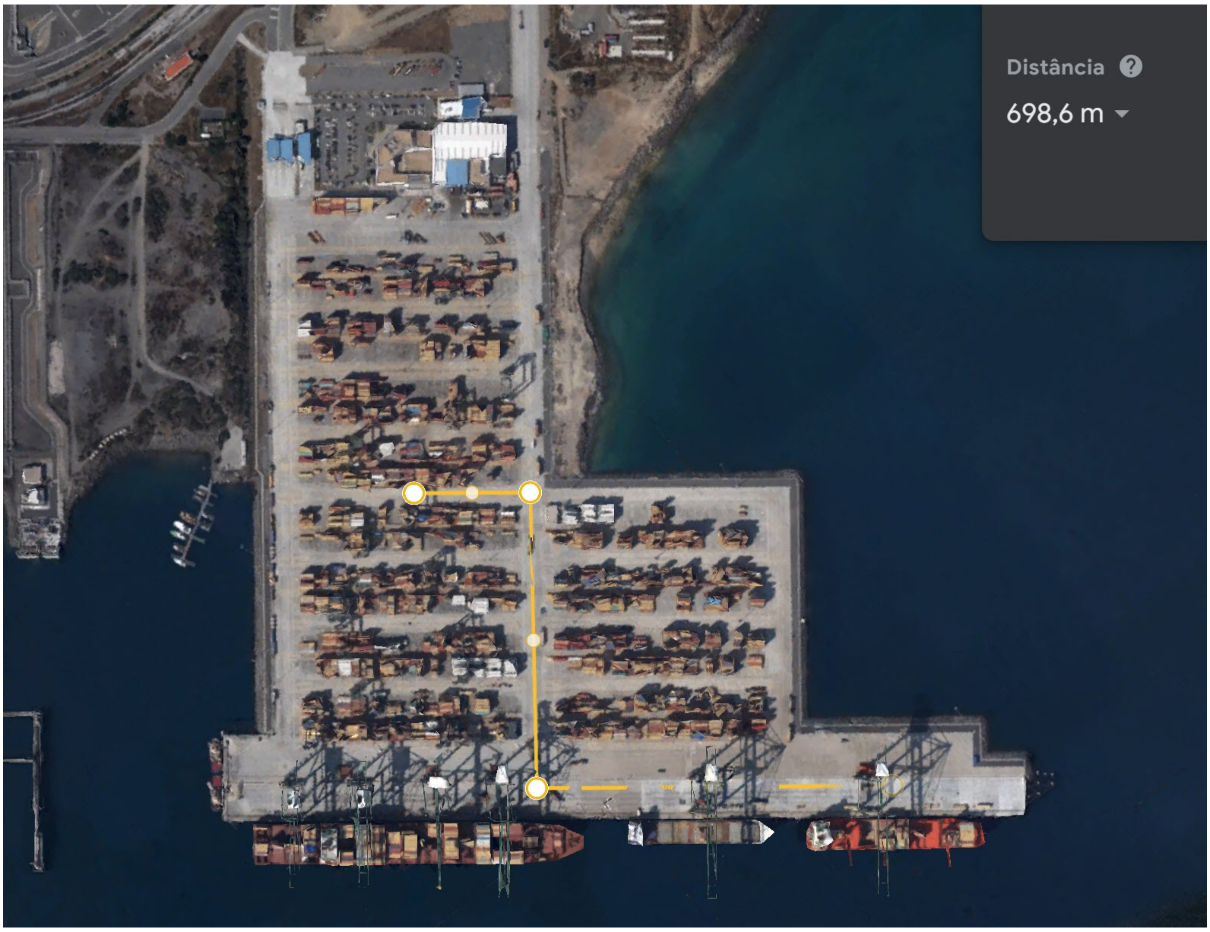

Figure 4.3: Satelite image of the containers' terminal with the distance measurement [124].

From this distance and the number of containers loaded and unloaded (table 4.2), considering that the trucks need to go to the storage and then return to the quayside and can do both with a container, the amount of kilometers a truck need to travel is illustrated in equation 4.11:

$$d\ [km] = 2 \times 0.7 \times max(number\ of\ containers\ imported; number\ of\ containers\ exported) \tag{4.11}$$

The application of equation 4.11 results in table 4.25.

Table 4.25: Total distance traveled by IT

Call	Distance [km]
1	112.0
2	914.2
3	280.0
4	1680.0
Total	2986.2

For the terminal trucks doing the movement of cargo, for simplification reasons, it is assumed that there is no waiting time, meaning that there is no energy spent when waiting.

From table 4.25 and the one with the consumptions (table D.1), table 4.26 presents the number of liters or amount of energy that is needed to travel the respective distance for the two different technologies.

Table 4.26: Total Liters or kWh needed for IT

Call	Distance [km]	Diesel [L]	Electricity [kWh]
1	112.0	361.8	123.2
2	914.2	2952.9	1005.6
3	280.0	904.4	308
4	1680.0	5426.4	1848
Total	2986.2	9645.4	3284.8

Applying the same procedure done for QCs, the emissions produced by ITs result in table 4.27.

Table 4.27: Emissions produced by IT

Usage % of each technology		Emissions [$kgCO_2$]		
Diesel	**Electricity**	**Diesel**	**Electricity**	**Total**
100	0	2.58E+04	0.00E+00	2.58E+04
80	20	2.07E+04	1.85E+02	2.08E+04
50	50	1.29E+04	4.62E+02	1.34E+04
20	80	5.16E+03	7.39E+02	5.90E+03
0	100	0.00E+00	9.23E+02	9.23E+02

The results are presented in a graphic way in figure 4.4.

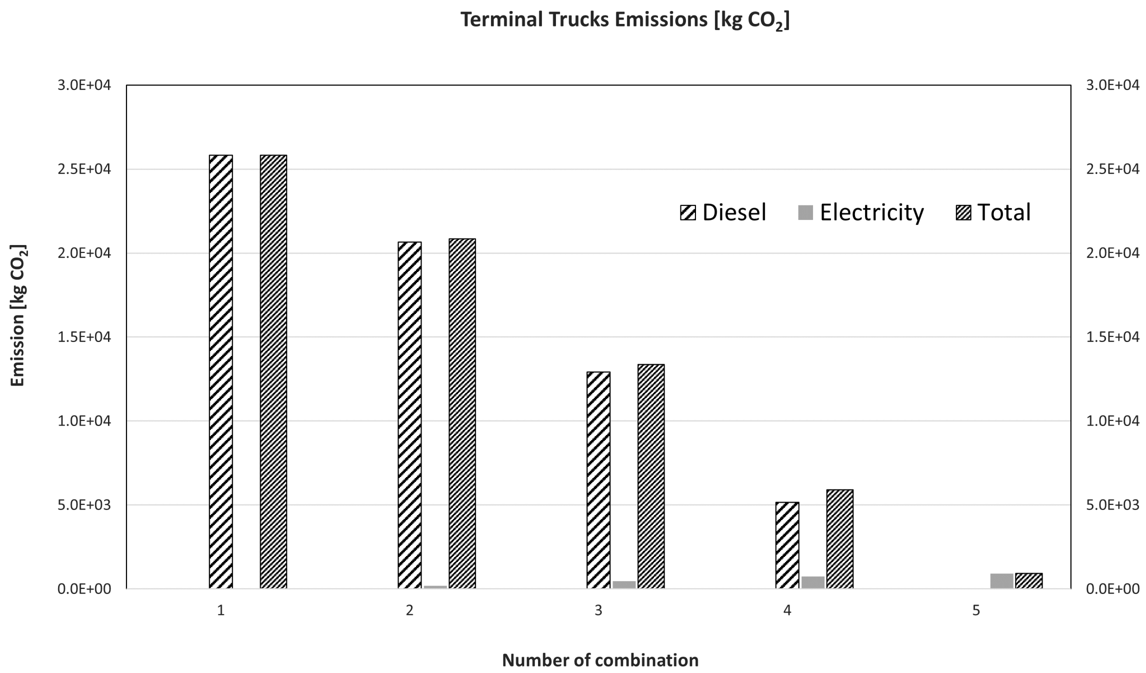

Figure 4.4: Graphical representation of the results of table 4.27.

Evidently, when they reach storage, the containers must be stored. Considering a container is responsible for one move only, the number of moves per call is given by multiplying the number of containers per call and the consumption of a given technology.

The consumption can be also retrieved from table D.1, as it happened for the two other cases. The diesel or electricity necessary for each call is presented in table 4.28.

Table 4.28: Total diesel and electricity consumed by YC

Call	Diesel [L]	Electricity [kWh]
1	211.2	1160.0
2	1310.8	7199.3
3	429	2356.3
4	2758.8	15152.5
Total	4709.8	25868.0

The emissions produced are depicted in table 4.29 below.

Table 4.29: Emissions produced by YC

Usage % of each technology		Emissions [kgCO_2]		
Diesel	**Electricity**	**Diesel**	**Electricity**	**Total**
100	0	1.26E+04	0.00E+00	1.26E+04
80	20	1.01E+04	1.45E+03	1.15E+04
50	50	6.30E+03	3.64E+03	9.94E+03
20	80	2.52E+03	5.82E+03	8.34E+03
0	100	0.00E+00	7.27E+03	7.27E+03

The results are presented in figure 4.5.

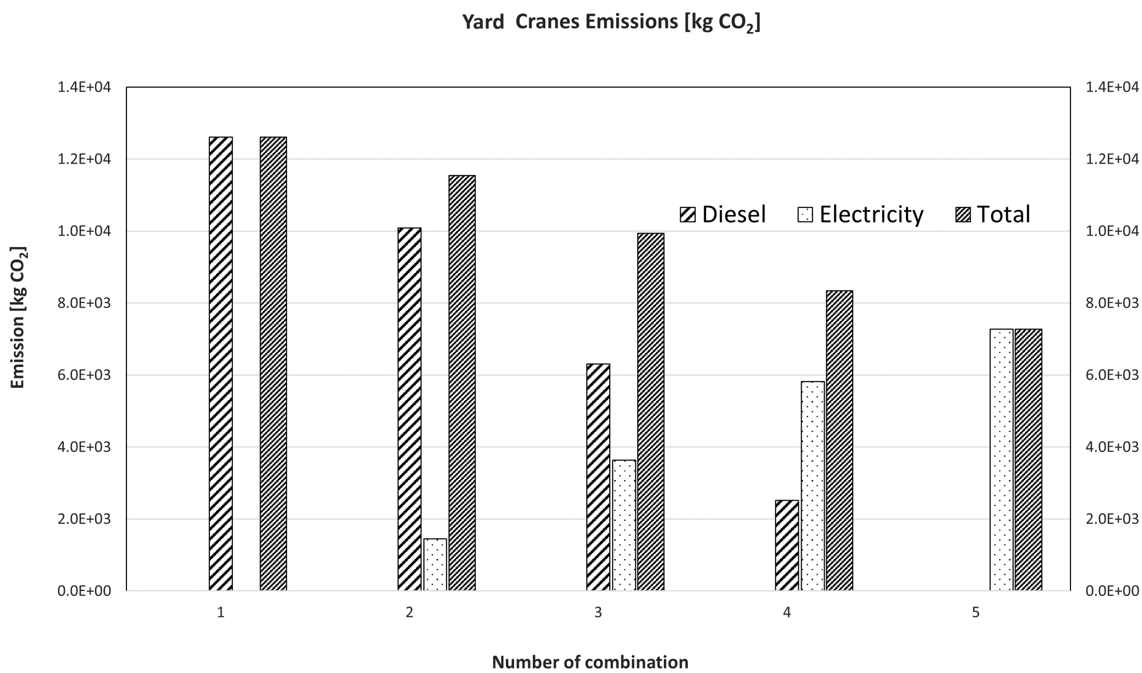

Figure 4.5: Graphical representation of the results of table 4.29.

The equipment responsible for the transportation from the storage to the hinterland is the same. Due to this fact, the procedure and the results for this action, where the containers are received or brought by trucks and trains are identical. In this step, there is one move for each container and the consumption is also the same. Due to this, the information will not be repeated once more.

The final step of transporting the goods is to put them in trains and trucks ready to deliver to the final consumer. In this case study, it was considered that each truck had the capacity of transporting only one container, whereas trains could transport 283 containers [51].

With this information, the number of trains and trucks necessary to transport the containers of a given call was calculated. This information is presented in table 4.30.

Table 4.30: Number of trucks or trains needed for each call

Call	Trucks	Trains
1	160	0.57
2	993	3.51
3	325	1.15
4	2090	7.39
Total	3568	12.61

It was considered that during the transportation of containers, trucks had an average consumption of 30 liters per 100 kilometers, which equals to 0.3 L/km. Trains, while carrying goods, have an average consumption of 8.8 L/km, both using diesel [129].

To calculate the emission, only one information is lacking: the distance traveled by each means of transportation. To assess the distance covered by each carrier, it was set an imaginary line in the map in which it was considered that the emissions were port's responsability. Once the trains or trains cross that line, the subsequent emissions are not accounted for. Using Google Earth once again, figures 4.6 and 4.7 were obtained with the relevant distance values for trucks and trains, respectively [124].

Figure 4.6: Satelite image of the truck's path inside the port boundaries with the distance measurement [124].

Figure 4.7: Satelite image of the train's path inside the port boundaries with the distance measurement [124].

At this point, it is possible to calculate the number of diesel liters needed for each call container's transportation inside the port. This is presented in table 4.31.

Table 4.31: Diesel consumption of trucks or trains needed for each call

	Diesel [L]	
Call	**Trucks**	**Trains**
1	64.3	8.8
2	399.2	54.7
3	130.7	17.9
4	840.2	115.0
Total	1434.3	196.4

To finalize, both the calculations of liters of diesel and the emissions produced when combining the utilization of both means of transportation are now in condition to be calculated. The results are depicted in table 4.32.

Table 4.32: Diesel consumption and emission when combining trucks or trains

Usage %			
Trains	**Trucks**	**Diesel [L]**	**Emissions [kgCO_2]**
100	0	196.4	5.26E+02
80	20	444.0	1.18E+03
50	50	815.4	2.18E+03
20	80	1186.7	3.18E+03
0	100	1434.3	3.84E+03

The emissions produced by the sources considered for this model have been calculated.

4.2 Characterization of energy use in the base year (2019) for a given week

For the reference evolution of the system, a business as usual, a scenario where no progress has been made towards decarbonization was implemented. This means that, in this port, all the fuels were either the most pollutant ones or the ones most currently used. This means that for ships, HFO (Heavy Fuel Oil) and MDO (Marine Diesel Oil) were used and for CHE (Cargo Handling Equipment), diesel was the fuel utilized.

Firstly, the emissions produced by the OGV are calculated, followed by the ones of HC and, finally, those of CHE. All the assumptions are addressed and explained.

Knowing all the information necessary to calculate the OGV emissions, tables C.1 to C.6 in the Appendix C were compiled for the baseline scenario. The emissions results obtained for each activity are shown in table 4.33, regarding OGV.

Table 4.33: Emissions produced by each activity (in grams of pollutant) and total (in grams and kilograms)

	CO_2	SO_2	NO_x	HC	CO	$PM_{2.5}$	PM_{10}	CH_4	N_2O
Cruising	1.14E+08	1.93E+06	3.91E+06	1.03E+05	1.03E+05	2.37E+05	2.55E+05	1.02E+03	5.58E+03
Manoeuvring	3.79E+07	6.45E+05	1.48E+06	6.79E+04	5.40E+04	7.16E+04	7.78E+04	4.78E+02	1.68E+03
At Berth	5.27E+08	8.97E+06	1.80E+07	1.01E+06	7.43E+05	9.99E+05	1.09E+06	7.03E+03	2.35E+04
TOTAL	6.79E+08	1.15E+07	2.34E+07	1.18E+06	9.00E+05	1.31E+06	1.42E+06	8.53E+03	3.07E+04
TOTAL [kg]	6.79E+05	1.15E+04	2.34E+04	1.18E+03	9.00E+02	1.31E+03	1.42E+03	8.53E+00	3.07E+01

Figure 4.8 illustrates the results of CO_2 emissions for the different activities performed by Ocean Going Vessels within the defined port limits.

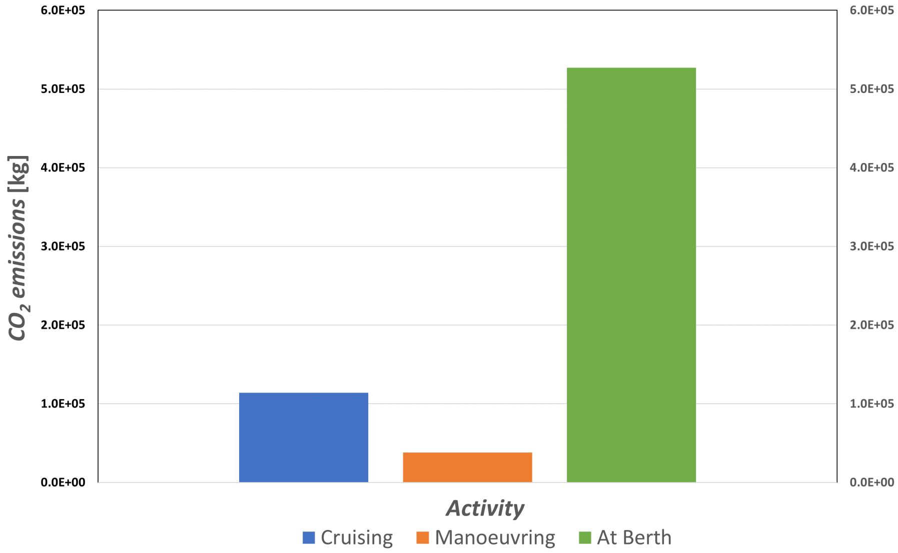

Figure 4.8: CO_2 emissions in kg of each activity done by OGV.

Figure 4.9 represents the responsibility of each activity in percentage of total emissions of OGV.

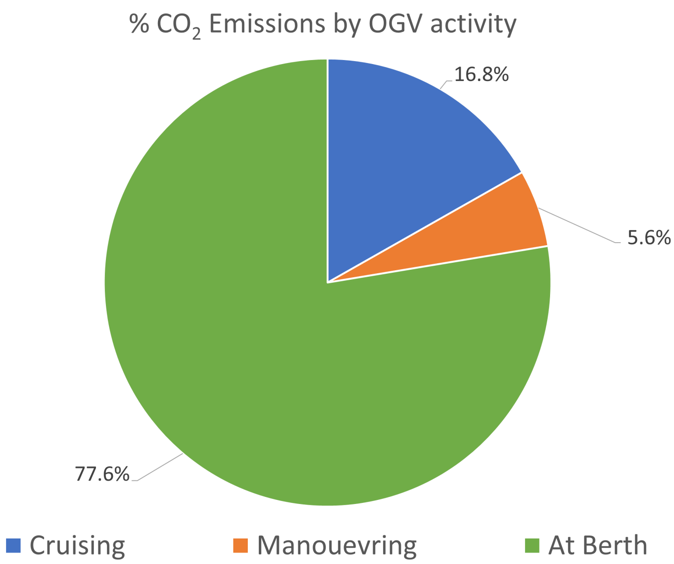

Figure 4.9: Percentage of emissions of CO_2 by activity of total emissions by OGV.

Having accounted for the emissions of every source of nautical operations within the scope of the case study, a table grouping all the emissions for the various sources was constructed. Thus, table 4.34 presents the total emissions for the various sources and the total for the nautical operations. The pilot vessels and tugboats were considered to be Harbour Craft (HC), as described in chapter 2. In this case, OGVs are only containerships (the four vessels entering the port in that time interval). Nevertheless, more types of vessels could be considered.

Table 4.34: CO_2 emissions for nautical operations

	Emissions [kgCO_2]
OGV	6.79E+05
HC	1.64E+04
Total	6.95E+05

Table 4.35: CO_2 emissions for nautical operations

	Emissions [tCO_2]
Cruising	114
Manoeuvring	38
At-Berth	527
Total	679

Table 4.36: CO_2 emissions for nautical operations

Emissions [tCO_2]
1.29

The emissions of each category of terminal oriented operations are defined by the emissions of the worst possible case, i.e., of the scenario in which the fuel utilized is always diesel and where exclusively trucks are used. The results are compiled in table 4.37.

Table 4.37: Emissions of terminal oriented operations in kgCO_2

	Vector/Vehicle	**tCO_2**
Quay Loading/Unloading	100% diesel	26.5
Quay to Storage		25.8
Storage		12.6
Storage to Receipt/Delivery		12.6
Receipt/Delivery	100% trucks	3.84
	Total	84.3

Figure 4.10 represents the percentage of each activity's emissions regarding total emissions of Terminal Oriented Operations.

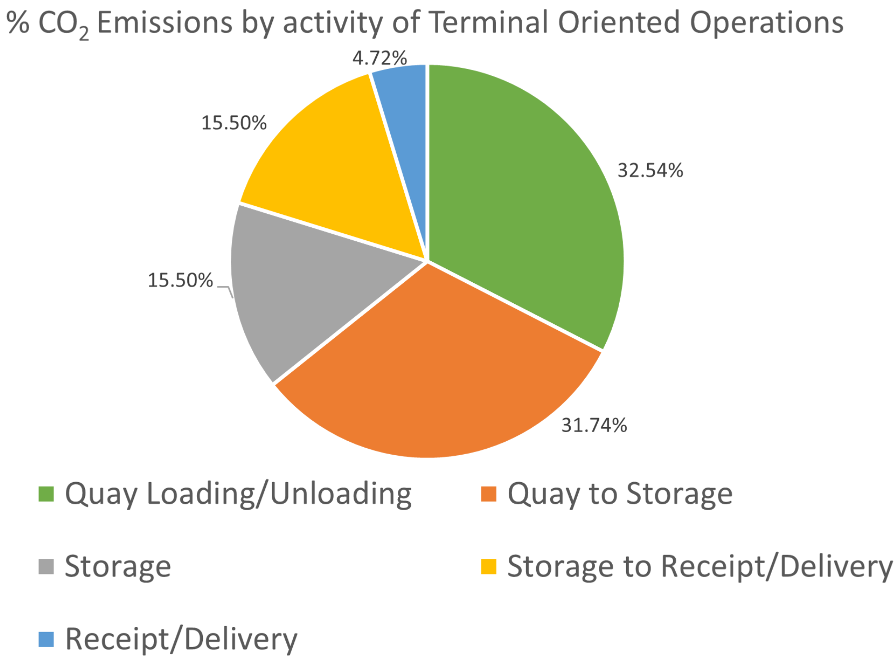

Figure 4.10: Percentage of Emissions of CO_2 of total emissions by each activity in the terminal.

Using the worst-case scenario for Nautical and Terminal Oriented operations, it is possible to assess how the emissions relate to each other in magnitude and perceive which is the biggest polluter inside a port (regarding the sources considered in this study). With this information, additionally, it is possible to determine which of the sources has the biggest prospect of reducing its emissions. Table 4.38 portrays the results obtained in the last chapter regarding emission per source.

Table 4.38: Emissions by sub-area (source) and percentage

Source	**CO_2 emissions** [tCO_2]
OGV	679
HC	16.4
CHE	84.3
Total	780

Figure 4.11 shows the percentage of total emissions that each source is responsible for in this situation.

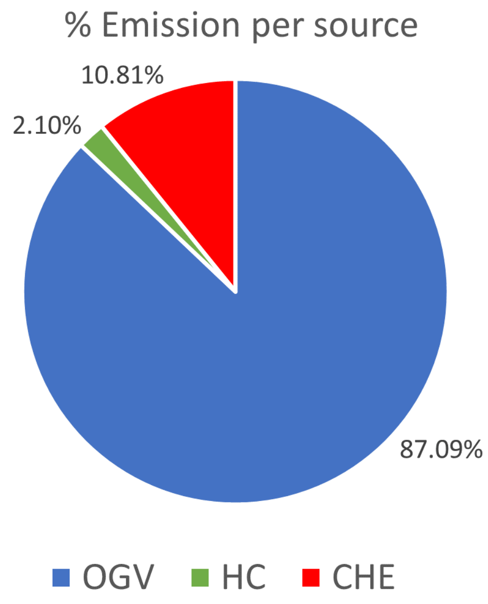

Figure 4.11: Percentage of emissions of CO_2 of total emissions per source.

Looking into the aforesaid figure, one can conclude that OGVs are responsible for more than 87% of CO_2 emissions during those days in which the four vessels entered the port. The next biggest pollutant is CHE with 10.81% of total emissions.

The obtainment of the diverse shares of emissions is certainly valuable information, being a crucial starting point for the future proposal and application of measures to the energy system at the port. In fact, from this point on, strategies to reduce the emissions of OGV can be put in place.

4.3 Future energy use for the case study: different scenarios of decarbonization

This section presents several scenarios for decarbonization towards 2050, with the aim of achieving the objectives set by the Paris Agreement. The current situation was presented in the last sub-section. The procedure presented in this section describes the process of building moderate scenarios of decarbonization and ending with a more ambitious one, which combines measures from both. In these scenarios, the technologies implemented are also addressed.

The measures employed within the various scenarios are some of the measures presented in chapter 2. To have applications of different types of solutions, it was chosen at least one of each three types of measures addressed. The use of OPS (Onshore Power Supply), the creation of a RSZ (Reduction Speed Zone), electrification of CHE and the changes in the Electricity Specific Factor (ESF). The latter can be achieved by the production of greener electricity of the entire country at stake, the region or the incorporation of renewables at the port.

Table 4.39: Scenarios of the case study

	Shipping					CHE					
	OPS				RSZ	Diesel	Electricity				
Scenario	**1**	**2**	**3**	**4**			**1**	**2**	**3**	**4**	
1	x	x	x	x	x	100%	x	x	x	x	**Baseline Scenario**
2	25%	x	x	x	x	100%	x	x	x	x	**OPS**
3	50%	x	x	x	x	100%	x	x	x	x	
4	75%	x	x	x	x	100%	x	x	x	x	
5	100%	x	x	x	x	100%	x	x	x	x	
6	x	100%	x	x	x	100%	x	x	x	x	
7	x	x	100%	x	x	100%	x	x	x	x	
8	x	x	x	100%	x	100%	x	x	x	x	
9	100%	x	x	x	✓	100%	x	x	x	x	**OPS and RSZ**
10	x	100%	x	x	✓	100%	x	x	x	x	
11	x	x	100%	x	✓	100%	x	x	x	x	
12	x	x	x	100%	✓	100%	x	x	x	x	
13	x	x	x	x	x	75%	25%	x	x	x	**Electrification of CHE**
14	x	x	x	x	x	75%	x	25%	x	x	
15	x	x	x	x	x	75%	x	x	25%	x	
16	x	x	x	x	x	75%	x	x	x	25%	
17	x	x	x	x	x	50%	50%	x	x	x	
18	x	x	x	x	x	50%	x	50%	x	x	
19	x	x	x	x	x	50%	x	x	50%	x	
20	x	x	x	x	x	50%	x	x	x	50%	
21	x	x	x	x	x	25%	75%	x	x	x	
22	x	x	x	x	x	25%	x	75%	x	x	
23	x	x	x	x	x	25%	x	x	75%	x	
24	x	x	x	x	x	25%	x	x	x	75%	
25	x	x	x	x	x	x	100%	x	x	x	
26	x	x	x	x	x	x	x	100%	x	x	
27	x	x	x	x	x	x	x	x	100%	x	
28	x	x	x	x	x	x	x	x	x	100%	
29	100%	x	x	x	x	x	100%	x	x	x	**OPS and electrification of CHE**
30	x	100%	x	x	x	x	x	100%	x	x	
31	x	x	100%	x	x	x	x	x	100%	x	
32	x	x	x	100%	x	x	x	x	x	100%	
33	100%	x	x	x	✓	x	100%	x	x	x	**All measures combined**
34	x	100%	x	x	✓	x	x	100%	x	x	
35	x	x	100%	x	✓	x	x	x	100%	x	
36	x	x	x	100%	✓	x	x	x	x	100%	

The numbers under OPS and Electricity correspond to the electricity mix factors used in this case study: **1** is the residual mix in Portugal equal to 0.28016 $kgCO_2/kWh$, **2** is the production mix in Portugal equal to 0.16418 $kgCO_2/kWh$, **3** is a lower value (0.1 $kgCO_2/kWh$) and **4** is the greenest electricity possible, obtained by renewable energy (0 $kgCO_2/kWh$).

During this subsection, the same structure used above in section 4.2 is use. In the next subchapters, a brief description of how the calculation is performed under the different scenarios is presented

As mentioned before, vessels are one of the biggest pollutants at ports. This justifies the fact that the first pair of measures is applied to them. The solutions applied for this case study are the use of OPS, also known as cold ironing, and having a Reduced Speed Zone, in which vessels can only travel at a maximum speed of 11 knots. These two measures will be studied throughout the next sub-chapter.

4.3.1 Scenario 2 - 8: OPS

First, the effect on the emissions of different OPS usage percentages will be studied. This means that a certain percentage of energy needed during berth is supplied using electricity from the shore. Cases 1 to 5 compare this by changing the percentage of OPS (0%, 25%, 50%, 75%, and 100%). Then, the effect of ESF is evaluated, resorting to the values provided in table 4.39. During this set of scenarios, it is assumed that 100% of energy needed during berth is provided by OPS (cases 5 to 8).

In table 4.40, the emissions and respective emissions reduction during at berth operations are depicted.

Table 4.40: Emissions at Berth of the different scenarios (1-5) with different OPS percentage usages

	OPS with an ESF of 0.2801 kgCO_2/kWh				
Scenario	**1**	**2**	**3**	**4**	**5**
kgCO_2 emissions	5.27E+05	4.54E+05	3.82E+05	3.09E+05	2.36E+05
% Reduction	-	-13.78%	-27.57%	-41.35%	-55.14%

It is also essential to get a grasp of the reduction of emissions, not only at berth, but also in a more general light. This wider approach can be seen in terms of OGV emissions or total emissions. The reduction in OGV emissions is compiled in table 4.41.

Table 4.41: OGV emissions of the different scenarios (1-5) with different OPS percentage usages

	OPS with an ESF of 0.2801 kgCO_2/kWh				
Scenario	**1**	**2**	**3**	**4**	**5**
kgCO_2 emissions	6.79E+05	6.06E+05	5.34E+05	4.61E+05	3.88E+05
% Reduction	-	-10.70%	-21.40%	-32.10%	-42.80%

The total emissions and respective emission reduction for each scenario for total emissions are shown in table 4.42.

Table 4.42: Total emissions of the different scenarios (1-5) with different OPS percentage usages

	OPS with an ESF of 0.2801 $kgCO_2/kWh$				
Scenario	**1**	**2**	**3**	**4**	**5**
$kgCO_2$ emissions	7.80E+05	7.08E+05	6.35E+05	5.62E+05	4.90E+05
% Reduction	-	-9.31%	-18.62%	-27.93%	-37.24%

After establishing a comparison between the cases where the percentage of OPS is altered, the same will be done for the scenarios in which the ESF is changed keeping the OPS utilization at 100%. Table 4.43 presents the reduction of these scenarios related to total emissions as well as the total emissions in each.

Table 4.43: Total emissions of the different scenarios (1-5) with different OPS percentage usages

	ESF $kgCO_2/kWh$	0.2801	0.16418	0.1	0
Scenario	**1**	**5**	**6**	**7**	**8**
$kgCO_2$ emissions	7.80E+05	4.90E+05	3.91E+05	3.37E+05	2.53E+05
% Reduction	-	-37.24%	-49.88%	-56.81%	-67.60%

4.3.2 Scenario 9 - 12: OPS and RSZ

The next step is to use the RSZ (Reduced Speed Zone), which is a facultative measure that ships can take to help reduce emissions near coastal areas. This measure is added to cases 5 to 8, which creates cases 9 to 12.

4.3.3 Scenario 13 - 28: Electrification of CHE

Through cases 13 to 28, the measure studied is the electrification of all the cargo handling equipment that allows the transportation of containers from the ships, through the yardside and to the trucks and trains that take the goods to their final destination. In this subsection, the effect of different combinations of diesel and electricity, as well as the change in ESF is analyzed. The different cases are shown in a simpler way in table 4.44. These cases are compared directly with the one that has an exclusive diesel consumption, i.e., case 1.

Table 4.44: Energy use in percentage of diesel and electricity

Cases	Diesel [%]	Electricity [%]
13-16	75	25
17-20	50	50
21-24	25	75
25-28	0	100

Once again, for each group of cases, the ESF is corresponding to the ones provided in table 4.39.

4.3.4 Scenario 29 - 32: OPS and Electrification of CHE

This subsection presents the scenarios in which the combination between the OPS and electrification is done. This is important to realize what is the impact of the measures applied by the port users and PA. These measures can be seen as mandatory, whereas reducing the speed within a closer area to the port is not.

This subsection deals with the solutions where 100% of OPS and 100% of electrification of the CHE can be found. With these measures, it is possible to acknowledge the effect of having a different electricity mix in the port. The 4 cases (29-32) have the 4 electricity mixes studied before.

4.3.5 Scenario 33 - 36: Ambitious Decarbonization: All measures combined

The final case study scenarios are the ones that gather all the measures mentioned in this chapter. To the last subsection, it is added the reduction of speed during cruising, which will in fact decrease emissions during that activity.

4.3.6 Results

The final results are presented in table 4.45, where a color scheme illustrates the level of emissions reduction for each case. The red ones (between 0 and 10%), were considered to be insufficient as a single measure. The application of these measures needs to be complemented with others. With the green scenarios, at least a 50% reduction is achieved, with the darker one having a 80% minimum reduction. This color scheme is presented in table 4.46.

Table 4.45: Total emissions reduction of the different scenarios

Scenario	Reduction [%]	Scenario	Reduction [%]
1	-	19	4.62
2	9.32	20	5.16
3	18.64	21	5.45
4	27.95	22	6.56
5	37.27	23	6.92
6	49.88	24	7.74
7	56.81	25	7.27
8	67.60	26	8.74
9	50.59	27	9.23
10	63.20	28	10.32
11	70.12	29	44.54
12	80.91	30	58.63
13	1.82	31	66.04
14	2.19	32	77.91
15	2.31	33	57.85
16	2.58	34	71.94
17	3.63	35	79.35
18	4.37	36	91.23

Table 4.46: Emission reduction color scheme by intervals used to create table 4.45

Color	Lower Limit [%]	Upper Limit [%]
	0	10
	10	20
	20	50
	50	80
	80	100

Chapter 5

Conclusions

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

5.1 Summary of main findings

The development of an energy system model for ports is complex due to the multiple activities taking place within ports, the variety of port structures, the number of stakeholders, and functions. Furthermore, the definition of the main purpose of the energy system mapping depends on the goals that each port is trying to achieve. For example, focusing on the decarbonization of the port as a whole or specifically in the decarbonization of the operations managed directly by the Port Authority leads to completely different energy system boundaries and therefore mapping of activities, end uses, vectors and technologies.

Finding the best way of identifying, characterizing and dividing the various activities and sources of energy use is also challenging. Existing norms are already adopted to some degree for energy management of, at least, some systems in ports and can be used as a starting point, such as the ISO 50001 or the 3 Scopes approach. This study used as an inspiration the categories proposed in the ISO 50001, but then developed and proposed a new structure for the energy system of Ports, considering also studies carried out for other sectors.

The emphasis of the work was the characterization of the activities that are particular to ports which were mainly included in the "Operations" branch of the "Energy Demand" category of the energy system structure proposed. Specifically for this work, the scope of the activities within "Operations" that were described in detail included those that take place in the process of a port call, including the activities supporting the safe maneuvering of the vessel entering and leaving the port, and those supporting the berthing, loading and unloading of cargo, the Nautical and Terminal Oriented operations.

Since specific data for the port of Sines was not available, only part of the nautical and terminal operations were characterized. Furthermore, mostly data from literature with some additional input and "sanity check" from a Port Expert. The detailed analysis of the energy use and emissions ended up focusing on a subset of the "Operations" branch, which included the activities as the vessel approaches the berth, the berthing process, the consumption at berth, the loading and unloading of cargo, their movement to storage, and finally the delivery of the cargo to be picked up for further transport to hinterland. The transport beyond the port, the consumption of reefers - which can be substantial for container terminals, and the other activities that take place in ports were not considered.

For the use case that was defined for more detailed study, Ocean Going Vessels (OGV) were found to be the major contributors in terms of emissions, especially during the time that the vessels spend at berth. For this particular energy use, the implementation of low carbon alternatives to the use of the (mostly) HFO auxiliary engines to power the vessels at berth, can eliminate a very significant share of the emissions. Particularly, connecting the vessels to OPS and implementation of a Reduction Speed Zone (RSZ) were found to almost eliminate the emissions from the OGVs within the activities considered in the use case.

The emissions of the OGVs represented roughly 87% of the total emissions considered, while the CHE represented 11% and the HC the rest. With the measures applied to the system, it was possible to achieve a significant reduction (up to almost 70%) when using only OPS. When complimenting it with the creation of a RSZ or the electrification of the CHE, the reduction increased by 10%. Combining these three measures, a reduction in CO2 emissions of around 90% was possible, which indicates that electrification of operations in ports is a very promising route to the complete decarbonization of the operations considered in the use case by 2050.

It should be noted though that the scenarios that delivered the highest emissions reductions were the ones with the lowest electricity emissions factors, with some considering descarbonization of the electricity vector. Additionally, part of the improvement in the system also stems from the improvement in efficiency of conversion of final energy into useful that results from substituting the fossil fuel technologies by electrical motors and battery based systems.

The results obtained in this work reinforce the strategies that are already being discussed for ports that include investments in local renewable electricity generation and installation of OPS infrastructure, alongside electrification of CHE. It should be noted that the results obtained in this study may be hard to reproduce at whole port scale, or even for specific ports as the impact of the measures depend on infrastructural, social, geographical, and environmental factors specific to each port.

5.2 Limitations and challenges

Given 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. In fact, note that this work compiles a variety of different technologies and aims to realistically capture the complexity of the system existing in a port.

The division in areas and categories of the different emission sources was challenging to perform initially, because there is a large number of approaches to this problem in the literature. To find one that would represent the problem in a perspective that would be suitable for the scope of this work was complex. This is due to the fact that ports may be located in different countries or even continents that have different policies, priorities, and perspectives.

The existence of diverse nomenclatures used to describe and characterize activities in ports added another layer of difficulty to the analysis. Further, the varied structure of ports made the implementation of this work complex and therefore simplifications of the scope were needed.

When developing the system, the focus was mainly on a container port and the possibility of being a (dry or liquid) bulk port was added, which added an extra layer of complexity. Thus a decision was made to focus the detailed analysis of the emissions and decarbonisation measures in a case study for a container terminal, which is representative of many ports.

Another challenge was the lack of information specific for the port. This brought some difficulty to validate the developed model. During the course of this work, some assumptions had to be made which could potentially have led to some errors (over or sub-estimations in emissions of some areas). However, this does not undermine the work developed because the model is coherent with the literature and respects the studies consulted. The model is apt to be used by any user.

Regarding information related to ships, such as the licenses to obtain access to World Shipping Register, Lloyd's Register, and IMO documents, some were demanding to find. Some data, due to confidentiality agreements and other reasons, was impossible to obtain. Other was retrieved from articles citing other publications. Moreover, some of the information found for the same system/equipment had contradictory values in different sources.

The information about Cargo Handling Equipment was scattered throughout numerous web pages and articles which made the search for information more cumbersome. In addition, no information was found for some of the equipment used in ports.

Within this work, the objective was to characterize the sources of emissions that exist in a port geographical area. However, due to the limitations in accessing specific information from the port, and the contradictory or missing data described above, the use case that was described may be incomplete.

Chapter 6

Future Work

In the present chapter, after having reflected on the conclusions emerging from the work performed, some improvements and other aspects of potential future studies in this scope are addressed. First, regarding the potential upgrades of the model and then on what could be added to the system in terms of decarbonization measures and other sustainability aspects.

6.1 Potential improvements to the energy system model

Regarding potential improvements, it is clear that the model must be tested for longer periods of time, additional equipment and systems, and stakeholders. The best potential end users of the model most suitable to test the model developed are in port operators and stakeholders (port authorities, tenants, or researchers). These users could provide some insights into the port and what they think it is better for their specific one. By doing this, it's possible to evolve the model created into a more complete and general port model. This gives every Port Authority or regular user the chance to simulate a port's emissions without any necessity for changes. When working with a specific port, this model is also easily adapted to a given port's requirements and needs.

Within the scope of this work, the data collected was not given by any port authority. This creates a lack of information that could be improved if the PA supplied the data necessary (for example, real ship data and real CHE data). Many ports, especially in Europe, release their sustainability reports yearly. This is a sign of transparency and also gives them more social approval. In Portugal, this is not the case at the moment.

For the verification of the model, the time scope of the data was not taken into account. It is known that, in some ports, fluctuations in the cargo moved through the port throughout the course of a year are verified. For this reason, it would be a good improvement if the data could be collected over one year to observe these fluctuations and eliminate potential errors.

For some technologies, there exist some gaps within the present and future efficiencies that allow to evaluate the emissions. This information could be added to make the work more complete and ready to utilize the competent users. This is not only relevant for this work, but also for someone eventually looking for technologies and their efficiencies, powers, etc.

With the COVID-19 pandemic, growing trend of the marine trade came to a halt. It is still uncertain how the next year will develop in these terms. Due to this, oftentimes pre-COVID numbers are still used in studies (2019). When the numbers reach a more stable rise, it will be easier to evaluate all matters, in terms of: population growth, economic growth, marine trade growth, and consequently port growth.

Another aspect that could be added to enrich this study is the economic factors. During this work, the only focus was the environmental impact of a port, and the monetary value of adding new or improved technologies was not addressed. Evidently, it would be advantageous to understand if, economically, one technology is preferable instead of the other.However, studies regarding the economic impact on ports are scarce. In terms of costs, they could be, for instance, the addition of a RES (Renewable Energy Source) facility in the port area or the cost of investing in a patrol boat fueled with hydrogen. This could be a valuable improvement to this study and make it more desirable and complete for users.

6.2 Integration of other sustainability aspects (e.g., social, economic)

Ports' sustainability is based in three pilars. The environmental one and two equally important pillars, social and economical [130].

Social sustainability is related to enhancing people's quality of life by supporting port activities that address socioeconomic objectives and promote a higher social stability in the port's surrounding region [130]. The social impacts may be in the form of [91, 130]:

- Employment (amount of jobs).
- Job training.
- Gender equality.
- Well-being (health and safety).
- Climate robustness.
- Urbanization.
- Safety against flood.
- Public relations.
- Social image.
- Quality of living environment.
- Social participation.
- Education.

Maximizing the economic performance that comes from putting sustainable development concepts into practice, without having a negative impact on social and environmental development, is what economic sustainability is about. The economical impacts can be [91, 130]:

- Cargo growth (TEU).

- Port throughput.
- Cruise Tourism and general tourism.
- Foreign direct investment.
- Investment in industry, fishery.
- Value generated productivity.
- Benefits from external stakeholders.
- Port development funding.
- Port infrastructure construction.
- Operating costs/revenue.
- Port operational efficiency.

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Appendix A

Disaggregation of Activities

Figures A.1, A.2, A.3 and A.4 show the disaggregation missing in chapter 3 from the sub-area "Nautical".

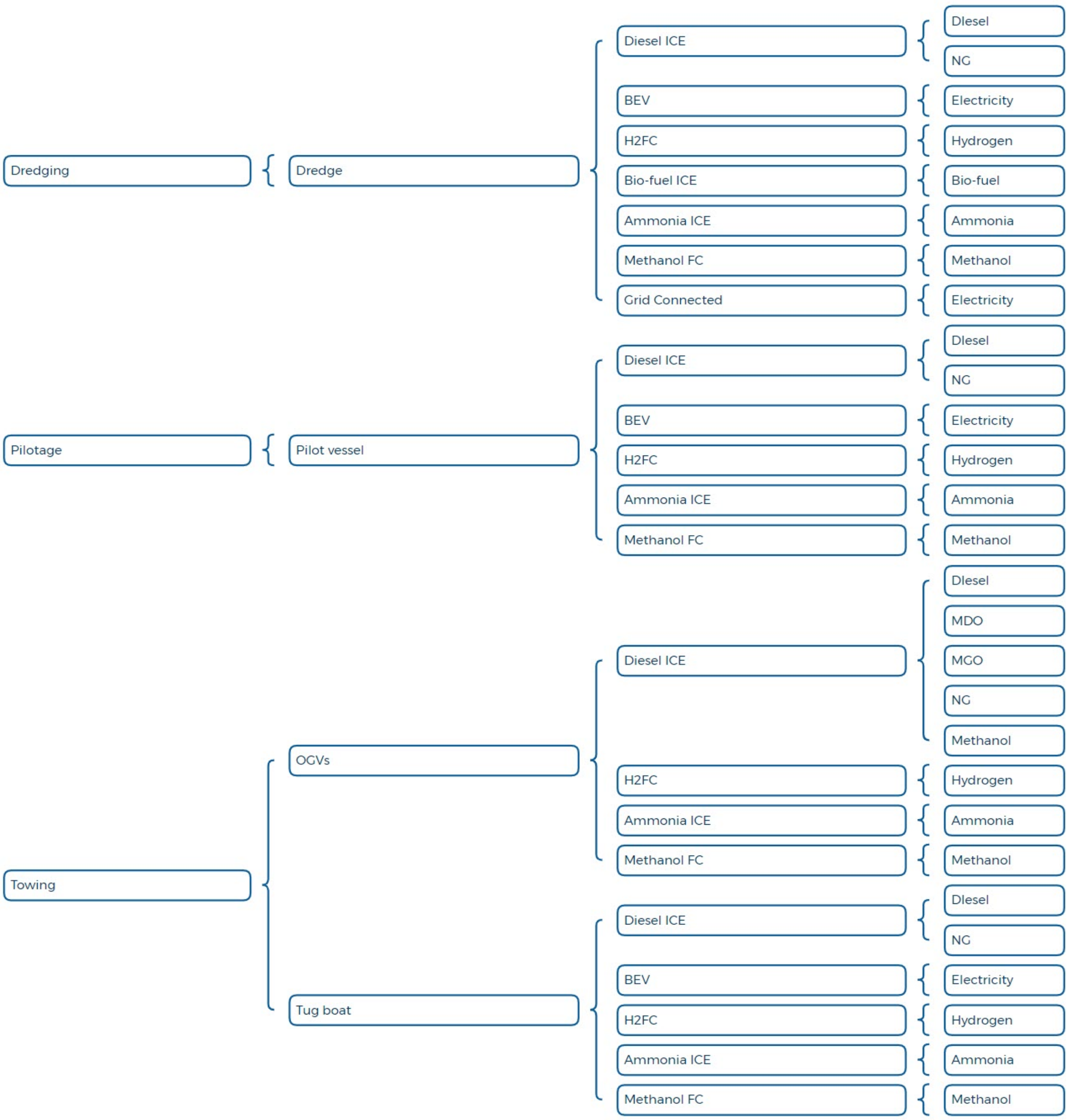

Figure A.1: Disaggregation of Activities of Operations (Dredging, Pilotage and Towing).

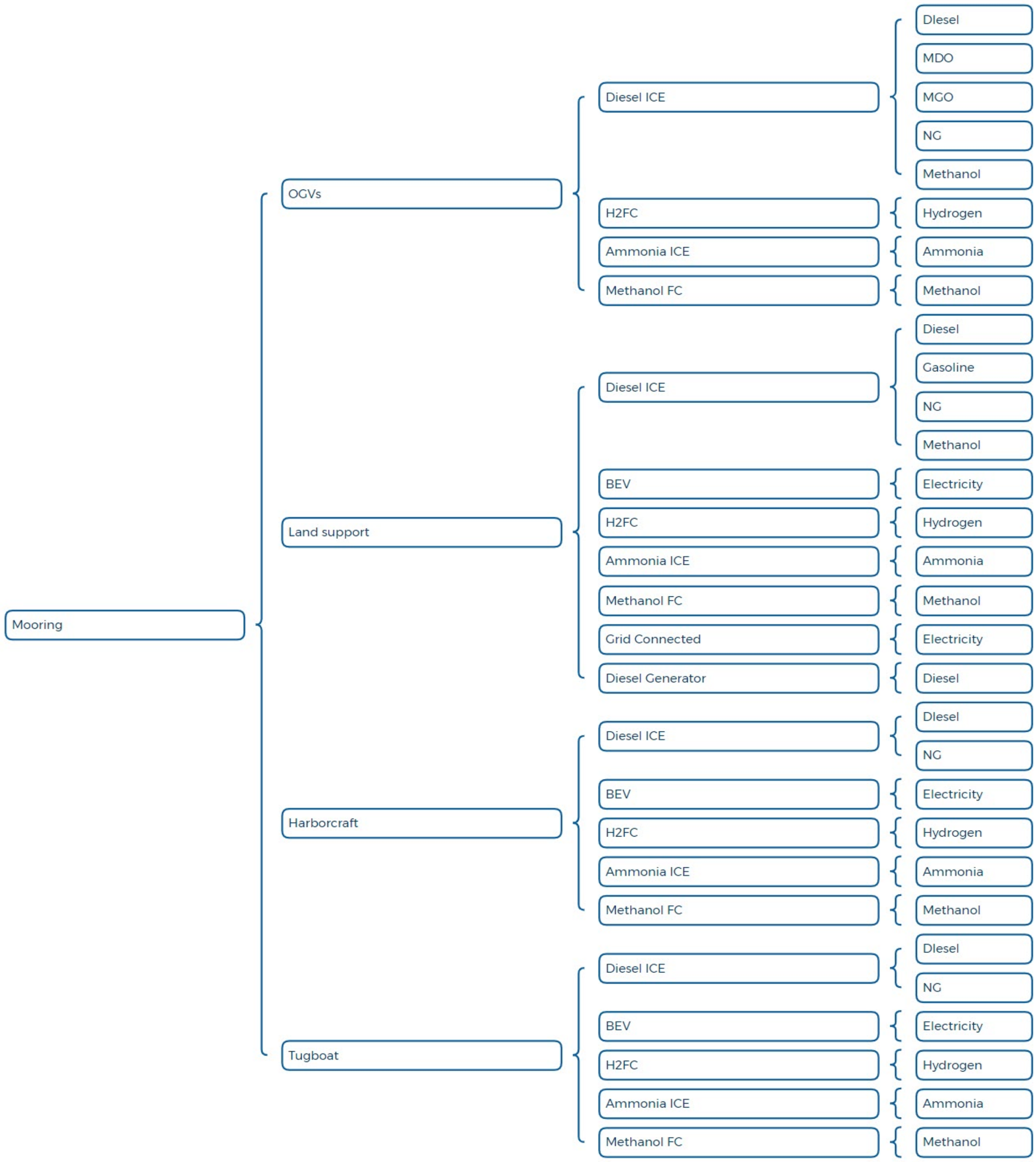

Figure A.2: Disaggregation of Activities of Operations (Mooring).

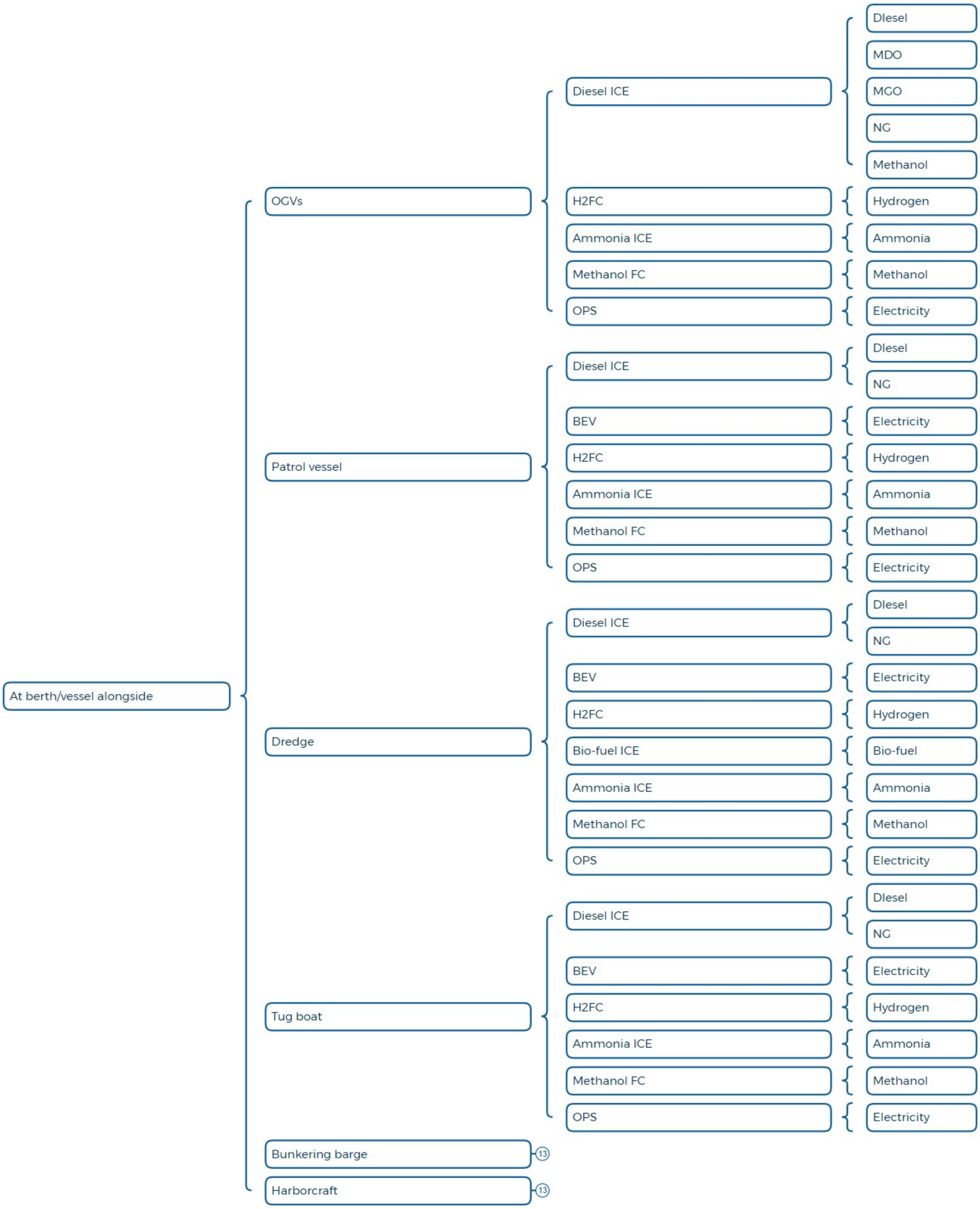

Figure A.3: Disagregation of Activities of Operations (At berth/vessel alongside).

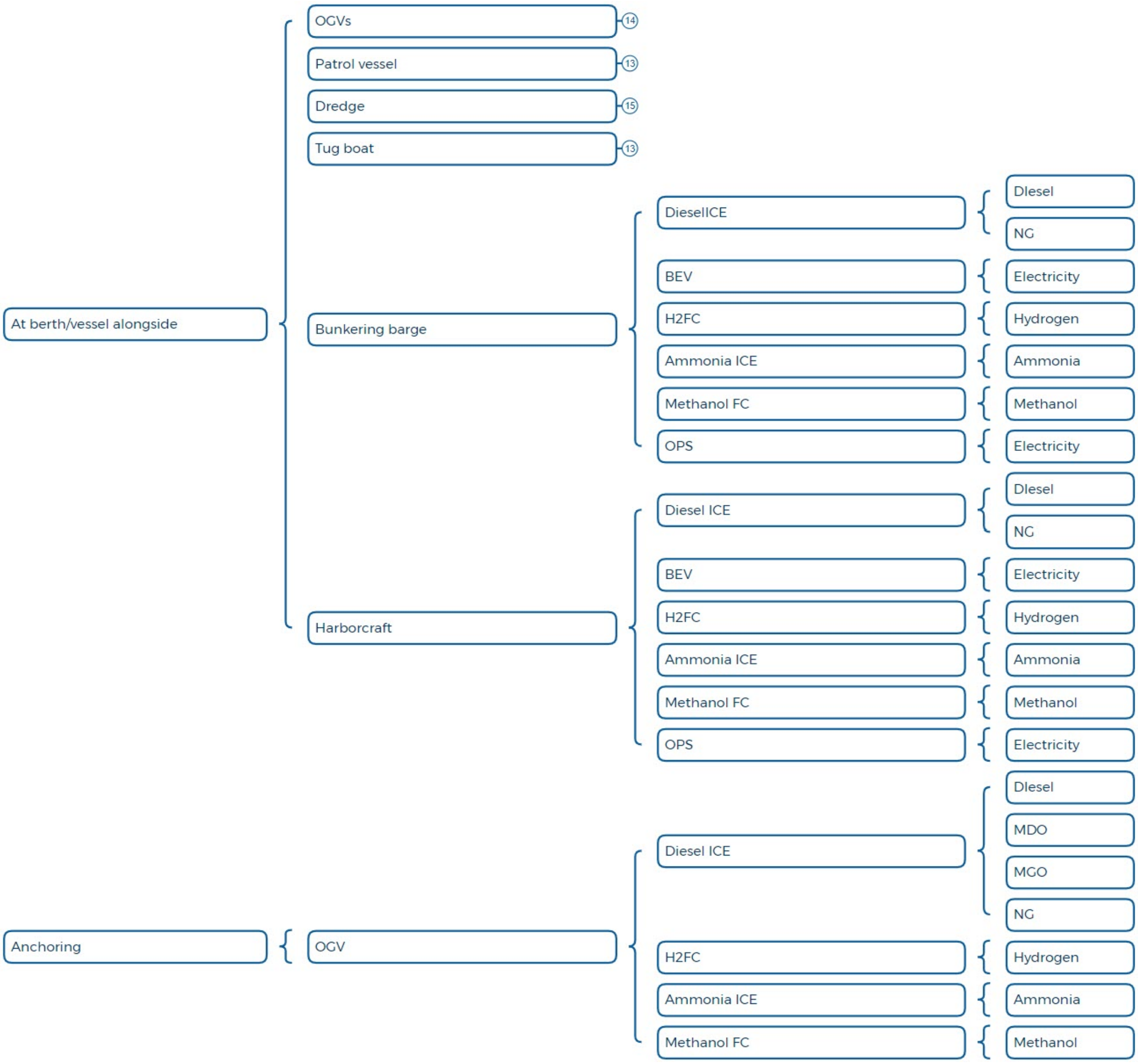

Figure A.4: Disaggregation of Activities of Operations (At berth/vessel alongside (continuation) and Anchoring).

Figures A.5, A.6, A.7 show the rest of the disaggregation of the activities that correspond to the Operations area. These three figures depict the model regarding the sub-area "Terminal Oriented".

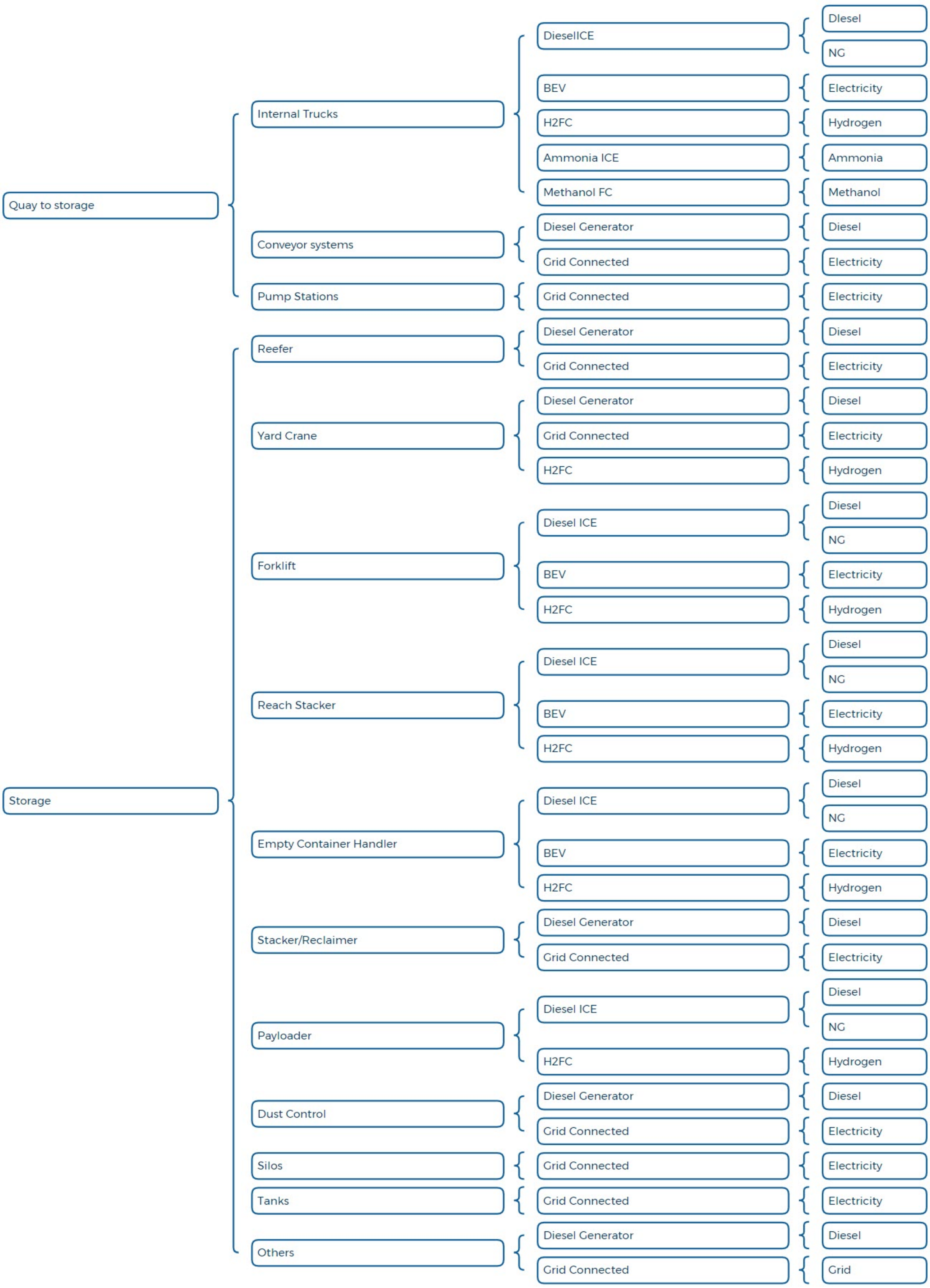

Figure A.5: Disaggregation of Activities of Operations (Quay to storage and Storage).

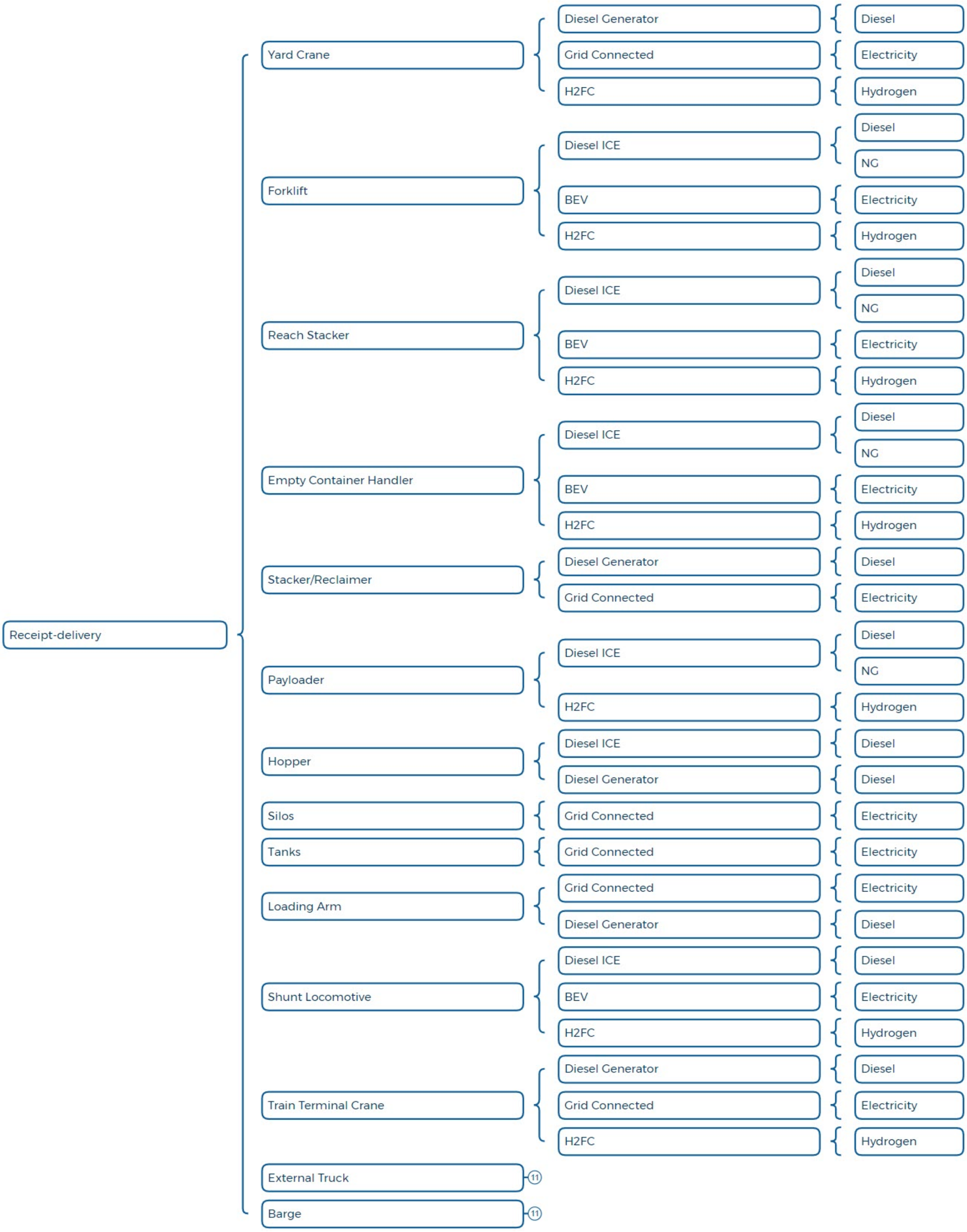

Figure A.6: Disaggregation of Activities of Operations (Receipt-delivery).

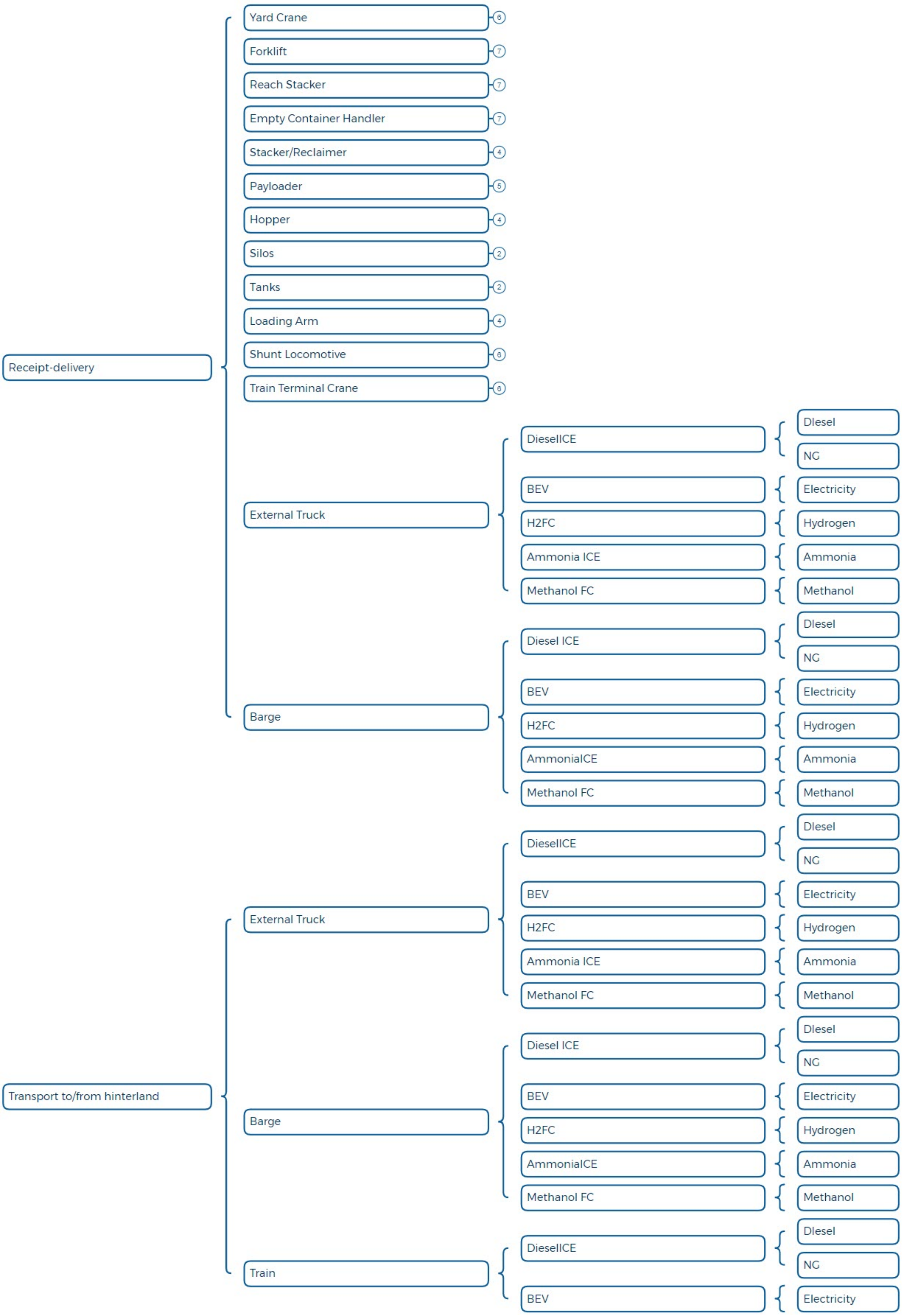

Figure A.7: Disaggregation of Activities of Operations (Receipt-delivery (continuation) and Transport to/from hinterland).

Figures A.8, A.9, A.10, A.11 show the disaggregation left for the area "Support & Maintenance" and the respectives sub-areas.

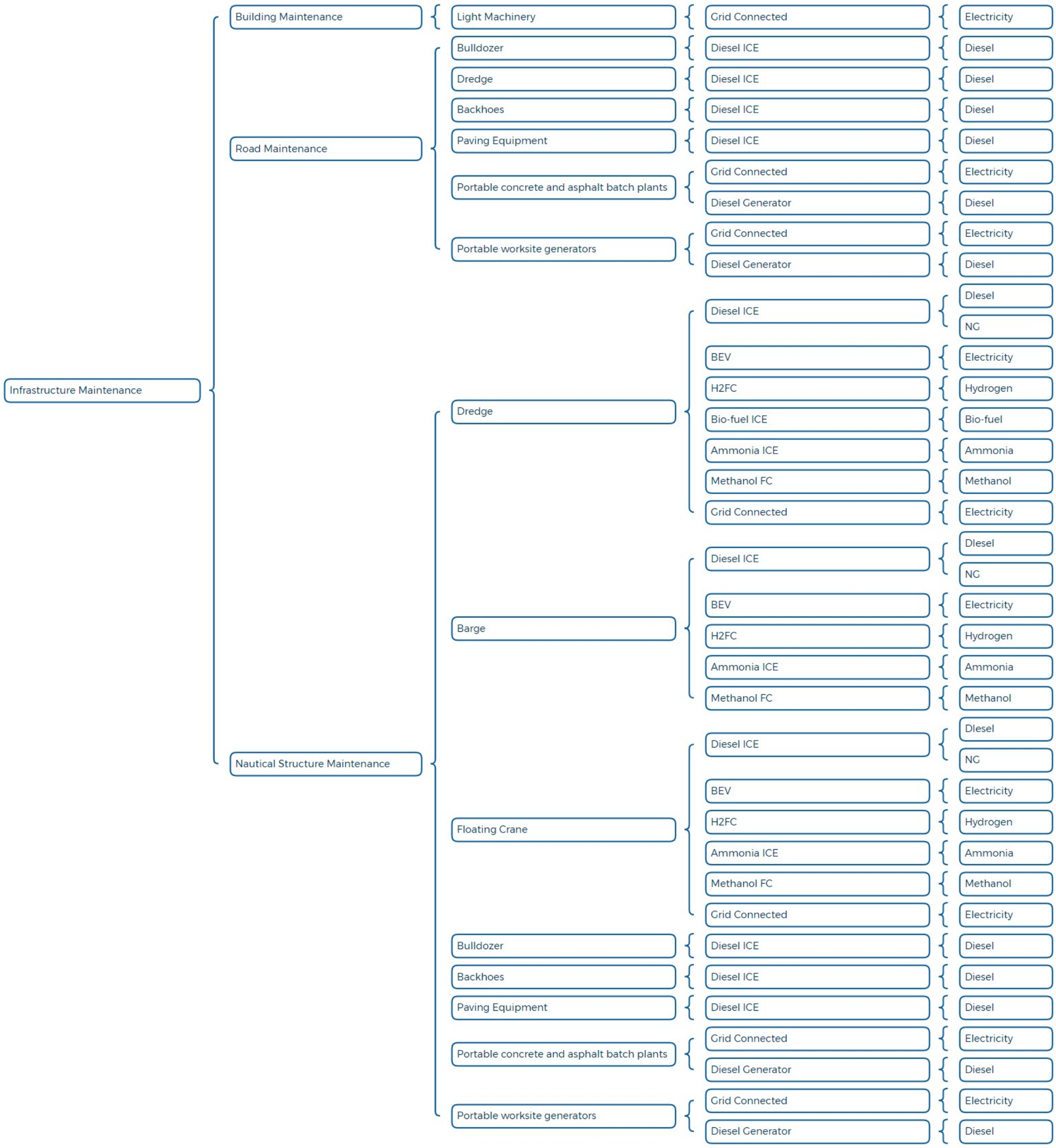

Figure A.8: Disaggregation of Activities of Support & Maintenance (Infrastructure Maintenance).

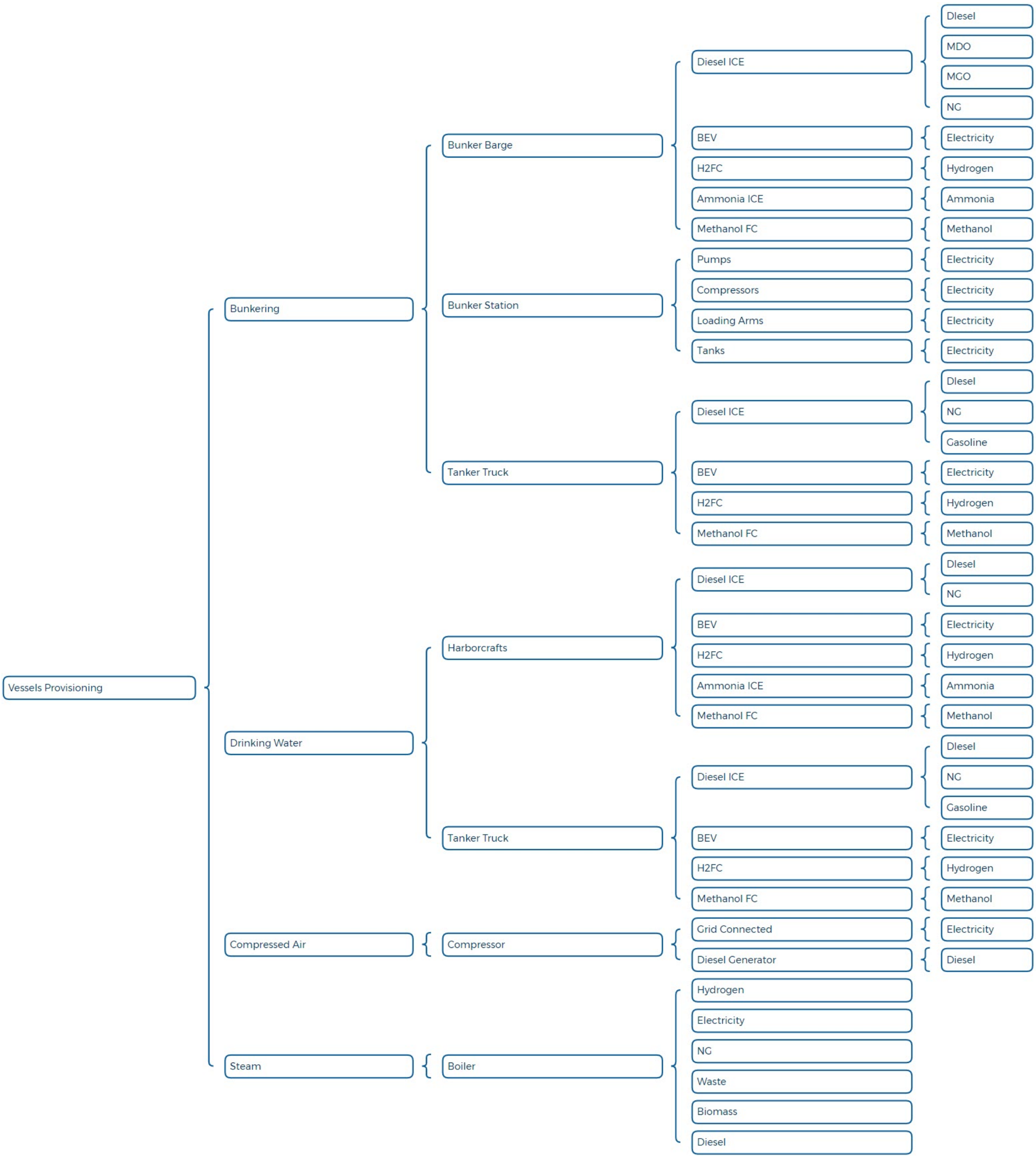

Figure A.9: Disaggregation of Activities of Support & Maintenance (Vessel Provisioning).

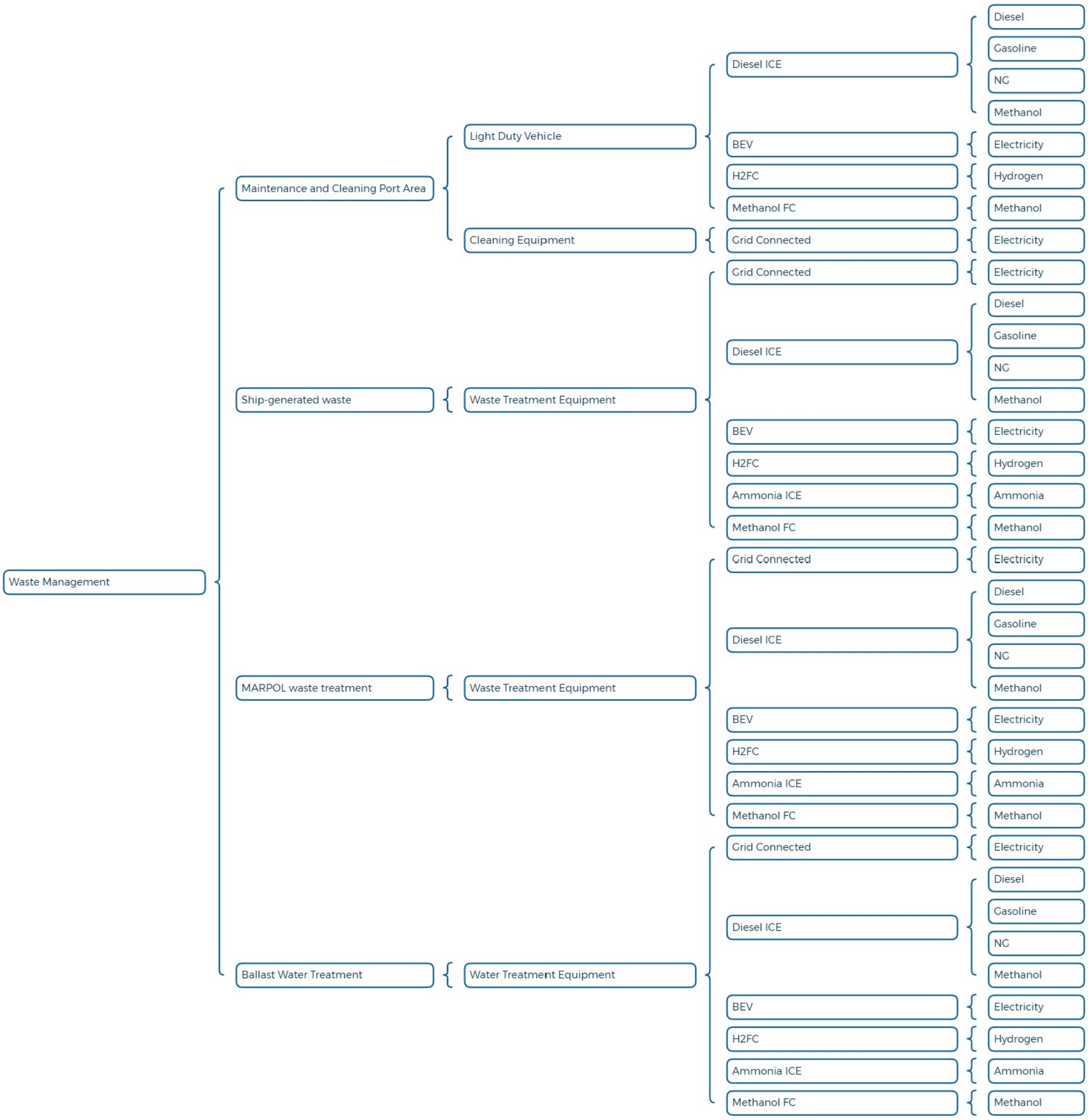

Figure A.10: Disaggregation of Activities of Support & Maintenance (Waste Management).

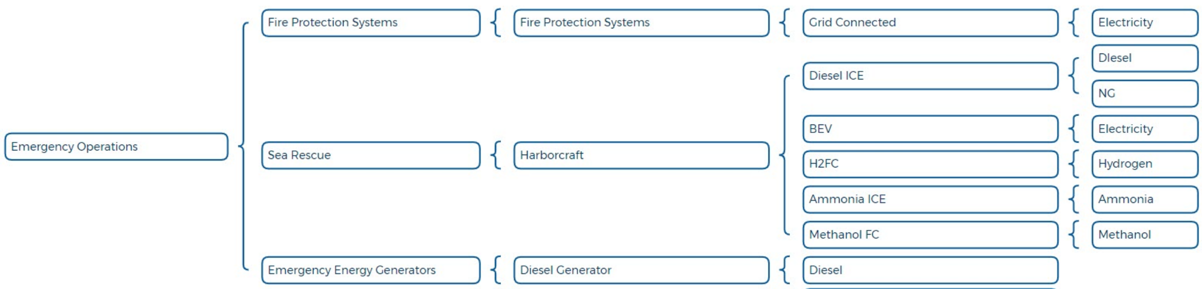

Figure A.11: Disaggregation of Activities of Support & Maintenance (Emergency Operations).

Figures A.12, A.13, A.14 and A.15 show the disaggregation of the sub-ares of the area "Buildings".

The disaggregation verified for the sub-areas "Staff and Other" and "Firefighters Headquarters" and the sub-sub-area "Buildings Services" belonging to the sub-area "Maintenance and Industry" are the same as the one in figure A.13.

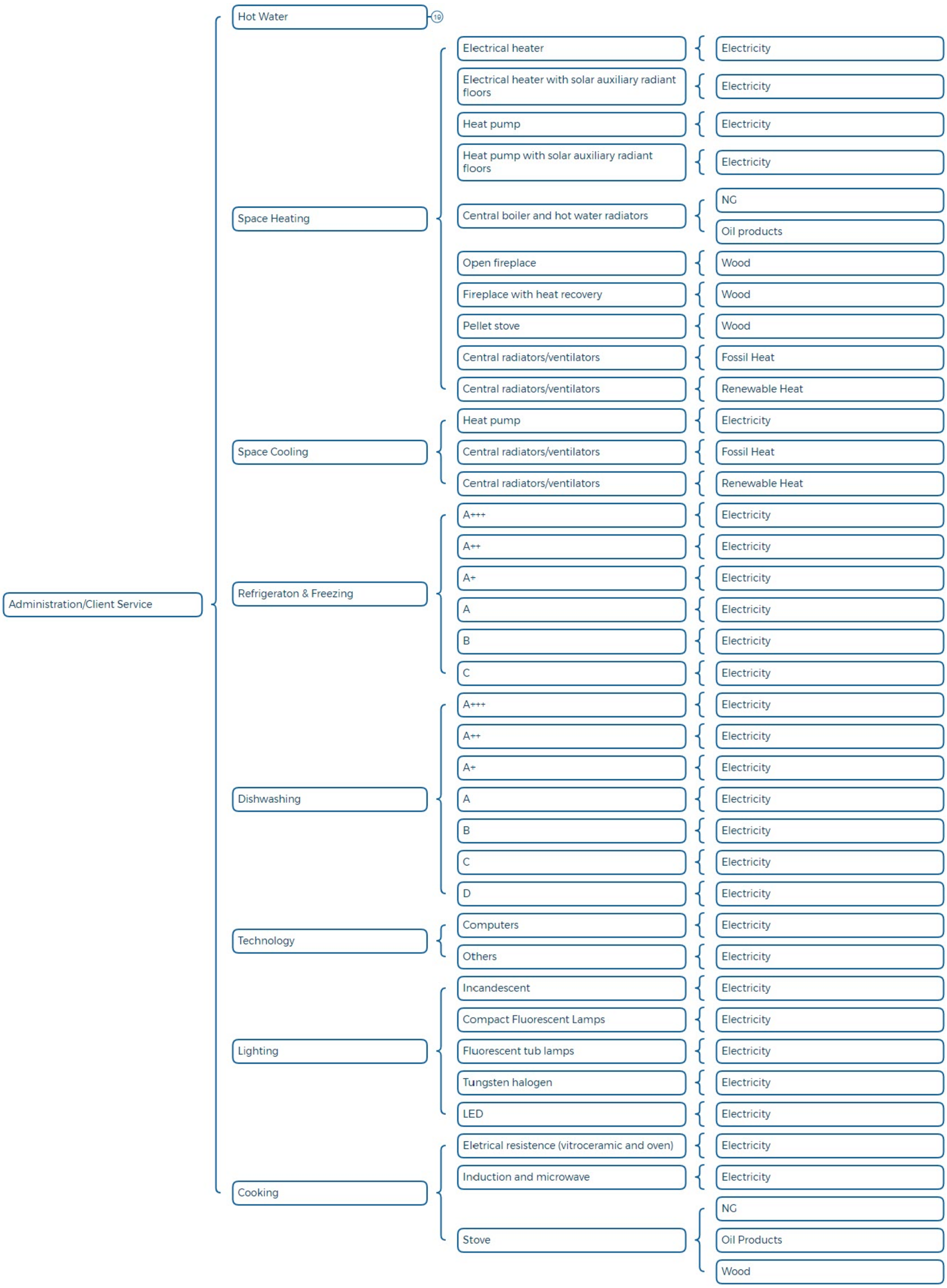

Figure A.12: Disaggregation of Activities of Buildings (Administration/Client Services).

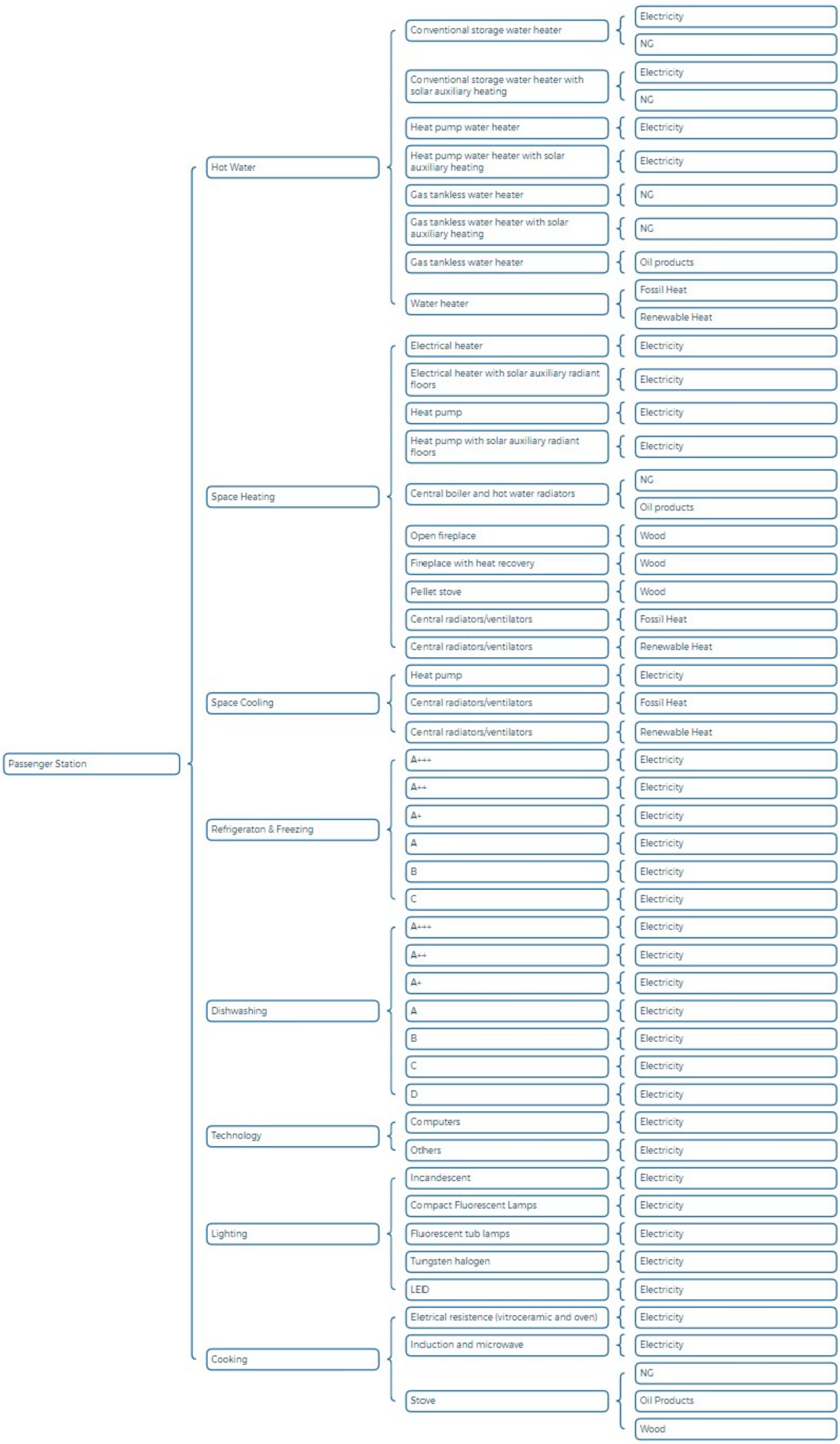

Figure A.13: Disaggregation of Activities of Buildings (Passenger Station).

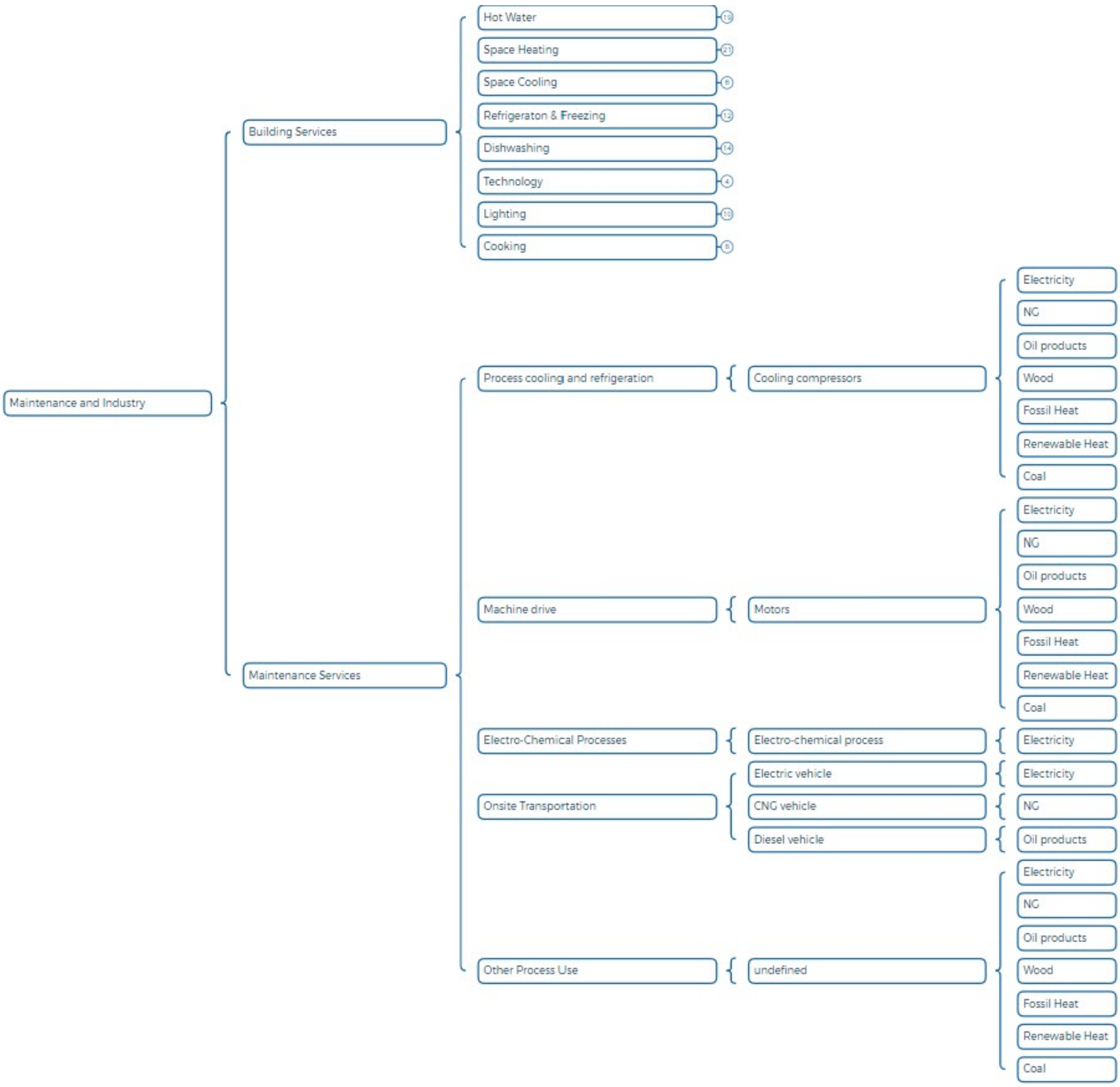

Figure A.14: Disaggregation of Activities of Buildings (Maintenance and Industry).

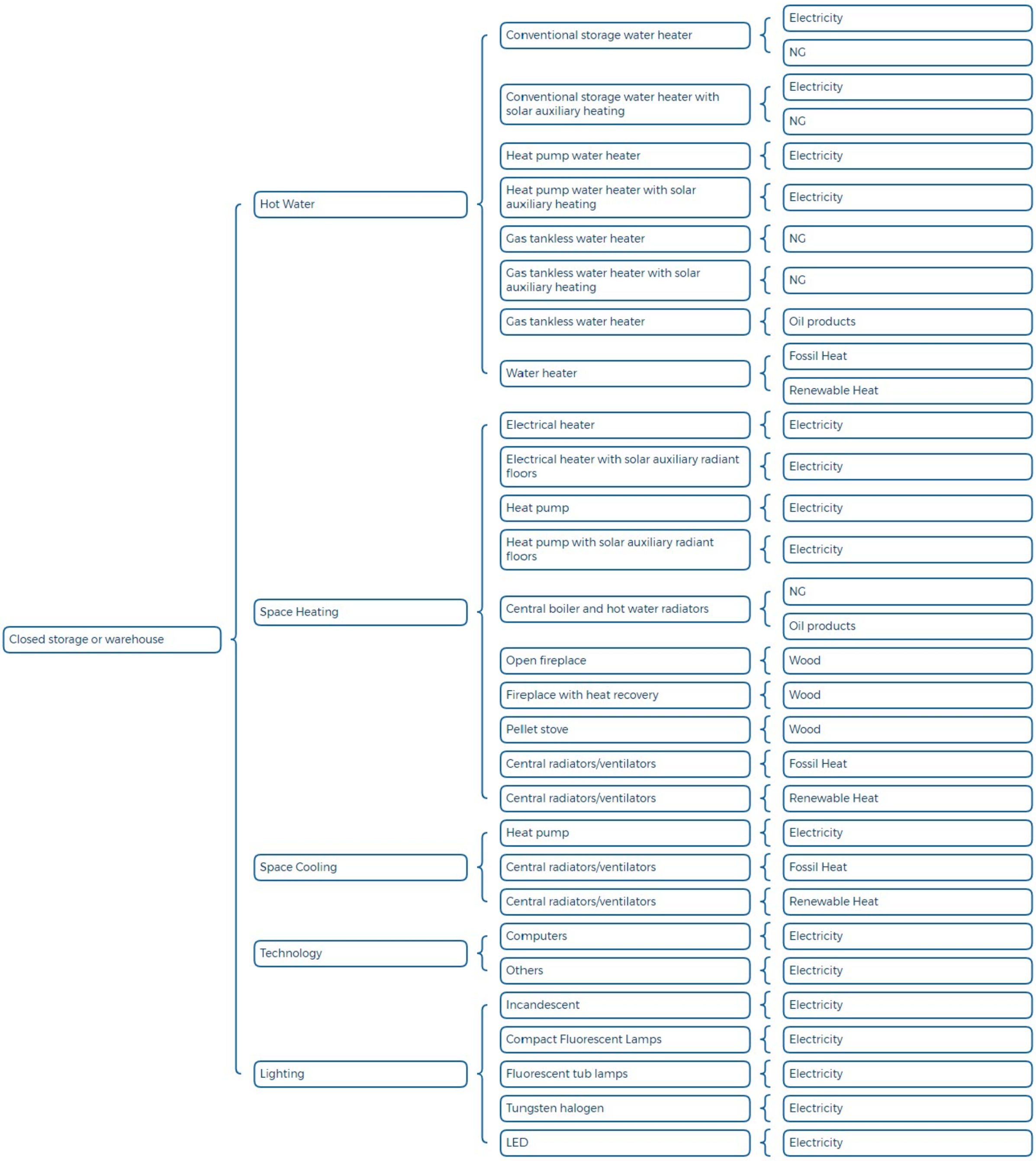

Figure A.15: Disaggregation of Activities of Buildings (Closed storage or warehouse).

In the area "General", the sub-area "Truck Parking" has the same disaggregation as the one seen in figure A.13. Figures A.16, A.17 and A.18 represent the rest of disaggregation of the area "General".

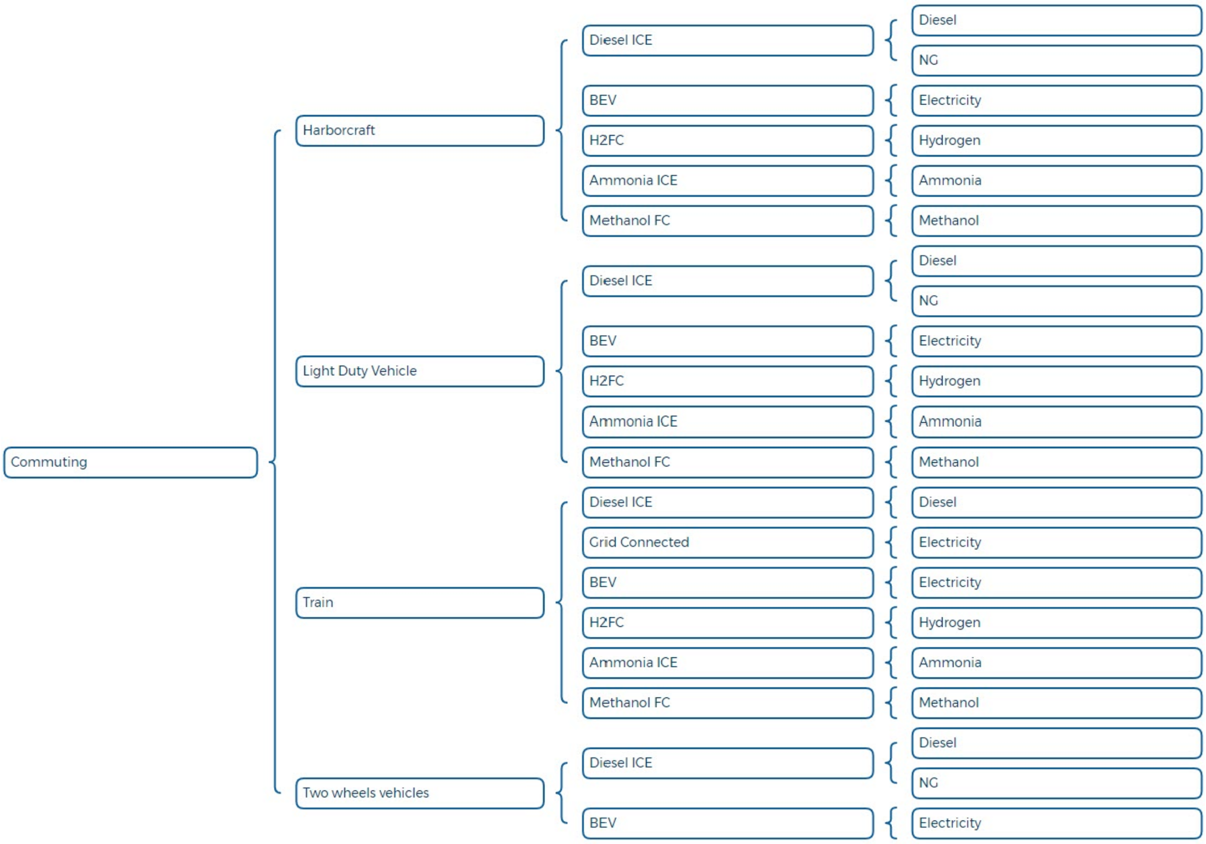

Figure A.16: Disaggregation of Activities of General (Commuting).

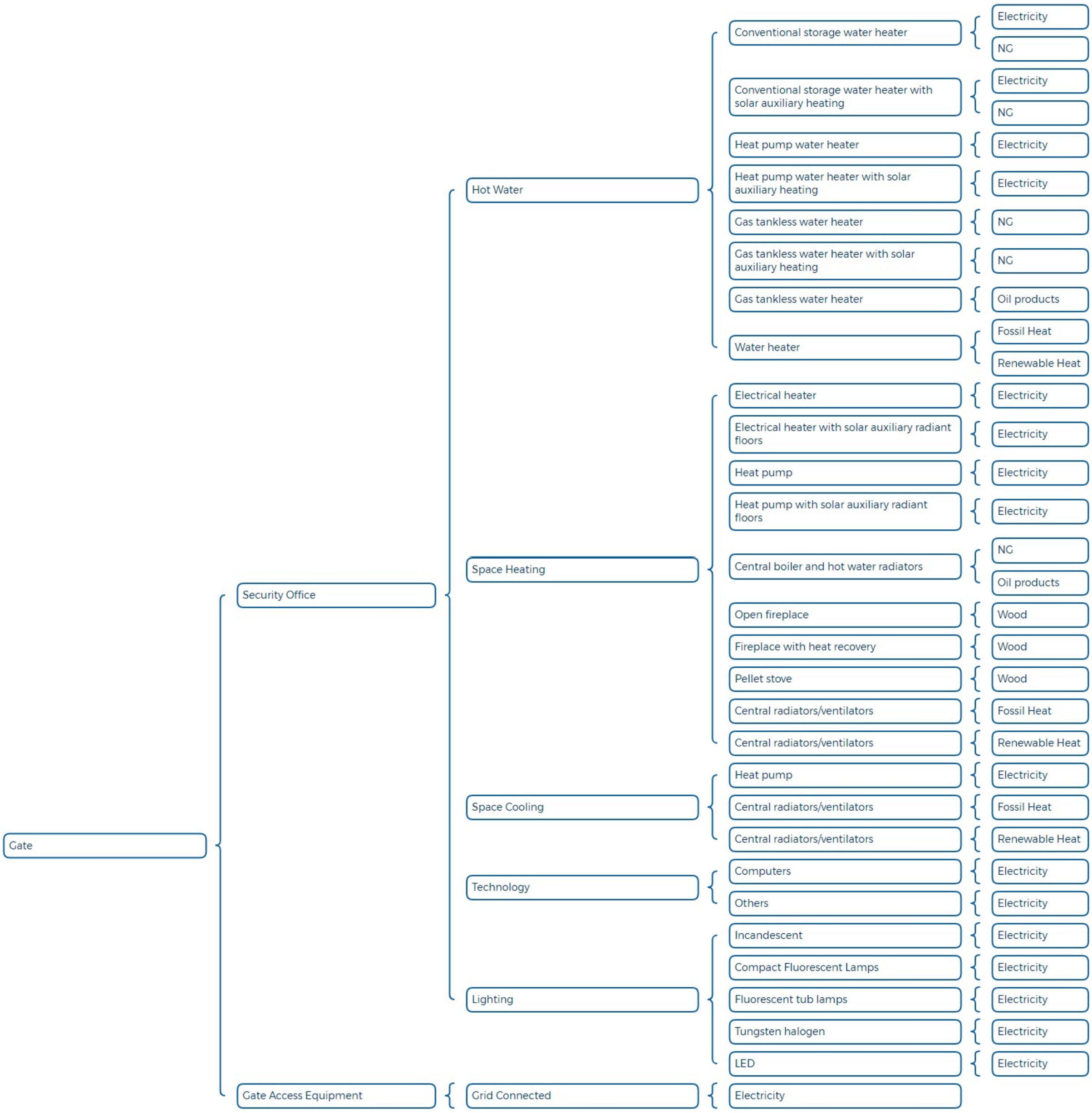

Figure A.17: Disaggregation of Activities of General (Gate).

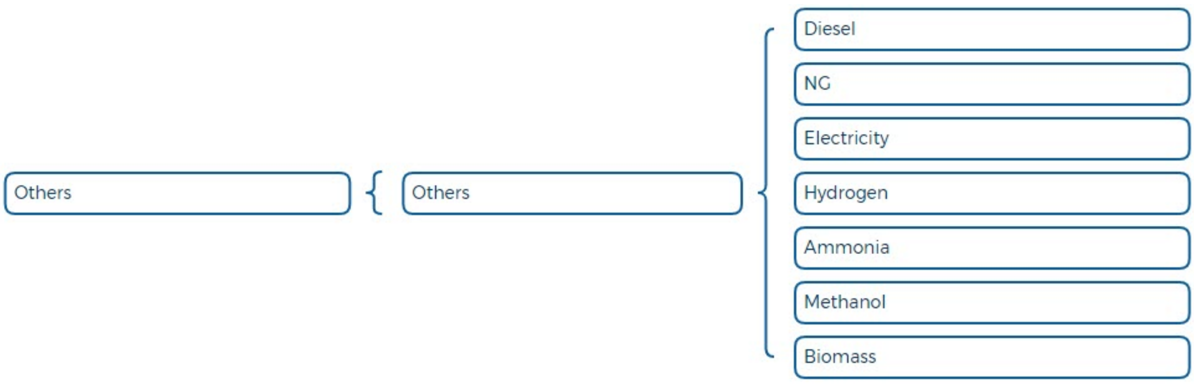

Figure A.18: Disaggregation of Activities of General (Others).

Figure A.19 depict the disaggregation of the area "Energy Supply".

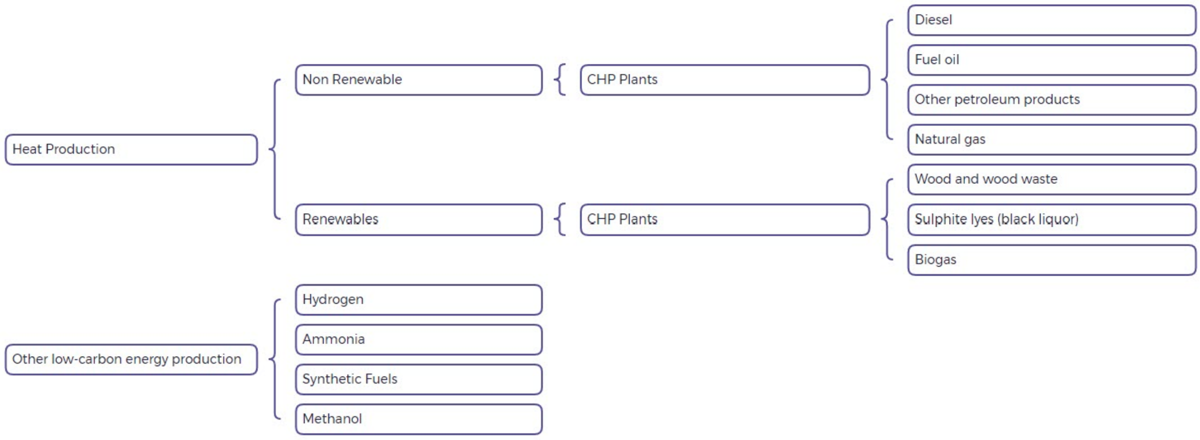

Figure A.19: Disaggregation of Activities of Energy Supply (Heat Generation and Other low-carbon energy production).

Appendix B

Information Related with Vessels

Appendix B has a set of information that is relevant to accessing the energy consumption and respective emissions from vessels. These tables range from table B.1 to table B.11.

Table B.1: Installed ME Power depending on gross tonnage (GT) [76]

Ship Type	Non-linear regression of 2010 World Fleet
Bulk Carrier	$14.755 * \mathrm{GT}^{0.6082}$
Container Ship	$2.9165 * \mathrm{GT}^{0.8719}$
General Cargo	$5.56482 * \mathrm{GT}^{0.7425}$
Passenger	$9.55078 * \mathrm{GT}^{0.7570}$
Ro-Ro cargo	$164.578 * \mathrm{GT}^{0.4350}$
Tanker	$35.912 * \mathrm{GT}^{0.5276}$
Others	$59.049 * \mathrm{GT}^{0.5485}$

Table B.2: Ratio between AE Power and ME Power [76, 127]

Ship Type	AE Power Ratio
Bulk Carrier	0.30
Container Ship	0.25
General Cargo	0.23
Passenger	0.16
Ro-Ro cargo	0.24
Tanker	0.30
Others	0.35

Table B.3: Default cruising speed for each OGV type (km/h and knots)

Ship Type	Default cruising speed [km/h]	Default cruising speed [knots]
Bulk Carrier	26	14.0
Container Ship	36	19.4
General Cargo	23	12.4
Passenger	39	21.1
Ro-Ro cargo	27	14.6
Tanker	26	14.0
Others	20	10.8

Table B.4: Average Manoeuvring and Hotelling times [127]

Ship Type	Manouvering time [$hours$]	Hotelling time [$hours$]
Bulk Carrier	1.0	52
Container Ship	1.0	14
General Cargo	1.0	39
Passenger	0.8	14
Ro-Ro cargo	1.0	15
Tanker	1.0	38
Others	1.0	27

Table B.5: Load Factors for the different operation per engine [76, 127]

Operational Mode	ME load (%)	AE load (%)
Cruising	80	30
Manoeuvring	20	50
Hotelling	20	40; 60

Table B.6: Emissions factors and BSFC for 3 different fuels for different engines [76]

Engine	**Phase**	**Engine Type**	**Fuel Type**	Sulphur %	CO_2	SO_2	NO_x	HC	CO	$PM_{2.5}$	PM_{10}	CH_4	N_2O	BSFC
Main	Cruising	SSD	RO	2.70%	620	10.5	16.9	0.6	0.5	1.31	1.42	0.006	0.031	195
		SSD	MDO	1.00%	588	3.7	15.8	0.6	0.5	0.45	0.42	0.006	0.031	185
		SSD	MGO	0.50%	588	0.9	15.8	0.6	0.5	0.31	0.28	0.006	0.031	185
		MSD	RO	2.70%	677	11.5	13	0.5	1.1	1.43	1.32	0.004	0.031	213
		MSD	MDO	1.00%	645	4.1	12.3	0.5	1.1	0.47	0.43	0.004	0.031	203
		MSD	MGO	0.50%	645	1	12.3	0.5	1.1	0.31	0.29	0.004	0.031	203
		HSD	RO	2.70%	677	11.5	11.8	0.2	1.1	1.47	1.35	0.004	0.031	305
		HSD	MDO	1.00%	645	4.1	11.2	0.2	1.1	0.58	0.53	0.004	0.031	290
		HSD	MGO	0.50%	645	1	11.2	0.2	1.1	0.35	0.32	0.004	0.031	290
	Manoeuvring Hotelling	SSD	RO	2.70%	682	11.6	4.7	1.8	1	1.32	1.43	0.012	0.031	215
		SSD	MDO	1.00%	647	4.1	4.7	1.8	1	0.44	0.47	0.012	0.031	204
		SSD	MGO	0.50%	647	1	4.7	1.8	1	0.29	0.31	0.012	0.031	204
		MSD	RO	2.70%	745	12.7	44.6	1.5	2.2	1.32	1.44	0.008	0.031	234
		MSD	MDO	1.00%	710	4.5	44.3	1.5	2.2	0.46	0.5	0.008	0.031	223
		MSD	MGO	0.50%	710	1.1	44.3	1.5	2.2	0.3	0.32	0.008	0.031	223
		HSD	RO	2.70%	745	12.7	40.6	0.6	2.2	1.32	1.44	0.008	0.031	234
		HSD	MDO	1.00%	710	4.5	40.1	0.6	2.2	0.46	0.5	0.008	0.031	223
		HSD	MGO	0.50%	710	1.1	40.1	0.6	2.2	0.3	0.32	0.008	0.031	223
Auxiliary	Cruising Manoeuvring Hotelling	MSD	RO	2.70%	722	12.3	60.4	0.4	0.9	1.32	1.44	0.004	0.031	227
		MSD	MDO	1.00%	690	4.3	59.7	0.4	0.9	0.45	0.49	0.004	0.031	217
		MSD	MGO	0.50%	690	1.1	59.7	0.4	0.9	0.29	0.32	0.004	0.031	217
		HSD	RO	2.70%	722	12.3	47.6	0.4	1.3	1.32	1.44	0.01	0.031	227
		HSD	MDO	1.00%	690	4.3	46.8	0.4	0.8	0.45	0.49	0.01	0.031	217
		HSD	MGO	0.50%	690	1.1	46.8	0.4	0.8	0.29	0.32	0.01	0.031	217
Boilers	Manoeuvring Hotelling	-	RO	2.70%	1067	18.1	1.6	0.3	0.4	1.35	1.47	0.02	0.08	336

Table B.7: Fuels used for each engine for each category of OGV [76]

Ship Type	ME Fuel Type	AE Fuel Type
Bulk Carrier	RO	MGO
Container Ship	RO	RO
General Cargo	RO	MGO
Passenger	MDO	MDO
Ro-Ro cargo	RO	RO
Tanker	RO	MGO
Others	MGO	MGO

Table B.8: Type of engine for each category of OGV depending on the Gross Tonnage (GT) [76]

Ship Type	≤ 5 000 GT	5 000 – 25 000 GT	>25 000 GT
Bulk Carrier	MSD	SSD	SSD
Container Ship	MSD	MSD	SSD
General Cargo	MSD	SSD	SSD
Passenger	HSD	MSD	MSD
Ro-Ro cargo	MSD	MSD	SSD
Tanker	MSD	SSD	MSD
Others	MSD	MSD	SSD

Table B.9: Percentage of installed Main Engine power by engine type/fuel class per category of vessel in the 2010 world fleet [127]

Ship category	SSD MDO /MGO	SSD BFO	MSD MDO /MGO	MSD BFO	HSD MDO /MGO	HSD BFO	GT MDO /MGO	GT BFO	ST MDO /MGO	ST BFO
Liquid bulk ships	0.87	74.08	3.17	20.47	0.52	0.75	0	0.14	0	0
Dry bulk carriers	0.37	91.63	0.63	7.29	0.06	0.02	0	0	0	0
Container	1.23	92.98	0.11	5.56	0.03	0.09	0	0	0	0
General cargo	0.36	44.59	8.48	41.71	4.3	0.45	0	0.1	0	0
Ro Ro Cargo	0.17	20.09	9.86	59.82	5.57	2.23	2.27	0	0	0
Passenger	0	3.81	5.68	76.98	3.68	1.76	4.79	3.29	0	0.02
Fishing	0	0	84.42	3.82	11.76	0	0	0	0	0
Others	0.48	30.14	29.54	19.63	16.67	2.96	0.38	0.2	0	0
Tugs	0	0	39.99	6.14	52.8	0.78	0.28	0	0	0

SSD - Slow Speed Diesel, MSD - Medium Speed Diesel, HSD - High Speed Diesel, GT- Gas Turbine, ST - Steam Turbine, MDO -Marine Diesel Oil, MGO - Marine Gas Oil, BFO - Bunker Fuel Oil

Table B.10: Reducing Speed Zone (RSZ) speed and zone size for US ports [82]

Port	Speed Limit	Zone Size
Los Angeles	12 knots	20-40 nm
Long Beach	12 knots	20-40 nm
San Diego	12 knots	20 nm
New York/New Jersey	10 knots	20 nm

Table B.11: Number and power of tugboats required for each vessel tonnage (adapted from [131])

Vessel Tonnage	Power [hp]	Number of Tugboats	Max Tugboat Speed [knots]
Below 5000	1800	1	20
5000-10000	2400	1	20
10000-15000	4200	2	20
15000-30000	5600	2	20
30000-45000	6400	2	20
45000-60000	8000	2	20
Above 60000	12000	3	20

Appendix C

Vessel Emissions in the Case Study

Tables C.1 to C.6 in Appendix C present in a structured way the information obtained for the emissions belonging to the OGV in the case study done.

Table C.1: Emission in grams for each pollutant: Cruising ME

ME Cruising		**Emissions [grams of poluttant]**								
Call	**Vessel**	CO_2	SO_2	NO_x	HC	CO	$PM_{2.5}$	PM_{10}	CH_4	N_2O
1	WEC Van Goh	4.99E+06	8.48E+04	9.59E+04	3.69E+03	8.12E+03	1.05E+04	9.74E+03	2.95E+01	2.29E+02
2	Maersk Serangoon	3.85E+07	6.52E+05	1.05E+06	3.73E+04	3.11E+04	8.14E+04	8.82E+04	3.73E+02	1.93E+03
3	MSC Manya	1.72E+07	2.92E+05	4.70E+05	1.67E+04	1.39E+04	3.64E+04	3.95E+04	1.67E+02	8.62E+02
4	MSC Mumbai VIII	3.84E+07	6.51E+05	1.05E+06	3.72E+04	3.10E+04	8.12E+04	8.80E+04	3.72E+02	1.92E+03
TOTAL		9.92E+07	1.68E+06	2.66E+06	9.48E+04	8.41E+04	2.10E+05	2.25E+05	9.41E+02	4.94E+03

Table C.2: Emission in grams for each pollutant: Cruising AE

AE Cruising		**Emissions [grams of polutant]**								
Call	**Vessel**	CO_2	SO_2	NO_x	HC	CO	$PM_{2.5}$	PM_{10}	CH_4	N_2O
1	WEC Van Goh	6.90E+05	1.18E+04	5.77E+04	3.82E+02	8.60E+02	1.26E+03	1.38E+03	3.82E+00	2.96E+01
2	Maersk Serangoon	5.81E+06	9.90E+04	4.86E+05	3.22E+03	7.24E+03	1.06E+04	1.16E+04	3.22E+01	2.50E+02
3	MSC Manya	2.60E+06	4.43E+04	2.18E+05	1.44E+03	3.24E+03	4.76E+03	5.19E+03	1.44E+01	1.12E+02
4	MSC Mumbai VIII	5.80E+06	9.88E+04	4.85E+05	3.21E+03	7.23E+03	1.06E+04	1.16E+04	3.21E+01	2.49E+02
	TOTAL	1.49E+07	2.54E+05	1.25E+06	8.26E+03	1.86E+04	2.73E+04	2.97E+04	8.26E+01	6.40E+02

Table C.3: Emission in grams for each pollutant: Manoeuvring ME

ME Manoeuvring		**Emissions [grams of poluttant]**								
Call	**Vessel**	CO_2	SO_2	NO_x	HC	CO	$PM_{2.5}$	PM_{10}	CH_4	N_2O
1	WEC Van Goh	1.15E+06	1.96E+04	6.89E+04	2.32E+03	3.40E+03	2.04E+03	2.23E+03	1.24E+01	4.79E+01
2	Maersk Serangoon	8.87E+06	1.51E+05	6.11E+04	2.34E+04	1.30E+04	1.72E+04	1.86E+04	1.56E+02	4.03E+02
3	MSC Manya	3.97E+06	6.76E+04	2.74E+04	1.05E+04	5.82E+03	7.69E+03	8.33E+03	6.99E+01	1.81E+02
4	MSC Mumbai VIII	8.86E+06	1.51E+05	6.10E+04	2.34E+04	1.30E+04	1.71E+04	1.86E+04	1.56E+02	4.03E+02
	TOTAL	2.29E+07	3.89E+05	2.18E+05	5.96E+04	3.52E+04	4.40E+04	4.77E+04	3.94E+02	1.03E+03

Table C.4: Emission in grams for each pollutant: Manoeuvring AE

AE Manoeuvring		**Emissions [grams of polutant]**								
Call	**Vessel**	CO_2	SO_2	NO_x	HC	CO	$PM_{2.5}$	PM_{10}	CH_4	N_2O
1	WEC Van Goh	6.97E+05	1.19E+04	5.83E+04	3.86E+02	8.69E+02	1.27E+03	1.39E+03	3.86E+00	2.99E+01
2	Maersk Serangoon	5.87E+06	1.00E+05	4.91E+05	3.25E+03	7.32E+03	1.07E+04	1.17E+04	3.25E+01	2.52E+02
3	MSC Manya	2.63E+06	4.48E+04	2.20E+05	1.46E+03	3.28E+03	4.80E+03	5.24E+03	1.46E+01	1.13E+02
4	MSC Mumbai VIII	5.86E+06	9.98E+04	4.90E+05	3.25E+03	7.31E+03	1.07E+04	1.17E+04	3.25E+01	2.52E+02
	TOTAL	1.51E+07	2.56E+05	1.26E+06	8.34E+03	1.88E+04	2.75E+04	3.00E+04	8.34E+01	6.46E+02

Table C.5: Emission in grams for each pollutant: Berthing ME

ME Berthing		**Emissions [grams of polutant]**								
Call	**Vessel**	CO_2	SO_2	NO_x	HC	CO	$PM_{2.5}$	PM_{10}	CH_4	N_2O
1	WEC Van Goh	7.04E+06	1.20E+05	4.21E+05	1.42E+04	2.08E+04	1.25E+04	1.36E+04	7.55E+01	2.93E+02
2	Maersk Serangoon	11.27E+08	2.16E+06	8.77E+05	3.36E+05	1.86E+05	2.46E+05	2.67E+05	2.24E+03	5.78E+03
3	MSC Manya	4.03E+07	6.85E+05	2.78E+05	1.06E+05	5.91E+04	7.80E+04	8.45E+04	7.09E+02	1.83E+03
4	MSC Mumbai VIII	1.70E+08	2.90E+06	1.17E+06	4.50E+05	2.50E+05	3.30E+05	3.57E+05	3.00E+03	7.74E+03
	TOTAL	3.45E+08	5.87E+06	2.75E+06	9.06E+05	5.16E+05	6.66E+05	7.22E+05	6.02E+03	1.56E+04

Table C.6: Emission in grams for each pollutant: Berthing AE

AE Berthing		**Emissions [grams of poluttant]**								
Call	**Vessel**	CO_2	SO_2	NO_x	HC	CO	$PM_{2.5}$	PM_{10}	CH_4	N_2O
1	WEC Van Goh	3.41E+06	5.81E+04	2.85E+05	1.89E+03	4.25E+03	6.23E+03	6.80E+03	1.89E+01	1.46E+02
2	Maersk Serangoon	6.73E+07	1.15E+06	5.63E+06	3.73E+04	8.39E+04	1.23E+05	1.34E+05	3.73E+02	2.89E+03
3	MSC Manya	2.13E+07	3.63E+05	1.78E+06	1.18E+04	2.66E+04	3.90E+04	4.25E+04	1.18E+02	9.16E+02
4	MSC Mumbai VIII	9.02E+07	1.54E+06	7.54E+06	4.99E+04	1.12E+05	1.65E+05	1.80E+05	4.99E+02	3.87E+03
	TOTAL	1.82E+08	3.10E+06	1.52E+07	1.01E+05	2.27E+05	3.33E+05	3.63E+05	1.01E+03	7.82E+03

Appendix D

Information about the CHE (consumption and LFs)

In Appendix D, it is presented the information needed to calcultate the energy consumption and emissions of CHE. This includes the average consumptions from the literature as well as the LF (tables D.1 and D.2, respectively).

Table D.1: Information about the consumption of cargo handling equipment (based on [43, 40])

Energy Vector	Equipment	Consumption per move	Consumption per km
Diesel	Rubber-tired gantry cranes (RTGs)	1.32 L	-
	Straddle carrier (SC)	0.80 L	3.50 L
	Terminal head trucks (TT)	-	3.23 L; 1.11 kWh [132]
	Automated terminal tractor (ATT)	-	1.67 L
	Reach stacker/top (RS)	-	5.00 L
Electricity	Quay crane (QC)	6.00 kWh; 2.77 L	-
	Ship to shore (STS)	6.70 kWh	-
	Rail-mounted Stacking crane (RSC)	7.25 kWh	-
	Automated Stacking crane (ASC)	5.00 kWh	-

Table D.2: Load Factors of cargo handling equipment (based on [47])

Cargo Handling Equipment	**Load Factor (LF)**
Container Reach Stacker (CRS)	0.59
Empty Container Handler (ECS)	0.59
Forklift Truck	0.3
Mobile Harbour Crane (MHC)	0.43
Rail Mounted Gantry (RMG)	0.51
Rubber Tired Crane (RTG)	0.43
Ship to Shore Crane (SSG)	0.43
Terminal Tractor	0.39
Container Trailer	0.39