Shore power for liquid bulk vessels

Modelling of terminals and vessels for cost-effectiveness of different shore power systems

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by

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Abstract

As liquid bulk vessels are berthed in ports, auxiliary engines generate the electrical power demand, which emissions have a negative effect on the environment and local air quality in ports. Shore power is an effective solution for this problem. However, the large costs of implementing shore power and the absence of a technical safe design standard led to no adaption of shore power. Currently, there are no insights in the costs and utilisation of shore power in the liquid bulk industry.

This thesis used an adapted systems engineering approach for a framework with a technical background and shore power concept evaluation. The shore power evaluation on costs and power utilisation combines the Life Cycle Costs approach and operational tanker data. By designing a model that evaluates the costs and utilisation for terminal and ships, insights for the business case for shore power have been obtained.

Shore power implementation is extremely sensitive to utilisation, if the shore power readiness of ships is low at the terminal, it will be economically unfeasible. As well as for the ships, if no ports with shore power can be visited, shore power is not at all cost-effective. The chemical shortsea market has the most potential for shore power implementation, due to the frequent visits of ports in Europe. This thesis has found that shore power can be economically feasible when European shortsea shipping is implemented in EU ETS with a CO_2 price. The required CO_2 price ranges from 33 to 84 €/ton depending on either 100% to 50% of shore power visits of the vessels, respectively. The terminals are unable to provide low shore power prices with only the vessel utilisation, therefore subsidy ranging from 25-100% is required on the investment, depending on the terminal. The emission reduction potential of shore power is good, with no local emissions in ports and the power generation emission reduction of 80 to 90% per pollutant.

Currently, shore power for the chemical industry is not economically feasible but provides a good emission performance in the port. For all evaluated shore power systems, EU ETS CO_2 prices are required for shipping and subsidies for the terminal investment. The best performing shore power concept on based on technical, economical and utilisation feasibility is the aftship based shore crane and reel, resulting in the best cost-effectiveness. In order to introduce shore power to the liquid bulk market, CO_2 prices on shipping of at least 50 €/ton is required and subsidies of at least 50% of the investment for terminals are required.

Preface

Before you lies the master thesis ”Shore power for liquid bulk vessels”, which marks an end to my studies at the TU Delft. During my studies, the negative effect of shipping on climate change raised awareness, both in the industry and for myself. Therefore, the choice of performing research in the field of sustainable shipping was an easy one to make. And I believe that the energy transition of the maritime industry will be the biggest challenge for the coming decades and I will participate in it with great interest.

The scope of this thesis is initiated by the Port of Rotterdam Authority, as part of their shore power strategy for the port. Therefore, I want to thank them for the opportunity that they gave me to do my master thesis for the largest port of Europe. I am gratefully that everybody at the Port of Rotterdam wanted to help me during my thesis and made time to have meetings or even sail through the port. I hope that Rotterdam will successfully proceed with the ambitious shore power projects and I believe my thesis has provided useful insights in the shore power projects for the shortsea chemical industry.

Secondly, I would like to thank my TU Delft supervisor, Jeroen Pruyn, for all the help with both theoretical and practical problems during my thesis. Jeroen has been extremely helpful during my thesis and always made time for me during the graduation project, online or even in real life.

Furthermore, I would like to thank family, friends and girlfriend for always supporting me through every stage of my studies and my graduation process. During COVID times, working individually on this thesis was often quite hard, but the people around me always cheered me up and motivated me. Many coffee breaks with friends provided some well deserved distractions as well as useful discussions on maritime and other topics.

Hopefully this thesis contributes to the introduction and further implementation of shore power for the liquid bulk industry.

J.P.B. Willeijns
Rotterdam, September 2021

Contents

Abbreviations & Nomenclature

List of Abbreviations

AE	Auxiliary Engine
ATEX	ATmosphères EXplosibles
CMS	Cable Management System
ETS	Emission Trading System
HV	High Voltage
HVSC	High Voltage Shore Connections
KPI	Key Performance Indicator
KPI	Key Performance Indicator
LCC	Life Cycle Costs
LCOE	Levelised Cost Of Energy
LV	Low Voltage
MMSI	Maritime Mobile Service Identity
PoR	Port of Rotterdam
SSE	Shore Side Electricity
UCRN	Unique Call Reference Number

Nomenclature

b_d	Berthing direction factor	[-]
Cof_{SP}	The fleet coverage of the shore power system	[-]
$EF_{p,AE}$	The MGO emission factor of an Auxiliary engine for pollutant p	[g/kWh]
$EF_{p,SP}$	The electricity grid emission factor in the Netherlands for pollutant p	[g/kWh]
ER_p	The yearly emission reduction of pollutant p	[ton/year]
$lf_{ship,n}$	Load factor of the ship and operation n	[-]
$ops_{i,n}$	The yearly amount of operation n of vesseltype i	[-]
$P_{n,i}$	The electrical power demand during loading operations of vesseltype i	[MW]
$P_{SP,ship}$	The total yearly shore power demand	[MWh/yr]
P_{SP-sys}	The yearly power that the shore power system delivers	[MWh/year]
P_{total}	The total yearly electrical power demand from all visiting vessels	[MWh/year]
PI_{ship}	Installed electrical power median per shiptype	[MW]
$R_{f,SP}$	Shore power Readiness of the fleet that visits the terminal	[-]
SFC	The specific fuel consumption of an engine	[g/kWh]
$t_c(x)$	The estimated time for connecting shore power system x	[hr]

$t_{berth,i}$	The historical average of time at berth in Rotterdam of vesseltype i	[hr]

List of Figures

List of Tables

I

Introduction & problem analysis

1 Introduction

Worldwide, 40% of the human population lives within a range of 100km to the coast [20]. In these coastal areas, the shipping industry plays a large role in the coastal and in port emissions [21, 22]. When ships are berthed in ports, the onboard auxiliary diesel engines are still used for generating the electrical power demand of the vessel [7]. Using fuel in shipboard diesel generators for electricity production results in local air- and water emissions. These emissions consist of CO_2, SO_x, NO_x and PM_x, which have a negative effect on the climate and the living environment near ports. These emissions, especially the PM_x, have a negative effect on the people that live close to port areas [23]. In the Netherlands, 14% of the CO_2 emissions on the Dutch continental shelf stems from auxiliary power use at berth, and 11% for NO_x, 10% for SO_x and 7% for PM_{10} [7]. The Port of Rotterdam has estimated that each year the berthed vessels have a contribution to the local emissions of 800,000 tons of CO_2 and 8,000 tons of NO_2 for all electrical generated power [24]. To reduce the emissions in the port, the Rotterdam Port Authority has ambitious plans for using shore power for the berthed vessels, which has a lot of emission reduction potential for the environment and local area [25].

To achieve the shore power ambition, the Port of Rotterdam and the municipality has laid out a strategy for these plans, consisting of three main pillars [24]. The first one is to focus on the quality of living in residential areas near the port. The second one aims to extensively implement shore power for vessels which are relatively easy to connect with shore power. Rotterdam aims for a shore power utility rate of 90 % in 2030 for Ro-Ro-, offshore-, ferry- and cruise-vessels visiting the port and at least 50% of the visiting container vessels. The third pillar, which is important for this thesis, is to innovate and stimulate standardisation in the segments where needed because limited shore power systems exist for these vessels. These vessels are the bulk- and liquid bulk vessels, of which the latter one is discussed in this thesis. The liquid bulk vessels have a large share in the port visits in the Port of Rotterdam, therefore the focus is on liquid bulk vessels in this thesis [26].

1.1. Shore power

Shore power is the principle of powering a vessel at berth with electricity generated by the shore's electricity grid and therefore zero local emissions are produced. Shore power goes by many names, Cold-Ironing (CI), Onshore Power Supply (OPS), Shore Side Electricity (SSE) and Power-to-Ship (P2S). When ships use shore power, the electricity from the shore grid provides the electrical energy demand of the vessel, who shuts down the auxiliary engines, which results in zero local emissions from the engines onboard. The potential of emission reduction has been endorsed widely by many studies [7, 25, 27, 28, 29]. The concept of connecting ships to shore power in ports is used in the ferry and cruise industry for about 20 years [30].

In the Netherlands, the CO_2 emissions of a vessel when using shore power can be reduced with about 40%, depending on the energy mix of the electricity grid [7], which means for a total SSE demand of 651 GWh, 200kt of CO2 can be reduced. The European Commission has plans to reduce the Greenhouse gas emissions in Europe for 2030, including a renewable energy share of at least 32% [31]. This would be beneficial for the shore power projects, which will have a higher emission reduction if the use of renewable energy for electricity generation increases.

To use shore power a vessel and the terminal have to install equipment in order to safely transport electrical energy from shore to ship. To provide this electricity to the vessel, a shore power system is constructed on the terminal and the vessel needs a receiving point for the shore power cable [12]. The electricity that is provided by the national grids does not always meet the electrical requirements from the vessel, therefore transforming the voltage and converting the frequency is often required [32]. Depending on the type of vessel, the shore power cable has to be transported from shore to ship. For container vessels the cable is stored onboard and all other vessels receive the cable from shore [15]. Thereafter, the cable must be connected to the onboard switchboard and eventually, the ship's generators are shut off when the electrical power from shore is provided correctly. When the ship is ready to leave the port, the shore power connection will be disconnected and the auxiliary engines of the vessel will provide the electrical energy demand.

There are two main types of benefits to using shore power, environmental benefits and financial benefits.

The environmental benefits of implementing shore power for berthed vessels in ports are widely endorsed. Ballini, found four major advantages for cruise ships on shore power, of which two environmental advantages are applicable for liquid bulk vessels, since both use auxiliary engines for generating electrical power [33]. First, shore power can effectively reduce the hazardous emissions in the local environment. In addition to that, the power that is supplied from the national electricity grid is subjected to stricter emissions control than power that would have been supplied by auxiliary engines on the vessel. Gillingham finds that the social benefits exceed the costs, especially as the electric grid decarbonizes more in the future. It shows that when all berthed vessels in the United States use shore power, a reduction of 8%-13% can be achieved for the shipping sector, related to NO_x, $PM_{2.5}$ and PM_{10} emissions [34]. However, the reductions are highly dependent on the onshore energy mix, and when more renewable sources are producing energy, the shipping related emissions can be further reduced. In general, the benefits of improving the air quality and the corresponding health benefits are one of the main advantages of using shore power [25, 33, 34].

From an economical view, the operational expenses and capital expenses of the auxiliary engines are reduced because of reduced engine hours [33]. As the need for auxiliary engines still remains while sailing at sea, the amount of engines required might be reconsidered as shore power is used for electrical power generation in the port. Other financial benefits are environmental improvements translated to a monetary value. Vaishnav et al. have estimated that if two-third of the vessels that call in U.S. ports use shore power, an air quality benefit of $70 - $150 million per year could be achieved [35]. However, this is dependent on the fuel prices and the assumptions for the social costs of pollution. The prevention of $PM_{2.5}$ and PM_{10}, which are a component of diesel emissions, is important because of the bad effect on human health.

Worldwide, the benefits of shore power are recognized and the amount of ferries, cruise vessels and container-ships which uses shore power in ports is increasing. However, the liquid bulk segment does not seem to implement shore power [29].

1.2. Liquid bulk vessels

In 2020, the liquid bulk vessels have a 35% share of the global commercial fleet in terms of deadweight tonnage [16]. The liquid bulk vessels include oil tankers, oil product tankers, gas tankers, chemical tankers and other tankers that transport liquid cargo in the cargo tanks. In Figure 1.1 a Very Large Crude Carrier (VLCC) is shown and in Figure 1.2 a medium range (MR) chemical vessel is shown for reference. Liquid bulk vessels have, depending on their trip, a lot of systems running which require energy when berthed in ports. The energy demand is either fulfilled by auxiliary engines, auxiliary boilers or both [36]. The auxiliary engine uses fuel to provide electricity and the boiler can either be electrically driven of fuel fired for producing energy on-board of the vessel.

Figure 1.1: A crude oil vessel [1]

Figure 1.2: A chemical vessel [2]

When all the liquid bulk vessels are using shore power instead of fuel for port operations, the local emissions in the port from the vessels are reduced. The emission monitor of the Port of Rotterdam has estimated the yearly total berthed emissions for the liquid bulk vessels at 135,444 ton of CO_2, 2,088.3 ton of NO_x, 172 ton of SO_x and 34.6 ton of PM_x [37].

1.3. Regulatory affairs

The shipping industry has been excluded from a lot of environmental regulations the past decades, only since 2015 regional emission caps are introduced in some of the European and North American coastal waters [38]. And since 2020 there is a global sulphur emissions cap present for all ships.

Also, the European Green Deal aims to further set the GHG reduction targets, and the shipping industry included [39]. The goal for 2030 is to connect the most polluting ships to shore power in 203. The Europe Maritime Safety Agency (EMSA) advises the EU in proper development and implementation of EU legislation on maritime safety. It advises about shore power implementation and discusses safety of the systems and strategies for determining power demand [40]. For instance, the power demand estimation strategy that is needed for designing a shore power installation is ideally be done by using port call history information combined with exact fuel consumption data. Yet, this information is not available for the whole visiting fleet.

The Netherlands also provides a lower tax rate for electricity when used for shore power in seaports [41], which is beneficial for the electricity price of shore power provided for vessels.

Currently, the EU uses an EU Emission Trading System (ETS), which has created a market for CO_2 emissions and allows companies to sell the right to emit a ton of CO_2 for a market based price [42]. However, this ETS is not yet implemented for the shipping industry since it is an international business and the exact implementation is still discussed with the industry. But, the EU proposed plans to implement the European shipping industry completely in 2026 [39].

1.4. Structure

The structure of the thesis consists of four parts in order to create an organised report structure. In Figure 1.3, the structure of this report is shown with the different parts. The four parts are: Part I - Introduction & Problem Analysis, Part II - Technical Background, Part III - Model & Case Study and Part IV - Conclusion & Discussion.

In Part I, this introduction is considered the first chapter. Secondly, the problem analysis is discussed in Chapter 2 and thereafter the solution approach and methodology is given in Chapter 3.

In Part II, the technical background of this subject is presented, which consists of literature study for shore power concepts in Chapter 4. Secondly, the operational analysis of liquid bulk vessels is done in Chapter 5. And a technology assessment of different shore power concepts is presented in Chapter 6.

In Part III, the ship and terminal model design is discussed in Chapter 7. Thereafter, in Chapter 8, the case study is discussed. Finally, in Chapter 9 the implementation of the model and the results of the case study is presented.

In Part IV, the conclusion of this research is presented in Chapter 10, as well as the recommendations. And in Chapter 11 the discussion on this research is discussed.

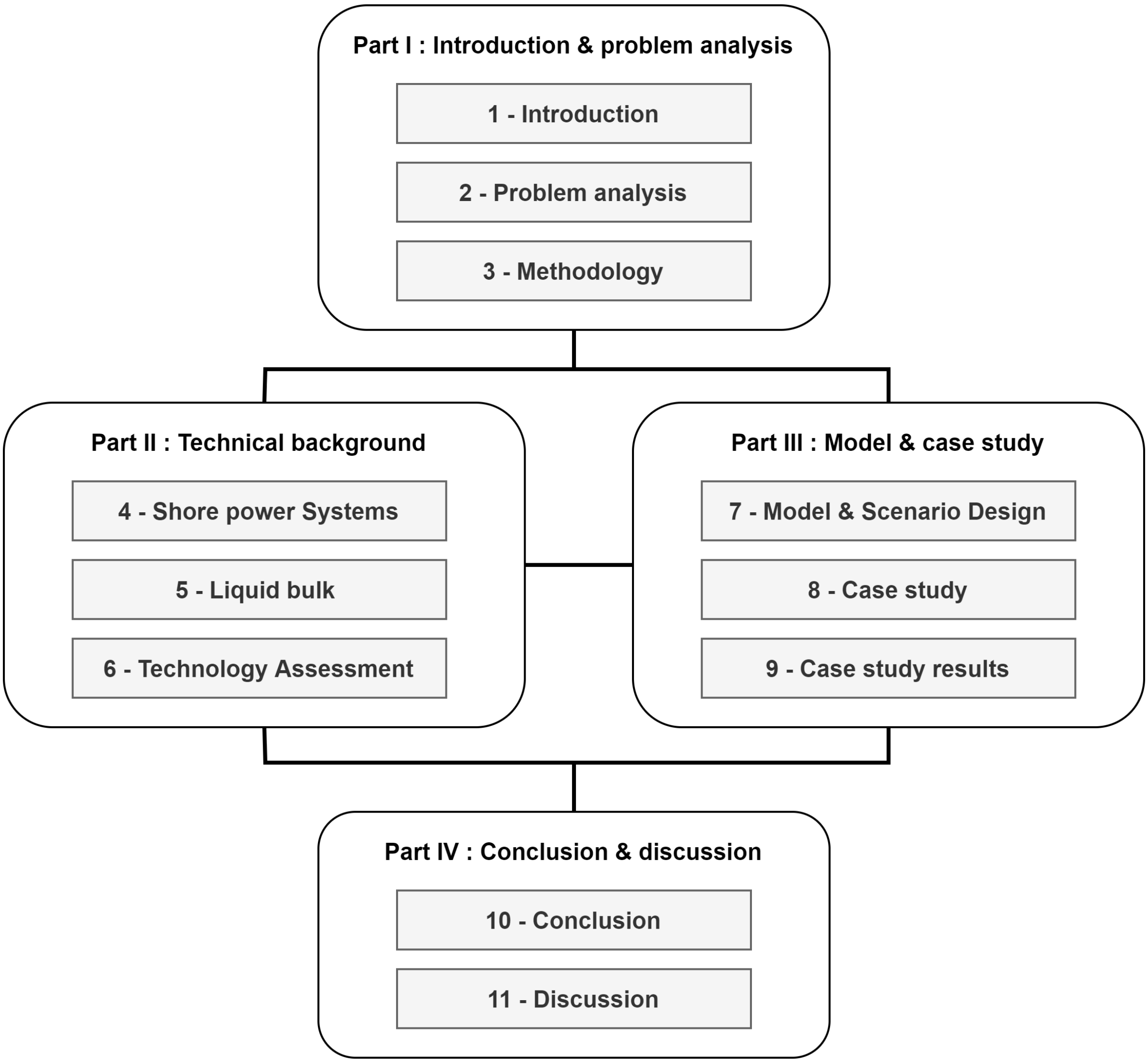

Figure 1.3: Thesis structure

2

Problem Analysis

Chapter 1 briefly outlined the potential for liquid bulk vessels using shore power. Yet, the liquid bulk industry is not implementing shore power. This chapter addresses the problem of connecting liquid bulk vessels to shore power. First, Section 2.1 shows the technical and operational barriers for implementing shore power for liquid bulk vessels. Then, Section 2.2 discusses the financial business case for installing and operating shore power projects. Thereafter, Section 2.3 summarises the problem in the problem definition. Finally, in Section 2.4 the research objective and the research questions are discussed. Figure 2.1 shows an overview of the problem by means of a problem tree approach.

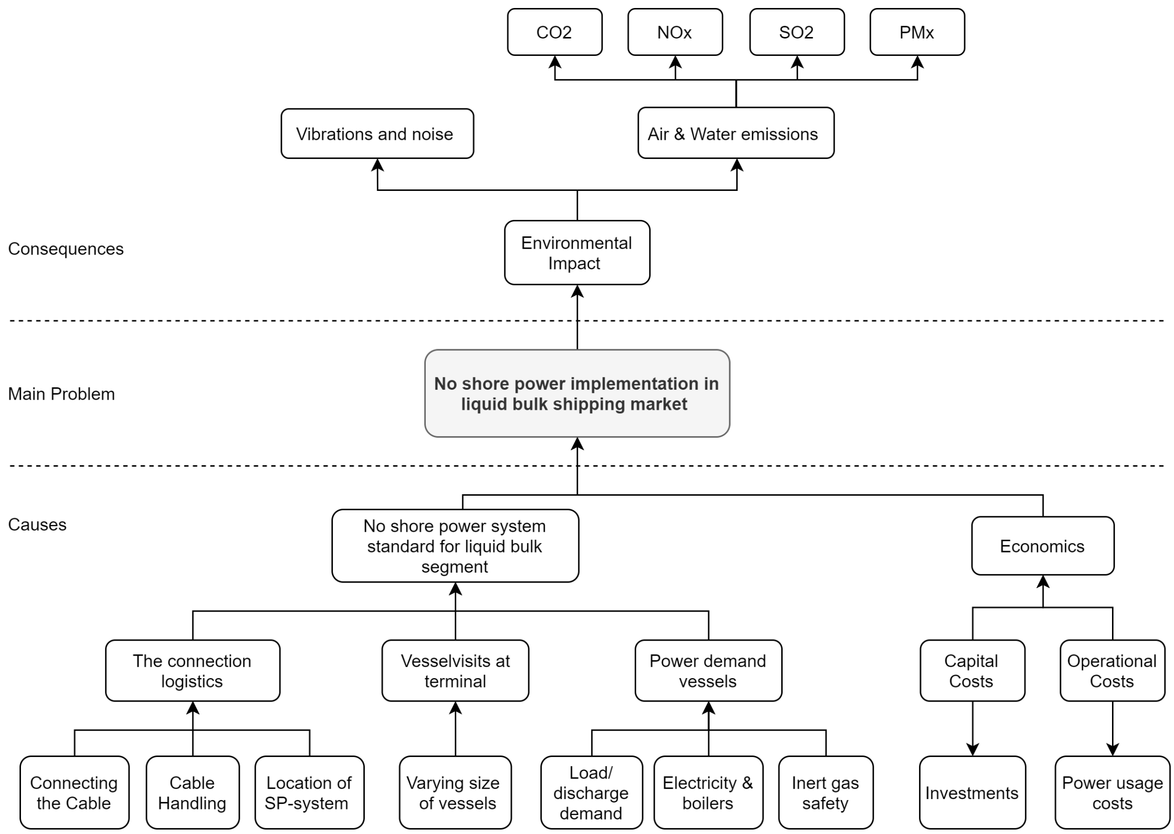

Figure 2.1: Problem tree visualisation

2.1. No standard solution

This section describes the absence of a technical feasible standard for a shore power connection concept for liquid bulk vessels. Currently, no feasible and safe standard 'off the shelf' shore power solution is available for liquid bulk vessels for two main reasons. First, the logistical and operational aspect of the shore power systems are yet undefined. This includes the cable connecting procedure without safety risks, the placement of the system with respect to the vessel and the handling and transporting of this cable from shore to ship. Secondly, the terminals have a variety of visiting vessels and overall insights in energy demand and size is yet missing. And the systems of each tanker that require electrical power vary from ship to ship. The insights in the power demand of the vessels is not yet complete to design a shore power system that works for all vessels. Due to the absence of a shore power standard for liquid bulk, the vessel operators, terminals and ports have not yet realised shore power systems for the liquid bulk vessels and terminals.

2.1.1. Connection logistics

The shore power system placement, the safe cable connection procedure and cable handling are still undefined factors in the shore power system for liquid bulk vessels.

First, the location of the shore power system on the terminal and the ship is undefined. Due to various jetty designs and a lot of different sizes of the vessels, the location of a shore power system is a difficult choice to make [16]. The terminal jetties are efficiently packed with the cargo manifold, pipelines and loading arms and the vessels have some operational flexibility to berth portside or starboard[1]. And jetties for liquid bulk vessels have different layouts as well, which makes it difficult to assign a standard location for all jetties where the shore power system should be placed. Also, each type of vessel has other main deck arrangements, which could result in little free space for shore power systems [36]. The shore power system placement at the shore side should be placed on the same place as the ships can receive the cable from shore, otherwise a lot of cable transporting and additional movements occur.

Secondly, the connection procedure onboard of a liquid bulk vessel does not yet exist. Connecting a high voltage cable comes with a spark risk and a spark from an high voltage cable in an area with a chance of explosive gases present could have dangerous consequences. The appearance of explosive gases are categorised in the ATEX regulations [43]. ATEX stands for Atmosphères Explosives and divides the risk of explosive gas appearance in three zones for tankers carrying cargo that have an explosion risk. Because of EU-regulation, the connection, which consist of electrical equipment should therefore be ATEX certified or should take place outside the ATEX zone. Since no ATEX certified High Voltage Shore Connections (HVSC) are currently available, it should be done outside an ATEX zone, or in a safe closed environment without explosive gases or a HVSC should be ATEX certified.

Lastly, it is not yet defined how to transport the shore power cable from shore to ship. Transporting the shore power cable(s), consists of bridging the distance over water and the vertical distance from the shore to the deck of the vessel. As seen in previous shore power projects for sea-going vessels this is done by using lifting equipment such as onboard cranes or shore based cranes [10]. The cable or cables can be heavy and stiff and it is not recommended to let people carry the cables across the ship or terminal. In addition to that, a fully loaded vessel, has a high draft and thus a low freeboard where as empty vessels have a small draft and high freeboard. The cable must be transported over this vertical distance which is also varying during operations. During loading or unloading operations the draft of the vessel changes since the vessel is getting heavier or lighter, respectively. Depending on the ship's size, the freeboard could range from a few meters to ten meters. Therefore using the right lifting equipment for transporting the cable from shore to ship is important.

2.1.2. Terminal vesselvisits

Liquid bulk terminals have a variety of liquid bulk vessels visiting each year, according to the Port of Rotterdam. For all different visiting vessels, the energy demand is of importance as well as the size of

[1] According to jetty equipment manufacturer and as seen on images of liquid bulk terminals

the vessels in order to design a shore power system. The difference in energy demands from small vessels compared to larger vessels can be quite significant, as well as the size [36]. The size of the vessels could be an important parameter to determine the placement of the shore power system. Currently, the vessel visiting data has not been used yet to gain insights in the visiting fleet at a terminal.

2.1.3. Power demand vessels

The exact power requirements for berthed liquid bulk vessels in general are not known, but only ranges of energy demands are known [7]. It is important to notice that the power demand varies for loading or discharging vessels as well as the power is not completely electrical onboard of ships.

Depending on if the ships are discharging or loading in the port, the ship uses its own cargo pumps or the shore's cargo pumps, respectively [36]. This creates a large variation in the energy demand of the vessel, depending on the operation in port. When loading a vessel, the vessel does not need to power its own pumps on board, since the shore based cargo pumps are used. However, for discharging the cargo from a liquid bulk vessel, the shipboard pumps are used. Also, for oil & gas tankers the cargo pumps are likely to be powered using a steam turbine, which uses steam from the boiler and chemical tankers have electrical powered pumps [36]. The difference in pump equipment onboard is important to analyse, in order to define the electrical power requirement for liquid bulk vessels.

Liquid bulk vessels come in different sizes and carry different types of cargo, which both will have influence on the power demand at berth. When berthed, a liquid bulk vessel has various systems running to ensure a safe operation in the port. These systems require energy, either steam from a boiler or electricity from an auxiliary engine [36]. For designing a shore power system, the power demand of the visiting fleet must be known. But the energy required on a ship is not constant, it varies over time and varies per type of operation in the port. For each type of liquid bulk vessels the energy demand needs to be estimated, depending on the operation in the port. To gain insight in the power requirements of liquid bulk vessels, the systems that require energy during port operations must be analysed as this is more complex than just plugging in the electricity.

Liquid bulk vessels have onboard inert gas systems running to prevent ignition or reaction of the cargo, as stated in the SOLAS convention of 1974 [44]. These systems have to be powered as well, depending on the source of inert gas, this can be electrical or fuel-fired. The inert gas systems on board regulate the oxygen levels of the ullage in the tanks, to ensure it stays below the combustion or reactive threshold of the cargo [44]. This inert gas is required in the cargo tanks at all time, however this inert gas has a different substance depending on the cargo that is transported. The production of inert gas in done onboard of the vessel, and requires either flue gas from boilers or electrical energy for nitrogen gas generating. For instance, the hydrocarbon gas that evaporates from oil can be ignited if an ignition occurs and enough oxygen is present. Therefore, the oxygen levels of this inert gas must be kept below the combustion threshold value, which is around 11% [45]. But, the inert gas must have a maximum of 5% of oxygen by volume. The flue gas from the ship's boiler is used for inerting in this case, after it is scrubbed by a flue gas system. However, some chemical cargoes can be reactive with water or air and these cargoes often require 95% to 99.9% pure nitrogen as inert gas. This nitrogen gas is generated by an electrical nitrogen generator onboard of the ship. The flammable vapours that vaporise from the cargo, must be purged by the nitrogen gas until the oxygen levels are below the reaction of combustion threshold [46]. For every inerting system, it is of the most importance that these systems keep on running otherwise the cargo could react with the environment or explode if an ignition happens.

2.2. Financial unfavourable

This section identifies why the shore power business case has not feasible for liquid bulk vessels so far. The negative financial business case has two main factors, the investment costs and the operational expenses. First, the operational expenses of a shore power system are discussed, these depend on the costs of connecting, the price of electricity and the contract costs for electricity. Secondly, the investment costs are elaborated, these include all costs that are made for the adjustment on the vessel and terminal for a shore power system.

2.2.1. Operational expenses

The operational expenses vary for the ship and the terminal. For the ship the operational expenses are dependent of the maintenance and the difference in price of electricity and running auxiliary engines on MGO. The price of for MGO is in a range of 200 €/ton and 700 €/ton and is heavily dependent on the world economics[2] [47]. With a specific fuel consumption of 220 g/kWh, the bunker prices can be expressed in cost per kWh of 0.04 €/kWh and 0.15 €/kWh, respectively[3]. The electricity prices in The Netherlands are around 0.07 €/kWh for industrial users, this price includes network costs and excluded taxes [48]. Comparing the energy prices, the MGO price must be rather high in order to make electricity financial favourable. However the shore power electricity price will be higher than 0.07 €/kWh, due to the business case of the terminal, which has to payback the shore power investment as well. The operational expenses of the terminal consist of maintenance and usage of the electrical systems and the contract costs for the installation to the electricity grid company. These costs can become a large part of the yearly costs, as the power demand of the shore power increases.

2.2.2. Capital costs

The second economical barrier, is the high capital costs for installing shore power systems. Both the ports and the shipowners have to make adjustments to their assets to be able to use shore power, which can result in a high investment for the owners [25, 35, 49]. The problem with investing in shore power for vessels is that it can only be used during port visits. The liquid bulk vessels mainly operate in a spot market, which means the ports that are visited are demand driven, and often not in a liner service [36]. When visiting a large range of ports in the spot market, the shore power utilisation will be heavily dependent on the availability of shore power in all those ports. For shipowners the shore power investment is too high, if the adaptation of shore power in the visited ports is too low. The adjustments on the ship side could add up to $500,000 for new build vessels and about $1,000,000 for retrofitting vessels, for a 2MVA connection [25]. However, these prices are varying dependent on the ship type, ship size and installation company. The shore power adjustments for ship and terminal consist of voltage transformers, frequency converters, switchboards, cable management system, shipboard connection and switchboard adjustments [32]. Also, the down-time of a vessel or terminal is also a loss of money for the owners of the assets.

2.3. Problem definition

Shore power for liquid bulk vessels is due to the above reasons not the standard in ports and neither it is economically feasible for both ships and terminals, right now. The problem that rises, can be compared to a Prisoner's dilemma, without collaboration all involved companies pay a high price for an one-of-a-kind emission reduction solutions, like shore power. With little to no existing shore power infrastructure for liquid bulk vessels, vessel operators and ports are dependent on each other to use shore power. Making the wrong decision for a shore power system, that will not be the standard in the future, can have large negative financial consequences for the shipowners and the terminal operators. The different shore power concepts must be analysed and evaluated for the liquid bulk market in order to provide an advise for a feasible shore power concept. Without clear insights in the use of shore power concepts for the liquid bulk industry, vessels and terminals will not yet make the first implementation step. In order to explore and evaluate the shore power concepts for liquid bulk, a technical analysis is needed for different shore power concepts, and the costs and yearly power utilisation must be estimate. And without insights in the operational and technical aspects of the liquid bulk fleet and terminal, the economics and power utilisation of shore power for liquid bulk can not be determined.

2.4. Research objective and research questions

In this section the research objective is discussed and finally the research question is presented.

[2]As seen on various bunker price websites, Dec 2020

[3]Without maintenance costs for the engine, and assuming a typical sfc of 220 g/kwh for auxiliary gensets

2.4.1. Research Objective

It is important to map all technical and operational factors that have influence on the design of a shore power system for liquid bulk vessels in order to propose a new system. The main objective of this research is to investigate and select an approach and concept for shore power systems for liquid bulk vessels. Therefore, the shore power system needs to be studied, to get insight in how such a system works and to find the requirements for a system. Previous operational installations are analysed and used for guidance in the design of a new system that fits the requirements for liquid bulk vessels. The liquid bulk fleet is therefore divided into groups, to find and analyse the required technical and operational parameters for these vessel groups. When the requirements for a shore power system are known, various solutions for a shore power system must be found and evaluated, in order to find the best feasible subsystems which will be part of the whole shore power system. Finally, different shore power concepts are proposed and evaluated in terms of cost and shore power utilisation. In addition to that, the circumstances that are required to make shore power feasible for both vessel and terminal are reviewed. This way, a road-map is constructed which will contribute to the implementation of shore power for liquid bulk vessels, with the potential of reducing local emissions from the liquid bulk vessels in ports. The final product will be a recommendation for a shore power concept for the high potential liquid bulk market, which is chosen in the case study.

To achieve this, the first phases of the Life Cycle Model of Systems Engineering is applied as framework to find the most feasible solution for all interests. Where the performance of different shore power concepts is assessed by performing a life cycle cost assessment and reviewing the power performance. Further explanation for the methodology choice is given in Chapter 3. The deliverables of this research are a report which includes the methodology, literature which forms the needs analysis, the model description and scenario design, a sub-market case study with results and the conclusion and recommendations.

2.4.2. Research questions

The main research question of this master thesis is:
"Determine the feasibility of conceptual shore power systems for berthed liquid bulk vessels, considering the technical, economical and emissions related conditions."

With the above main research question, the following sub-questions are formed of which the first three will be answered in the literature study.

- What is the current state of shore power systems for liquid bulk vessels; which research has been conducted already and how have similar questions been answered?
- How to categorise the various liquid bulk vessels in archetypes?
- Which operational and technical requirements are relevant for connecting a liquid bulk vessel to shore power from the vessels perspective?
- What are the criteria by which to assess technical feasibility of solutions for the shore power systems and which solutions are feasible?
- What is the synthesis of a model which demonstrates the economical and emissions related feasibility of the shore power system for a ship or terminal?
- How can this model be used to find a high potential shore power case for liquid bulk submarket?
- How can this model be used to create future scenarios in a case study by which the overall feasibility can be determined?

3 Methodology

This chapter describes the methodologies that are used in order to bridge the research gap for shore power implementation for liquid bulk vessels. The goal of this research is to do comparative analyses of technical feasible shore power systems for liquid bulk vessels and to be able to present an advise for shore power concepts for liquid bulk vessels. First, the motivation for a systems engineering approach is discussed, which will be partly adapted a framework for this thesis. Secondly, the use of a cost assessment model for emission abatement technologies is elaborated. Thereafter, the data-driven analysis of the vessel operations are briefly discussed. Then, the research gap is discussed and how the research goal adds value to this research gap. Finally, the solution approach with this methodology to resolve the research gap in this thesis is discussed.

3.1. Systems Engineering

For developing and designing a new concept for a system, the models and methods of the Systems Engineering field are suitable. The system life cycle model, as described by Kossiakoff, identifies three main stages of development in the life cycle of a system or technology [3]. The first stage is the concept development stage as seen in Figure 3.1. This phase is relevant for this research, since it aims to find requirements for a system and feasible concepts for a new system.

The needs analysis is an important step before starting with designing a system, to gather technical and operational knowledge of the system. And it assesses with what technology shore power systems can be designed. Secondly, the concept exploration in which the shore power concepts are evaluated for feasibility. This would fit well as framework for this research and therefore an adapted systems engineering framework is used for this research.

3.1.1. Adaptation in thesis

The adaptation of the concept development framework consists of the needs analysis and the concept exploration. The needs analysis structure is used for the technical background in which the shore power system is analysed, the vessels are studied and shore power concepts are discussed. The concept exploration will be performed by evaluating the shore power concepts in a model for the vessel and terminal.

3.1.2. Needs Analysis

As seen in Figure 3.1, the needs analysis consists of three parts the system studies, technology assessment and the operational analysis. These three subjects are discussed in the second part of this thesis, the technical background.

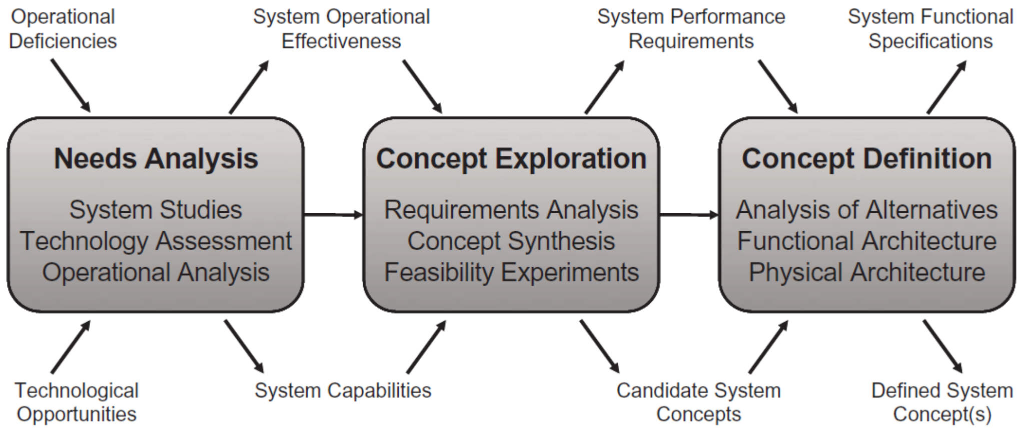

Figure 3.1: The concept development phases of a system life cycle by Kossiakoff [3]

System studies

First, this thesis discusses the system studies which are a large part of the literature study. This covers the analysis of shore power systems and a division into subsystems is made. These subsystems are analysed to find required equipment and possible limitations. Also, the systems operational effectiveness is expressed by using Key Performance Indicators (KPI's) which are to be determined in this sub-phase. Chapter 4 will discuss the shore power systems with the guidelines of the system studies approach.

Operational analysis

Secondly, the operational analysis will discuss the users of a shore power system, the liquid bulk vessels. In the operational analysis, the tanker fleet is analysed and divided into groups in order to find corresponding technical and operational parameters. Also, the energy demand of the vessels is estimated, which is a requirement for the shore power system. In Chapter 5, the liquid bulk fleet is discussed by using the guidelines of the operational analysis.

Technology Assessment

The technology assessment will discuss all relevant existing technology that can be used to solve the shore power problem. It will also provide criteria based on other literature to evaluate the technical feasibility for the technology concepts. The goal of this part is to evaluate the technology that can be used for the shore power system. The evaluation will be done by a multi criteria performance analysis for all systems that are discussed, in order to give insight in the scoring of a systems relative to another. This provides an overview of the various alternatives for a shore power system for liquid bulk vessels. In Chapter 6, the technology assessment as described in this paragraph is reviewed.

3.1.3. Concept Exploration

The second phase of the concept development, as seen in Figure 3.1, is the concept exploration. The principle of this phase is to evaluate the found shore power technologies for making a shore power system, based on various KPI's. In this thesis a model is designed to evaluate the shore power concepts for both the ship and the terminal. This is done, because the ship and terminal require different modelling approach since ship visits the terminal(s) and the terminal provides the shore power.

The concept exploration used different scenarios in order to find feasible scenarios for shore power systems. This is done by assessing the costs and the power utilisation of all discussed shore power concepts. The alternative scenarios also include changing operational or costs parameters of the model.

3.2. Cost Assessment Model

Cost assessment models are often used for performing the economic assessment for investments in sustainable concepts for shipping [50]. The most used cost assessment model is based on the life cycle cost of a system [51]. The approach of Life Cycle Costs (LCC) uses the capital costs and operational expenses and calculates the total costs over the lifetime of the installation and can give insight in the yearly costs of ownership. The capital costs will be annualised over a fixed amount of years, using a capital recovery factor which incorporates an interest rate to take the present value of money into account for annual capital costs.

For shore power systems, the considered costs are the investment costs and operational expenses. The investment costs for a shore power system include the equipment purchase and installation costs. For the operational expenses, the maintenance costs, costs for power utilisation and contract costs are considered. Additional costs for operating, such as labour costs for operating the systems are not considered in this thesis. Therefore, the Life Cycle Costs (LCC) method is used in this thesis, considering the annualised capital costs with a capital recovery factor, the operational expenses and the power usage of the vessels and terminals. Each different shore power concept is assessed by providing the LCOE of each concept as seen in Equation 3.1, this combines the economical assessment and the power utilisation.

$$LCOE = \frac{C_{cap,a} + C_{OM}}{P_{total,a}} \qquad [€/MWh] \tag{3.1}$$

3.3. Vessel Operations

The operations of all the vessels in the terminals have been excluded from earlier research into shore power. This is especially relevant for liquid bulk vessels, as the variety of visiting vessels in the terminal can be large and these vessels have different power demands [36, 52]. Exact vessel visits at each terminal are required to form an overview of the different kinds of vessels that berth at a terminal. Combining average power demands per operation vessel and operation together with visiting vessel data, is used as early estimation for shore power systems [29, 40, 53]. By using the historical vessel visiting data for a terminal, an good overview is created on what vessels are visiting and how much power is required.

For the terminal, the vessel visits need to be segmented to determine berth times, power demand per operation and give insights in vessel dimensions. The vessel visits are obtained by using shipping data from the Port of Rotterdam, then the vessels are segmented into groups and combined with technical data from the Clarkson database [6]. Using vessel technical data and visiting vessels per terminal, a more tailored shore power system per terminal can be estimated.

3.4. Research Gap

Other research into shore power implementation in ports for liquid bulk vessels are often not looking into what exact shore power system is used, but simply assuming shore power is provided. Therefore, finding general economical and utilisation results that should be addressed to a specific individual case vessel. The distinction in the loading operations and discharging operations of the liquid bulk vessels is also not taken into consideration for other studies, most literature assumes an overall average electrical demand. This would work for the vessel side, however a mainly designated loading terminal, will experience lower electrical power demands when compared to a discharging terminal during a year. Also, the liquid bulk market is really segmented, it is important to address the different types of liquid bulk vessels and to assign the right technical and operational parameters to those vessels [6, 36].

Information on the terminal side is often missing in the literature, other research does not point out whether the shore power system concept is either floating, mainly on the ship or on the terminal. As the system choice does matter for the cost effectiveness and power utilisation, this is important to address and evaluate for different systems. Especially, for liquid bulk vessels the location and type of shore power systems is very relevant due to safety considerations and size differences for the vessels.

The research gap consists of the intersection of the three parts, as shown in Figure 3.2. The operational knowledge of liquid bulk vessels and terminals in the shore power business cases in other literature is often incomplete. The advantages and/or disadvantages of different shore power systems are also not considered in other studies. Systems engineering aims to assess the requirements concept and to evaluate each different system based on KPI's [3]. The cost assessment for shore power concepts does often not take into account different shore power systems and the different vessel operations [51].

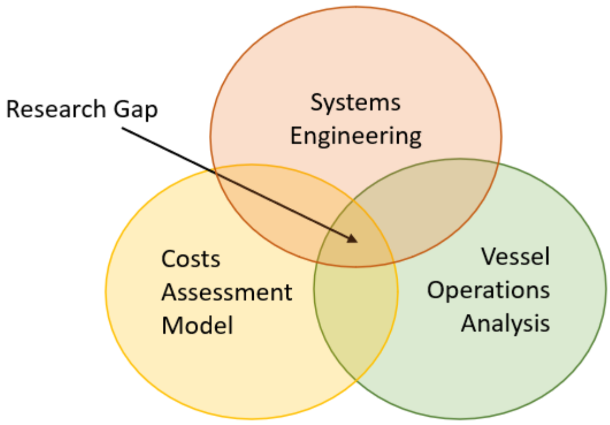

Figure 3.2: Research gap visualisation of this thesis

Therefore, the objective of this study is to address the economical and power utilisation effectiveness of shore power system concepts for different liquid bulk vessels, considering operational and technical relevant parameters of both the vessels and terminals.

3.5. Solution Approach

To solve the research problem, the framework of the concept development phase of Systems Engineering is used. This translates to analysing the shore power system, analyse the users of the system and review technologies which can be used for a shore power system. This is done in the second part of this thesis, the technical background, which will provide all relevant information for the shore power concepts evaluation in the third part.

To evaluate shore power system concepts for the liquid bulk fleet, Part III will assess the costs and the power utilisation for both the terminal and the ships. This is done using a model for the ship and the terminal, which use information found in Part II. This consists of the subsystem synthesis and operational data from databases such as Clarkson and the port monitor [6, 37]. These evaluated costs and power are required to review the cost-effectiveness of the system, the LCOE.

In Figure 3.3, the chapters are placed within the parts and show the relevant information that is required in order to model the ships using shore power. The lines represent which section provides the information for the model to calculate costs, power or emission reduction.

In Figure 3.3, the chapters are placed within the parts of this thesis and show the relevant information that is discussed in each chapter. The lines represent which section provides the information for the model to calculate costs, power or emission reduction.

The methodology for the ship and terminal have a lot of similarities, but the models are split into two structures to make the differences more clear. Where in each chapter information on the terminal side as well as on the vessel side is provided in order to design the ship model and terminal model in Chapter 7. The interdependence of the models is modelled by using alternative scenarios or future scenarios. As well as insights in the implementation of shore power for the liquid bulk market, in terms of costs

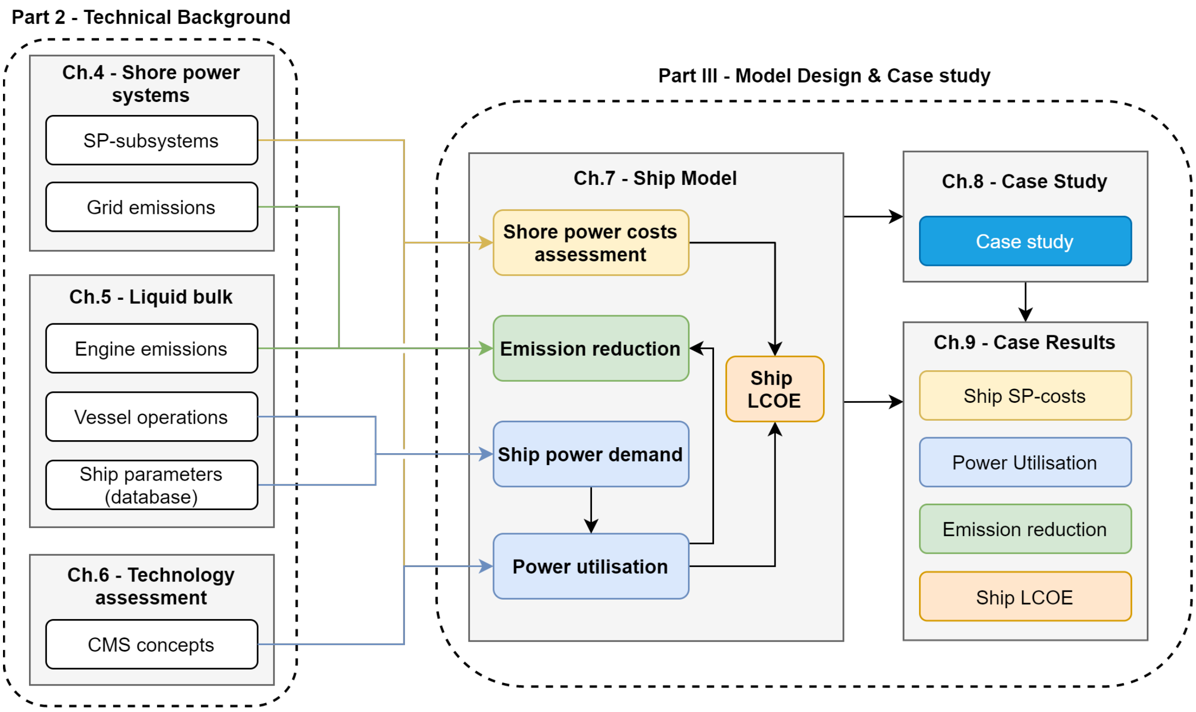

Figure 3.3: Ship model methodology structure

and power utilisation.

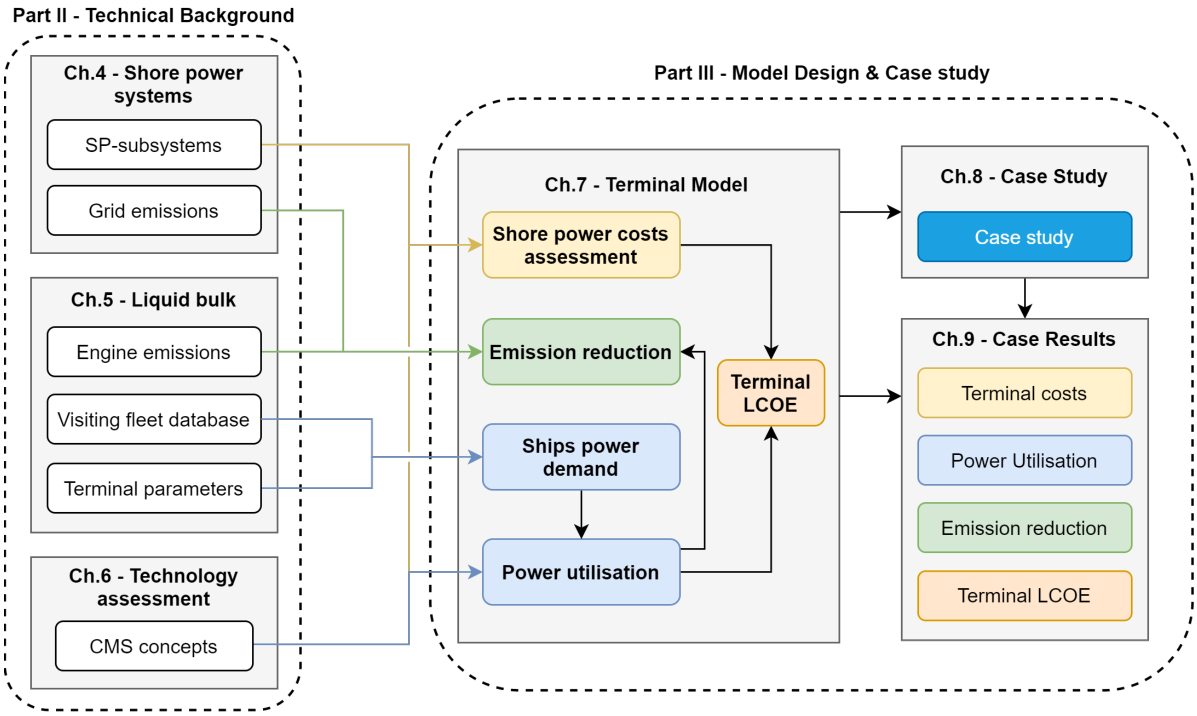

Figure 3.4: Terminal model methodology structure

II

Technical background

4

Shore power systems

This chapter provides a more in depth analysis into the shore power systems and provide the required equipment for a shore power system for liquid bulk vessels. The chapter is based on system studies approach of the needs analysis, however only in adapted form.

First, in Section 4.1 the shore power system as a complete system is discussed and divided into subsystems. Secondly, the subsystems analysis is done by discussing the working principle, provide background information and concluding what the functions and requirements are. This subsystem analysis is performed in Section 4.2 for the onshore energy supply, in Section 4.3 for the cable management system and in Section 4.4 for the onboard connection subsystem. Finally, in Section 4.5 the only operational liquid bulk shore power system is reviewed and similar project approaches are elaborated.

4.1. The shore power system

The goal of this section is to briefly describe a general shore power system and divide it into subsystems. First, the shore power system is analysed and the three subsystems are drawn, in order to look further into the requirements and functions for these sub systems according to the concept development phase [3]. Thereafter, the IEC code is briefly discussed as guideline for shore power systems.

4.1.1. System and subsystems

In Figure 4.1 a general shore power system is drawn based on information found on shore power systems in literature [10, 12, 15, 32, 33, 54]. The main shore power system is divided into subsystems in order to make a more in-depth analysis for each subsystem.

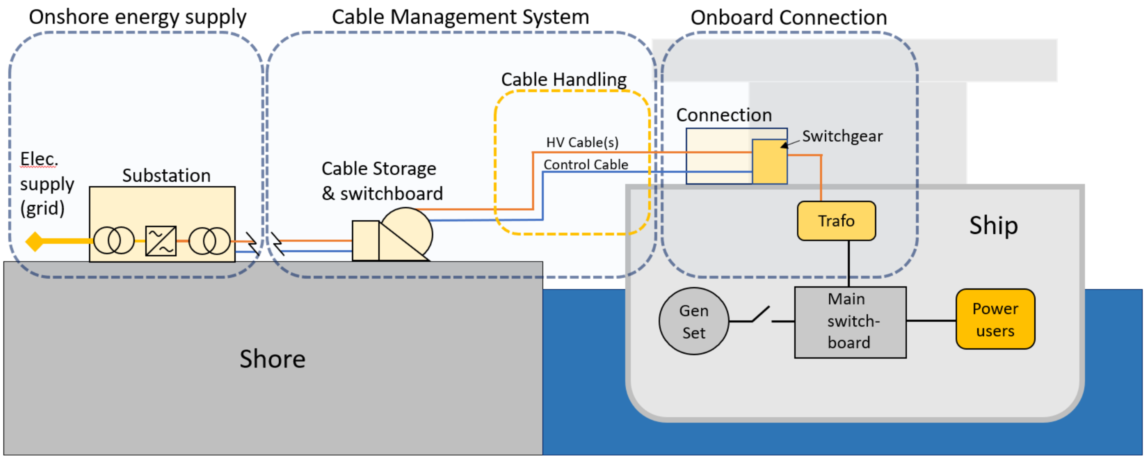

Figure 4.1: The shore power system which is divided into three subsystems, own figure

The subsystems are the onshore energy supply, the cable management system and the onboard connection and consist of everything within the dotted areas. These will be discussed in Sections 4.2, 4.3 and 4.4, respectively.

4.1.2. Vessel electrical characteristics

The general requirements for shore power systems for sea-going vessels are described in the IEC code for constructing a High Voltage Shore Connection (HVSC) [15]. However, the IEC-80005 code is incomplete for the liquid bulk segment, it lacks information for the connection logistics that were discussed as well in Section 2.1.1. It does partly cover the electrical characteristics of shore power systems, as shown in Table 4.1. The first three segments of the table are normative standards for, RoRo/Ferry, container and cruise. Yet, the Tanker/LNG characteristics are informative, which means it is still a guideline and not the standard, but it does give an indication.

Table 4.1: Electrical characteristics per vesseltype according to ABB and IEC [14, 15]

	Vessel Type			
Characteristics	RoRo/Ferry	Container	Cruise	Tanker/LNG
Voltage [kV]	11	6.6	11	6.6
Max Power Consumption [MVA]	6.5	7.5	16/20	7.2 - 10.5
Frequency [Hz]	60&50	60	60	60
Plugs/cables [-]	1	2	4	2/3

4.2. Onshore energy supply

This section aims to describe the onshore energy supply subsystem and its requirements and functions. The onshore energy supply consists of the national electrical grid and the substation on land. This section aims to discuss all relevant parameters regarding the electrical grid and electrical equipment for the substation. First, the electrical grid will be discussed, this is important to know where the power comes from and what characteristics the electricity grid has. Secondly, the onshore substation is discussed, why it is needed and what its functions are.

4.2.1. Electrical Grid

The electrical grid is not identical worldwide, but has voltage- and frequency differences per country [12], also national electricity is generated using different energy sources [55]. Three differences, voltage, frequency and energy mix are important to the shore power system.

Frequency

The voltage frequency of the electricity grid must be converted if it is not identical to the frequency of the ship. The European national grids are 50 Hz and over 75% of the the ships have a 60Hz network [6, 12], which is also visible in Appendix A. Different frequencies require a frequency converter on the shore side which converts the electricity from the grid to the same frequency as the ships is operating at. The frequency converter is placed onshore, to be able to deliver matching frequencies onboard without the need of converting onboard. This reduces the costs for the vessel operator as well. And when placing the frequency converter onshore, only one converter is needed, instead of every visiting vessel has one installed. The amount of space that is available on the ships is more limited than onshore, and with rather large frequency converters, the best placement is on land [14].

Voltage

The high voltage network of each grid does not have the same voltage as the receiving ships. The voltage is transformed to a lower voltage, in which the frequency converter is able to operate [32]. Thereafter, the electricity voltage is stepped up to the desired voltage for the receiving vessel, which is 6.6kV, which is also proposed by the IEC standard [15] and allows a sufficient amount of power to be transferred to the ship. To transform the voltage twice, at least two transformers are required in the substation onshore.

Energy Mix

The emission reduction of shore power is dependent on the electrical energy mix of the country where the system is used. The electrical energy supply is electricity that is obtained from a combination of different power sources [55]. The electricity mix is not a constant division in energy sources, but changes over the years, even days or hours. That is why it is important to notice, that the share of renewable energy sources is increasing. The goal of the EU is to achieve an average renewable energy share in the electricity grid of at least 49% [56]. The increasing share of renewable sources also increases the emission reduction when using shore power [55]. In Table 4.2 these emission factors for the Netherlands are shown. The factor for CO_2 is extracted from the European Environment Agency (EEA) for 2019, and the other factors are extrapolated from other similar country data [13, 29]. The forecast for 2030 is based on the CO_2-reduction forecast for 2030, and interpolated the other data as well [57].

Table 4.2: Emissions of the Dutch electric grid, CO_2 data is obtained from EEA 2019 data and other emissions are extrapolated from countries with a similar energy mix

Emission factors	CO_2 [g/kWh]	NO_x [g/kWh]	SO_2 [g/kWh]	PM_X [g/kWh]
Netherlands	390	0.223	0.185	0.025
Forecast 2030	100	0.2	0.015	0.02

4.2.2. Substation

As seen in other shore power projects, the onshore electrical equipment is housed in a onshore substation somewhere near the berth places at the terminal [10, 32, 58]. This substation provides a shelter for the transformers and the frequency converter(s) and other power management systems. Power cables with the desired voltage and frequency are from here routed to the berth places where the CMS is located. The substation is also referred as Ehouse in this thesis.

4.3. Cable management system

This section describes the Cable Management System (CMS) of shore power installations, which consists of the cable storage, cable handling and the switchboard. First, this section discusses the placement of the CMS with respect to the vessel, as it will define where to make the shore power connection with the ship. Secondly, the cable handling and the cable storage are discussed. Also, the grounding safety to prevent dangerous potential differences is briefly discussed.

4.3.1. CMS placement

The placement of the CMS for liquid bulk vessels is both on the terminal side and the vesselside, as been seen in a previous project and in the IEC-80005 [10, 15]. The location of the CMS with respect to the ship is important because, that will define the distance which the cable must be transported to the ship's receiving point. The placement of the CMS on the terminal side depends also on the current installed equipment and structures on the shoreside. It is therefore important to analyse different types of terminals, that are present in various ports. For the initial analysis of terminals is has been found that terminals for liquid bulk vessels, are mostly slender jetty structures with a manifolding area. However, some terminals have larger and wider concrete quays. In Figure 4.2, 4.3, 4.4 and 4.5 different terminal designs and layouts are shown for oil, LNG, chemicals and oil products respectively. This however does not guarantee that the terminal for each liquid bulk type a specific terminal is the standard.

As seen in the Figures 4.2, 4.3, 4.4 and 4.5, various terminal layouts and vessel types/sizes exist. The CMS placement is important, because it will define where the connection is on the ship is as well, and the other way around. It is also visible, that the manifold is always aligned with the midship, where the onboard cargo manifold is located. Thus, the CMS placement must align with the onboard connection in order to transport it from shore to ship by only bridging the water gap and vertical gap.

Figure 4.2: Terminal for oil tankers in Rotterdam (Source: Google Maps)

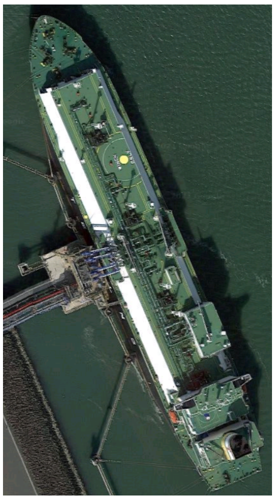

Figure 4.3: Terminal for LNG tankers in Rotterdam (Source: Google Maps)

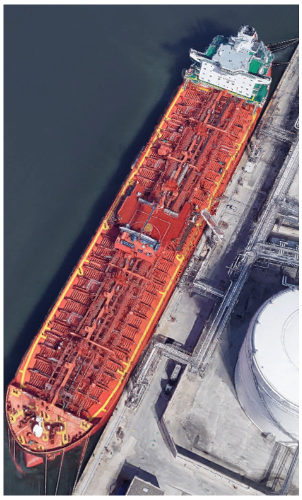

Figure 4.4: Terminal for chemical tankers in Antwerp (Source: Google Maps)

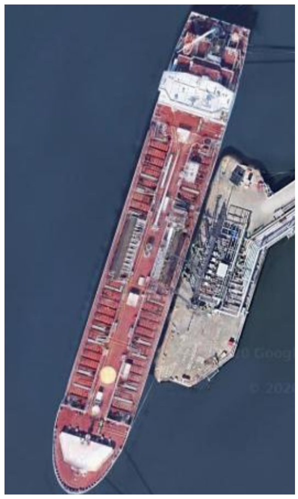

Figure 4.5: Terminal for mostly oil tankers in Gothenborg (Source: Google Maps)

4.3.2. Storage of cable

The storage of the cable is important, to prevent damage of the cable and proper storage of the cable makes it easier to lift and handle during lifting operations. Previous shore power projects used cable reels, to store the cable. However, when the cable is inside the ATEX-zone of the terminal or vessel, it needs to be ATEX-certified [43, 59].

4.3.3. Handling of cable

The process of handling the cable, involves lifting the cable from the storage point onshore to the receiving point on the ship. The lifting of the cable can be performed by a crane onboard of the vessel or onshore at the terminal or other types of lifting equipment. The crane should be able to transport the cable without exceeding any physical limits of the cable, such as minimum bending radius or too much tension in the cable [10, 15]. For this function, lifting tools or cable guidance trays can be used to safely provide the cable from shore to ship. At the ship, the cable should plugged in to a connection point.

4.3.4. Grounding safety

The electrical safety during in the cable management systems is of high importance [60, 61, 62]. Bringing a cable across the gap from shore to ship, causes a risk of touch potential due to the different potentials from shore and ship. The presence of an arc in a zone with flammable gases from the cargo can be very dangerous. This must be avoided at all times, it is therefore important that when installing a shore power system, sufficient ship grounding measures are taken.

4.4. Onboard connection

This section discusses and reviews subsystems onboard of the vessel. First, the connection point onboard is discussed. Secondly, the electrical equipment that is required is discussed. Thereafter, the cable run onboard of the vessel is elaborated. And then the emissions of the generator are discussed. Finally, the requirements and functions of this subsystem are discussed. ABB, a manufacturer of electrical equipment for ships has illustrated the ships engine room with shore power equipment in a general way in Figure 4.6.

This figure shows a vessel which has a powerplant of two main engines, two generator sets which are providing electrical energy to the Low Voltage (LV) switchboard. The LV switchboards are providing electrical energy to the electrical energy users onboard. The green sphere in Figure 4.6 represents the equipment related to shore power, the power cable(s), the connection panel and the transformer, as

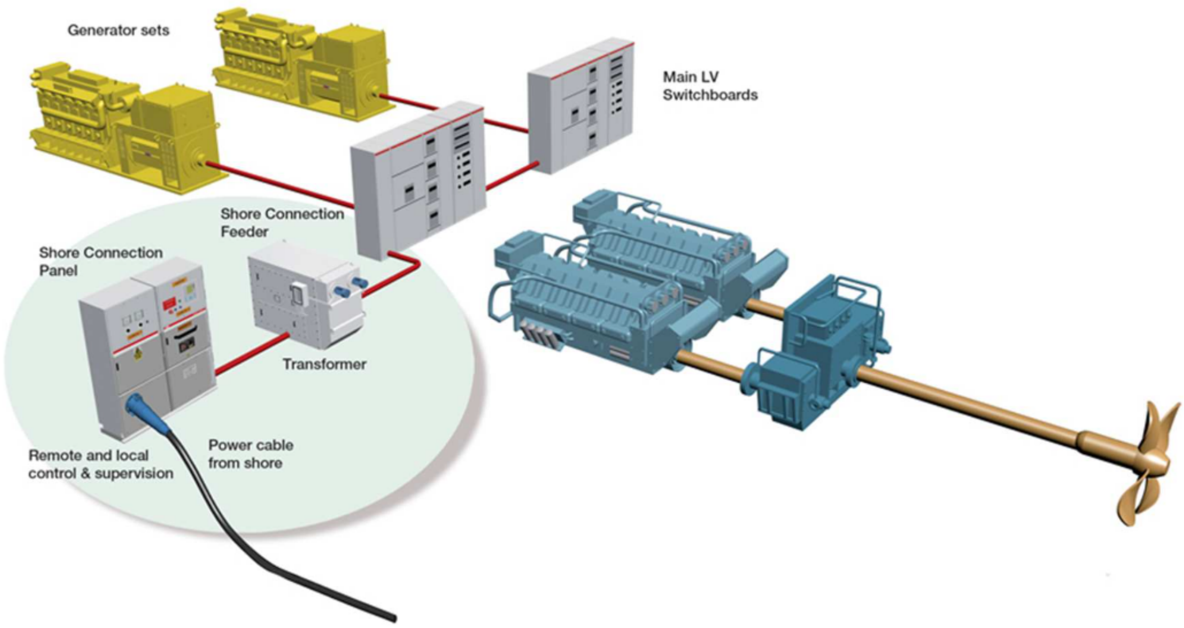

Figure 4.6: Ships power equipment visualisation with in the green area shore power equipment, and on the right the (non-electric) propulsion machinery, image obtained from [4]

seen as well in Figure 4.1.

4.4.1. Connection point

The connection point of the shore power system is the location of where the shore power cable is plugged into the connection panel onboard, as seen in Figure 4.6. The connecting of this cable involves moving the cable from the location where it enters the ship to the socket of the connection panel. The location of the connection point is a important design choice, because it preferably needs to be close to the cable management system onshore in order to reduce cable transportation onboard. It preferably needs to be close to the main switchboard of the ship to prevent a long cable from connection point to the switchboards. The ship has ATEX-zones on the deck that indicate the appearance of explosive gases [43]. When the cable is connected in an ATEX-zone, the connection point should also comply with the safety regulations of ATEX-zones and have an ATEX-certificate. An safe connection point is either locating it outside of the ATEX-zone or to have an enclosed area without ATEX-zoning.

4.4.2. Electrical equipment

The ship's side of a shore power system needs some additional electrical equipment onboard. To use the power that is delivered by the shore power cable(s), the voltage must be transformed to the same as the ship's electrical system is running on. Since not all ships have the same voltage, a transformer is needed on board of the vessel [32]. Before the power is delivered by the shore power system, the current needs to be synchronised with the ship to avoid a short power blackout, which is harmful for the electrical equipment [61]. This power synchronisation happens before the shore power takes over, and at the end of the port stay before the generators are taking over. An breaker and switchboard modifications are required to provide a synchronisation in order to match the shore power with the onboard power.

The cable that is needed for transporting the power from connection point to the switchboard, relies on the distance between those. Ideally, this is as short as possible in order to use less cable, less cable routing through compartments/decks and less voltage drop would occur. Although, the voltage drop will not be substantial for the cable routing on the vessel, it should be considered when routing for large vessels [58].

4.5. Other approach

This section aims to describe other approaches to the implementation of shore power. First, by reviewing the only operational liquid bulk shore power system in the world. Secondly, KPI's and other studies for shore power and other emission abatement technologies will be discussed.

4.5.1. Liquid Bulk implementation

Currently, there is only one operational shore power system for liquid bulk vessels in the world. This shore power system, located in Long Beach, California, is designed in 2007 and was operational in 2009. The design choices of the shore power system for the oil tankers in Long Beach are discussed by Nagel [5].

Design

This shore power system is constructed at the aft of the ship and uses the store's crane from the vessels. In Figure 4.7 the placement of the CMS is shown near the aftship. The CMS placement is not on the centre line of the ships shore power receptacle, but slightly moved to the left. Otherwise the CMS platform would interfere with the mooring lines of smaller ships. The important shore power design parameters that defined the project in Long Beach are listed in Table 4.3.

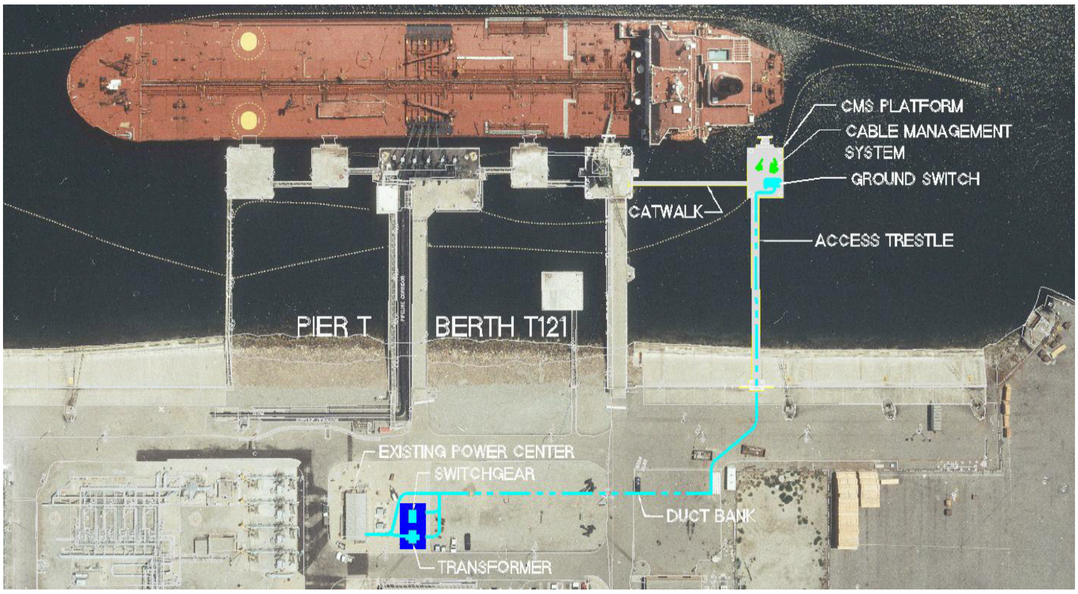

Figure 4.7: CMS Platform placement at berth T121 in Long Beach [5]

Table 4.3: Project parameters of shore power in Long Beach, CA [10]

Parameter	Value	Unit
Power	10	MVA
Voltage	6.6	kV
Frequency	60	Hz
Cable Handling	Ship's stores crane	
# of Cables	3	[-]
Cable cross section	350	mm^2
Current	360	A

Lessons from this implementation

The liquid bulk shore power project was executed for the BP terminal in Long Beach, for the Alaska class vessels. The Alaska class vessels all have similar dimensions, this makes the implementation of the shore power system a lot easier, since varying vessel lengths, varying ship lay-outs and power demands are not present. The system is placed near the aft of the ship, in order to avoid the ATEX-zone in the manifold area near the midship. The most important lesson is that a aft ship connection is safely operated for over 10 years now, this could be a feasible option for berths with more or less the same size of vessels visiting frequently. Concluding, this solution is good, however it does require an additional CMS-platform that needs to be constructed. And for terminals which receive a larger variety of ships, it would not be useful if the ships can't reach the cable platform if this is out of reach of the stores crane. Probably, the reason that this systems works well, is because the vessels are charted by an oil major, who also owns the terminal and the vessels have a more or less liner service including this terminal. That makes the utilisation of the system higher, and the diesel electric vessels have a relative high power demand compared to conventional oil tankers.

4.5.2. Cruise Study

Another study for the cruise industry was found and besides operational and economical parameters that were found, some key issues for business plan Onshore Power Supply (OPS) were discussed as well [54]. The key steps to overcome these issues, as listed by Green Cruise Port, are:

- Cooperation and coordination between ports and ship owners.
- Work for development of legal framework that promote use of OPS.
- Flexible discounted grid tariffs, with renewable obligation cost exemption.
- Work with national authorities to find instruments that provide investment support for OPS to overcome barriers and initial thresholds for OPS.
- Promote the benefits of OPS to ship owners.
- Work on bridging the development.

4.5.3. KPI's

To verify the performance of a developed concept for implementation, Key Performance Indicators (KPI's) are established. In other literature, which use system engineering approaches for developing emission abatement concepts, KPI are used based on costs and emission reduction [50, 63]. In the first and only shore power project that involved liquid bulk vessels, the main drivers were environmental improvements and safety, unfortunately the costs were not mentioned [10].

The work of Van Der Meer, shows by using game theory, that a rather high shore power factor and a high fuel price is needed to make shore power profitable for shipowners [64]. The shore power factor, is a percentage of at which ports the vessel can use a shore power system which is compatible with its own shore power system installed onboard. The results showed that the shipowners, who make decisions based on economical reasoning (CAPEX & OPEX), would implement the use of shore power when this was economical favourable. It is therefore important assess the economical effects of shore power as well.

The operational parameter that decribes the use of a shore power system is the amount of shore power that is delivered from the shore to the vessel. The reduced emissions are a more or less constant function of the amount of shore power delivered. If more shore power is used, than more local emissions are reduced.

Therefore, the two Key Performance Indicators (KPI's) of a shore power system for liquid bulk vessels are:

- **Costs**, the total annualised costs of owning and operating the shore power system as well for the terminal as the ship.
- **Power utilisation**, amount of shore power used, where each MWh of shore power has an constant emission reduction factor.

4.6. Conclusion

The shore power system has been studied and analysed, and the functions and requirements of its subsystems are found. The onshore power supply should provide the desired voltage for transporting and provide the frequency that is used on board. Also, the required equipment for this is placed on the terminal side in a sub station (ehouse). The desired voltage and frequency should then be provided to the CMS. The CMS placement should be aligned with the ship connection point, and not obstruct other port operations. The CMS placement should be chosen such that the most vessels could connect to the shore power system if available. The cable should be safely stored on land in order to provide the cable from shore to ship. Also, as part of the CMS, sufficient grounding of the system should be done, if that is not yet done for a vessel and terminal. The onboard connection subsystem has to provide a connection between the shore power cable and the vessels receiving point without spark hazards. It should provide a voltage transformation from the incoming 6.6 kV to the desired onboard voltage level in order to connect with the main switchboard. Also, it should provide a synchronisation of the power supplies before switching off the generators. The cable run on board should be as short as possible.

Therefore, the two Key Performance Indicators (KPI's) of a shore power system for liquid bulk vessels are:

- **Costs**, the total annualised costs of owning and operating the shore power system as well for the terminal as the ship.
- **Power utilisation**, amount of shore power used, where each MWh of shore power has an constant emission reduction factor.

The shore power systems that are reviewed only have differences in the cable management system. Therefore, the technology assessment chapter will only discuss various concepts for the cable management systems of shore power.

5
Liquid bulk

This chapter aims to find insights in different vesseltypes within the liquid bulk fleet and terminal characteristics. In order to determine the costs and power utilisation of shore power concepts, insights in energy demand and technical parameters of different vessels are required. Therefore, this chapter looks into different vesseltypes, the related vessel operations and the liquid bulk terminals to find operational and technical parameters.

First, in Section 5.1 the liquid bulk fleet is analysed, in order to find different archetypes of vessels. Secondly, in Section 5.2 the technical parameters which are of importance to design a shore power system are discussed. Thereafter, in Section 5.3 the tanker operations in ports are discussed to make an analysis of the berthing strategy and eventually the energy demand of the vessels.

5.1. Tanker fleet analysis

In this section the different types of liquid bulk vessels are reviewed. The liquid bulk cargo can be mainly divided into four types: oil & products, gas, chemicals and other liquid bulks. The fourth cargo category, is any liquid bulk that cannot be placed under the other three e.g. orange juice extract. The categorisation is based upon Maritime Economics by Stopford, the ship construction codes of the International Maritime Organisation (IMO), the IBC[1] and IGC[2] and the Port Authority [36, 46, 65]. The carriage of liquid bulk cargo is often hazardous and needs careful handling and storage, therefore liquid bulk vessels are designed to handle one or more specific cargoes. To analyse the different liquid bulk vessels, the World Fleet Register of the Clarkson database is used [6, 36]. This database provides information on all commercial vessels above 100 GT, which is a measurement for the ship size. The database has a lot of useful information on the world fleet, and is commonly used by other sources for fleet statistics [16, 36].

The differences between various tankertypes are large, to quantify this difference in numbers and deadweight, the Clarkson database was analysed. The number of vessels compared to the total deadweight of the liquid bulk world fleet is shown in Figure 5.1. All vessels that were build before 1975 have been manually removed from the database for this thesis due to the SOLAS regulation of 1974. Also, as only two vessels under 1000 ton deadweight have visited the Port of Rotterdam in the past 10 years, all vessels below 1000 dwt have been manually removed as well. Ships without tonnage or length data were also removed, in order to have a more complete data set for segmentation of the data.

[1] International code for the construction and equipment of ships carrying dangerous chemicals in bulk
[2] International code for the construction and equipment of ships carrying liquefied gases in bulk

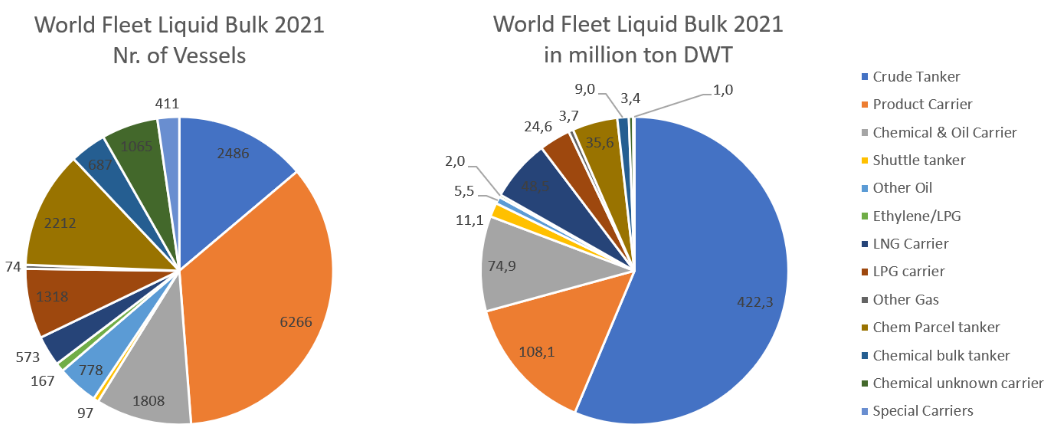

Figure 5.1: World Fleet liquid bulk statistics 2021 from Clarkson [6], figure is adaptation from data

What is clearly visible in the figures, is that the distribution of vessels is not evenly divided over the tanker types and in terms of deadweight, the oil tankers have more than three quarters of the total liquid bulk deadweight. Crude oil tankers are usually larger than oil product tankers [6].

The tanker fleet has increased in the past years, compared to 2007 [36], the current fleet consists more oil, gas and chemical tankers [6]. The amount of oil tankers increased with about 35% in the past 13 years. The amount of gas tankers increased with 80% in the past 13 years. As well the amount of chemical tankers, which increased by 45% in the past 13 years. The growth in tankers are showing the increasing demand for shipping and the increasing demand for gas products, which are considered as an alternative maritime fuel.

5.1.1. Size classes

To divide the tanker types based on sizing, the DWT of the vessels are commonly used. The size classes are bases upon physical constraints, such as the Suez channel or the Panama channel, or in case of the Aframax for freight rate reasons [36]. These size classes are also divided into Medium Range (MR) or Long Range (LR), to give a more specific range for the deadweight. The size classes definitions are not fixed and various companies use slightly different lower and upper bounds for the segmentation of the vessel types. The size classes of the Port of Roterdam and from the London Brokers panel are consulted, and slight differences in names and dwt boundaries are found. To be able to segment the vessels in this research, these classifications are consulted together with statistical data from the Clarksons database.

In the statistics from the Clarkson database the size division is clearly visible for the oil tankers which have specific dwt ranges. However, for the gas and chemical tankers the division is not so clear and the sizes, based on DWT, are more equally divided. The largest amount of tankers, fits into Table 5.1, while still have representative technical parameters for each tanker subtype [6]. The listed tankers in the Table 5.1 represent over 95% of the tanker fleet of the oil, gas, chemical tankers and special tankers.

The 14 size types are chosen because of the coverage of the world tanker fleet is optimal expressed in the least amount of types by covering the most amount of vessels. For instance, the DWT-range of 165,000 to 295,000 of oil tankers, only consists of 25 vessels corresponding to 0.3% of the world oil tanker fleet. To increase the range of a subtype, it should also increase in vessel number quite much, otherwise it would not be logical to enlarge the subtype if it is only representing about 20 vessels more on a number of 500.

Table 5.1: Most occuring tankersizes per cargotype [6]

Vessel cargotype	Sizetype	DWT-range [dwt/1000]	Amount	Percentage [%]
Oil	Shortsea/ parcel	0 to 20	4204	46.2
	MR	30 to 55	2092	23
	LR1	70 to 80	431	4.7
	LR2/Aframax	100 to 120	1004	11
	LR3/VLCC	150 to 165	476	5.2
	LR4/VLCC	295 to 320	771	8.5
Gas	Shortsea	0 to 15	840	40.6
	Handymax	15 to 30	255	12.3
	MR	45 to 60	317	15.3
	LR2	70 to 100	524	25.3
Chemical	Shortsea	0 to 10	1756	49.7
	Parcel	10 to 20	1167	33
	MR	25 to 50	509	14.4
Special	Shortsea	0 to 10	338	95.2

5.2. Technical parameters

This section discusses all the technical parameters of liquid bulk vessels, according to the segmentation that is made in the previous section. As discussed in the problem analysis, the varying length of the liquid bulk vessels is a problem First, a technical summary of each cargo type of the liquid bulk vessels is given. Secondly, the auxiliary engines are discussed and thereafter the crane availability.

5.2.1. Technical information per cargotype

This subsection provides technical background information on the different liquid bulk vessels, for each different cargo type.

Oil Tankers

The largest groups of oil tankers are the crude oil tankers, which are typically very large, the average deadweight is 173,000 ton [6]. The few cargo tanks are large and most of the times only carry one cargotype, crude oil. Crude oil must be heated in the tanks, to keep the liquid at a pumpable viscosity [36]. The ships pumps are generally located in a pump room and the vertical centrifugal pumps for the cargo are often direct driven by steam turbines, thus can't be powered by electricity.

When more different cargoes have to be handled, submerged deep well pumps are used. This is the case for oil product tankers. The product tankers are quite similar to the crude oil tankers, although something smaller, the average deadweight is 21,000 ton [6]. The installed electric auxiliary power is on average 1,500 kW. Because more different cargoes needs to be handled, the tankers are equipped with submerged pumps. However, product tankers do sometimes have centrifugal pumps as well.

The chemical and oil tanker is used for 'light' oil products and chemicals transports, these are the lighter oil products, e.g. naphtha which requires clean tanks. The average deadweight is 42,000 ton and the average installed electric power is 2,500 kW. A lot of chemical and oil carriers are equipped with centrifugal pumps, but about 25% has deepwell pumps and 10% has submerged pumps [6, 36].

Chemical Tankers

The chemical tankers are divided in to two main groups, chemical parcel tankers and chemical bulk tankers. Chemical tankers must be capable of dealing with the dangers of carrying chemical cargoes, which include: flammability, toxicity, corrosivity and reactivity. Therefore, the tankers are categorised by the IMO, in order of protective measurements which are required onboard. Protective measurements such as tank coatings, special valve operating gear and tank placements. All chemical tankers have the IMO type classification [46].

Chemical parcel tankers have many different cargo tanks, to ship various chemicals in one trip. And because these chemical cargoes are relatively expensive and sensitive to cargo contamination, they can be separated in the smaller cargo tanks of a parcel tanker. Each cargo tank has its own cargo-handling system, including a pump for discharging. These pumps are often submerged deep well pumps and hydraulically driven by a electrical power pack. The chemical tankers are using nitrogen for inert gas supply in the cargo tanks, which is supplied by an nitrogen gas generator onboard [46]. A nitrogen gas generator is typically powered by electricity.

The chemical bulk tankers, have less separated tanks and are not necessarily larger than chemical parcel tankers. These ships are used, when the cargo quantity is higher and therefore it it not required to put the cargo in separated tanks. The cargo pumps in chemical tankers are submerged in the tanks, like for the chemical parcel tankers as well. The chemical bulk tankers are also using nitrogen gas generators for onboard inert gas production.

Gas Tankers
Gas tankers consist of two main groups, LPG tankers and LNG tankers. LPG stands for Liquefied Petroleum Gas and LNG for Liquefied Natural Gas. Gas tankers use either nitrogen generation plants for their inert gas or fuel fired boilers [65]. The nitrogen plants use electricity as power and air as feedstock for the nitrogen, but the fuel fired boilers are using fuel to produce inert gas. The LPG tanker have an deadweight of about 5,000 to 65,000 ton, which is smaller compared to LNG tankers. Most of the LPG tankers are equipped with deepwell cargo pumps.

LNG tankers carry liquefied natural gas, which liquefies at -161.5 °C. This requires well isolated cargo tanks and even with this isolation the cargo still boils off each day. LNG vessels usually have submerged electric cargo pumps. LNG vessels are the largest gas tankers, with a DWT-range from 70.000 ton to 110.000 ton. Two types of tanks are commonly applied to carry LNG onboard of vessels, these tanks have different shapes and therefore different deck space [66]. Unfortunately, the pump type is not specified for LNG tankers in the Clarkson database. The new generation LNG tankers is increasing in size and requires less steam for operations, which will increase the electrical demand[3]

Special Tankers
The special tankers are all rather small and only a few of each type exist. Most special tankers are below the 7,500 ton deadweight, except for the fruit juice carriers. These range from 5,000 ton to 40,000 ton deadweight. The fruit juice carriers often sail from South-America to Europe or North-America, mostly on liner services. However, not a lot of information is found about special tankers in the database.

5.2.2. Auxiliary Engines

For calculating the amount of fuel that is needed to power the ship, the configuration of the vessels power plant must be analysed. Commercial ships use the main engine to power the propulsion plant and the auxiliary engines for powering the cargo plant and hotel load [52]. The specific fuel consumption (SFC) of an engine is dependent on the load conditions, as this is difficult to exactly determine when modelling over a long period of time an average SFC is used. The specific fuel consumption is estimated for auxiliary diesel engines at an average of 210 g/kWh during the port stays [52, 67]. The generator that converts the mechanical generated energy to electrical energy is estimated to have an efficiency between 0.95 and 0.97, according to the Wartsila specifications [68].

To quantify the emission reduction, the onboard generators needs to be studied and most importantly, their emissions estimations. As stated by Stolz, detailed data on specific fuel consumption, SFC, and emission factors, EF, is scarce and therefore, mainly constant values are used in te study [7]. Yet, various studies have estimated the emissions of auxiliary engines onboard of ships and some for different loads as well, the average of these studies is taken and shown in Table 5.2. Measuring or estimating the emission factors does not always present the exact emission values. The emissions are dependent on the exact chemical substance of the fuel and the load of the engine. Most auxiliary engines use MGO or MDO, which is more or less the same substance. Currently, no LNG auxiliary engines are used nor is there data from those engines, thus this thesis only reviews the MGO emisions from the auxiliary engines. Also, the NOx emissions are dependent of the engine type, as newer engines

[3]Forecast by PortXchange expert

(Tier 2) are emitting less NOx than the engines before 2000 (Tier 0) due to stricter regulations [7]. It is assumed that the auxiliary engines are Tier II, as the shore power will have to be compared with future engines.

Table 5.2: The ranges of MGO emissions from auxiliary engines, and the used value in this study

Particle	Value Range [g/kWh]	Used value [g/kWh]	Sources
CO_2	600 - 800	700	[7, 32, 58, 69, 70, 71]
NO_x	7.7 - 13.9	7.7	[7, 32, 58, 69, 70, 71, 72]
SO_2	0.14 - 0.44	0.27	[7, 32, 38, 58, 69, 70, 71]
PM_x	0.15 - 0.38	0.25	[7, 32, 38, 58, 69, 70, 71]

5.2.3. Crane availability

To transport the shore power cable from land to shore, a crane is used in other shore power projects. In order to determine if a similar solution as described in Chapter 4 can be used, an estimation of the availability of onboard crane should be made. For each type of vessel, various ships are analysed using images of vessels that were found online and images of vessels from Stopford [36]. Liquid bulk vessels can have one to three cranes onboard, one hose handling crane in the midship area, and one or two store cranes at the aftship. Hose handling cranes are used when the terminal does not have marine loading arms for connecting the ships manifold with the shoreside pipelines and flexible hoses must be lifted from shore to ship.

Allmost all liquid bulk vessels have an hose handling crane onboard, however the presence of stores crane at the aft of the ship varies per shiptype and depends on the size of the ship. Usually, smaller vessels do not have stores cranes but larger vessels tho.

5.2.4. General Ship Aspects table

In Table 5.3 the important technical aspects of the tankers are shown, the ranges for the values are minimum and maximum of the interquartile range of the boxplots that are made with the Clarkson database for the tanker types.

Table 5.3: General Ship technical aspects [6, 16]. The length is the median, the installed elec. power is the median, the frequency of 60 Hz is expressed in percentage, the Auxiliary Engine (AE) shows most occurring configuration, and cargo pumps

Vessel cargo-type	Sizetype	DWT-range [dwt/1e3]	Length [m]	Installed elec. power [kw]	Freq. 60Hz [%]	AE config.	Cargo pumps
Oil	Shortsea	0 - 20	96	600	52	3 DG	Electrical
	MR	30 - 55	183	2,700	90	3 DG	Electrical
	LR1	70 - 80	228	2,700	83	3 DG	Steam
	Aframax	100 - 120	248	2,400	87	3 DG	Steam
	Suezmax	150 - 165	274	2,850	88	3 DG	Steam
	VLCC	295 - 320	333	3,750	80	3 DG	Steam
Gas	Shortsea	0 - 15	100	900	94	2 DG	Elec/steam
	Handymax	15 - 30	160	2,970	77	3 DG	Elec/steam
	MR	45 - 60	226	3,900	88	3 DG	Steam
	LR2	70 - 100	290	10,350	84	4 DG	Steam
Chemical	Shortsea	0 - 10	105	944	69	3 DG	Electrical
	Parcel	10 - 20	140	1,650	90	3 DG	Electrical
	MR	25 - 50	180	2,952	82	3 DG	Electrical
Special	Shortsea	0 - 10	60	250	39	-	

The deadweight range is relevant for indication for the size of the ship. The length of the vessels is relevant for the distance of the manifold to the aft-ship, this is approximately the distance that the cable must be routed onboard or the distance of which an aft-connection point is located. The installed electrical gives an approximation of how much electrical power can be generated onboard, this must be combined with the load profiles of various tanker types in order to conclude what the power demand is. Also, the percentage of a subtype that operates the shipboard electrical network with 60Hz is shown, which is important to see whether the ships should receive 60Hz electricity or otherwise. The auxiliary engine configuration is of importance to give an insight of the maximum electrical working load in a port. Lastly, the cargo pump energy source is given, this is not exactly found, however the database did provide some additional info about the pump types. Pumps types are typically driven either by a hydraulic power pack, a steam turbine or electrical motors. Assumptions are that the hydraulic power pack could be powered by electricity as well, and the steam driven cargo pumps can not. In Appendix A the boxplots for the length of the vessels is shown, which show the sometimes small differences in length for the subtypes and the varying electrical demand. Also, the use of steam to power a steam turbine that is linked with the cargo pumps, is common use from a deadweight of about 50,000 to 60,000, according to Shell. This needs to be further studied, because this could be a clear distinction in the electrical power demand.

5.3. Tanker operations

In this section, the operations of a vessel outside as well as in the port are discussed. First, the typical vessel trips together with the liquid bulk trade is discussed. Secondly, the berthing procedure at a terminal is discussed in order to gain insight in the choice for berthing positions. Which is relevant for the shore power system location choice, for operational flexibility. Then, the energy demand at berth is discussed, including the at berth operations, which are of importance to define the electrical load of a vessel. Finally, the operational requirements are discussed in the conclusion.

5.3.1. Port visit frequency

Different bulk vessels make different trips during a year, smaller vessels make more shorter trips while large vessels make a few long trips. These estimations can vary for each individual ship, but give an indication on how many visits a ships approximately makes each year. The amount of port visits equals twice the amount of yearly voyages, since a voyage has a loading port and a discharging port. Estimations for yearly voyages of each shiptype are made together with an shipping expert and are shown in Table 5.4 and are also in line with estimations in books and literature [36, 73].

Table 5.4: Estimation of ship voyages per year for each vessel type

Vessel		Voyages per year
Oil	Shortsea	40
	MR	28
	LR1	20
	Aframax	14
	Suezmax	11
	VLCC	9
Gas	Shortsea	40
	Handymax	20
	MR	10
	LR2	9
Chemical	Shortsea	40
	Parcel	30
	MR	10
Special	Shortsea	32

5.3.2. Berthing

When a vessel enters a port, contact with the Port authority is made to make sure the vessel can safely sail the waterways to the destination terminal. Before berthing at the terminal, the crew of the vessel assesses the environmental conditions in the port, e.g. tides, currents and wind, after receiving the preferred berth position by the terminal[4]. The berthing strategy is important to see where the aft of the ship is located, in order to verify if this is a suitable location for a shore power connection point. In order to find the operational flexibility of the shore power system, it is required to find any data on the berthing directions of the vessels. Approximations of vessels that berth with the bow out front range from 75% to 95%, which is a large uncertainty. However, the Pilots in the Port of Rotterdam state that when an operational demand arises, such as shore power, the terminal will call for the vessel to berth in the desired position. The expectation is that, when a specific position is required for a shore power connection, in the case of a connection at the aft-ship, the terminal demands this berth position from the vessels. And approximations are that a maximum of 5 to 10% of the vessels are not berthing in this desired position. This can be due to environmental conditions, such as strong tides in which it is hard to turn the vessel when loaded. But, when more tugboats are used, it is almost always possible to berth in a desirable position at the terminal.

The berthing of the liquid bulk vessels is aligned with the cargo manifolds on deck and onshore. The cargo manifold is placed at the midship of the vessels, and thus all liquid bulk vessels align with the terminal with respect to midship [36]. Because the cargo pipelines are often static, and for convenience the vessel is positioned with the manifold in front of the manifold of the terminal side. This vessel positioning is also visible in the Figures 4.2, 4.3, 4.4 and 4.5.

5.3.3. Energy Demand

The energy demand of a vessel is particularly important to design a shore power system which has to satisfy the need for electrical power on a vessel. The energy demand of a vessel can be divided into the electrical energy demand and the fuel energy demand. Both the energy demands for various vesseltypes at berth are found by Stolz [7]. This research presents the demand box plots of the electrical power demand and the boiler energy demand. The energy demands are based on MRV emission report data combined with AIS ship tracking data. The method for extracting the auxiliary engines demand is based on ship emissions. The average auxiliary power is calculated by dividing the reported emissions data by the specific fuel consumption of all energy providers and the emissions factor of the used fuel, MDO. In Equation 5.1 this calculation is shown:

$$\bar{P}_{AE}(s) = \frac{E_{\mathrm{CO_2}}(s)}{(SFC_{AE} + r(c,dwt)SFC_{AB}) \cdot EF_{\mathrm{CO_2}} \cdot t(s,p)} \tag{5.1}$$

The average auxiliary engine demand is a time dependent function of the CO_2 emissions, the specific fuel consumption of the AE and AB considered MDO, which are constant of 225 g/kwh and 305 g/kWh respectively and the constant emission factor for CO_2 of 3.206 g CO_2 per g MDO. Stolz also used a ship type specific ratio, r(c,dwt), for the ratio between the AE and the AB, which are set at 2 and 0.7, for oil tankers and chemical/gas/lng carriers respectively.

[4]According to PortXchange expert and Pilots in the Port of Rotterdam

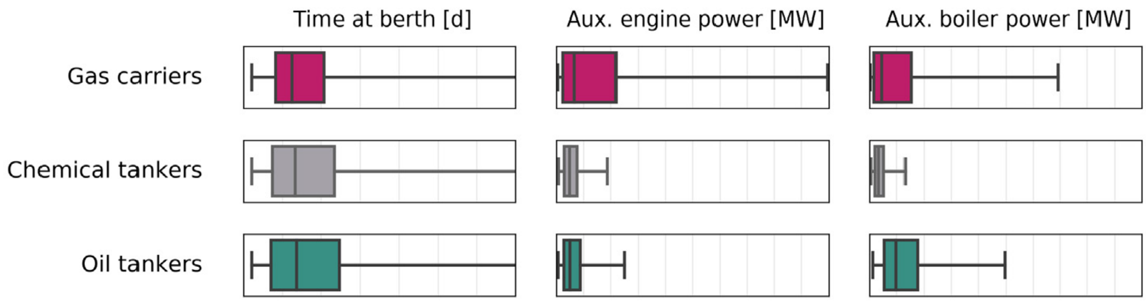

Figure 5.2: Left: Time at berth, Middle: Auxiliary engines power. Right: Auxiliary boiler power. The box plots display the median, interquartile range, and the 95% confidence interval [7]

However, Stolz assumed the yearly average power based on the emissions and the difference in loading or unloading at terminals is not considered for the energy demand. When liquid bulk vessels are berthed, the ships berth operations determine the power demand of the vessel. The maximum energy demand can be estimated by combining the maximum installed electrical power and the electric load profile of the tankers. The typical operations in port during berth of liquid bulk vessels are found on electric load balance sheets of tankers and in guidance documents [45]. The operation in port are shown below.

- Unloading
- Loading
- Tank Cleaning
- Tank Heating or Cooling
- Idle in port

The main differences in the port operations is for the loading and discharging operations, and the other operations could happen simultaneously during loading or unloading. An example of an electric load profile of a oil tanker is shown in Figure 5.3, including load profiles at sea and in port. This gives an indication of the electric load as percentage of the maximum installed electric auxiliary power. As seen in the figure, the maximum electric power is demanded when unloading the vessel and it does not exceed the 60% of the maximum installed electrical power onboard. Due to safety reasons and maintenance routine onboard[5], there is always one auxiliary engine not used, this is also visible in the Figure 5.3. This specific tanker has three auxiliary engines, and the maximum electric load does not exceed two third of the maximum installed electric power.

[5] As stated by former master and engineer of liquid bulk vessels

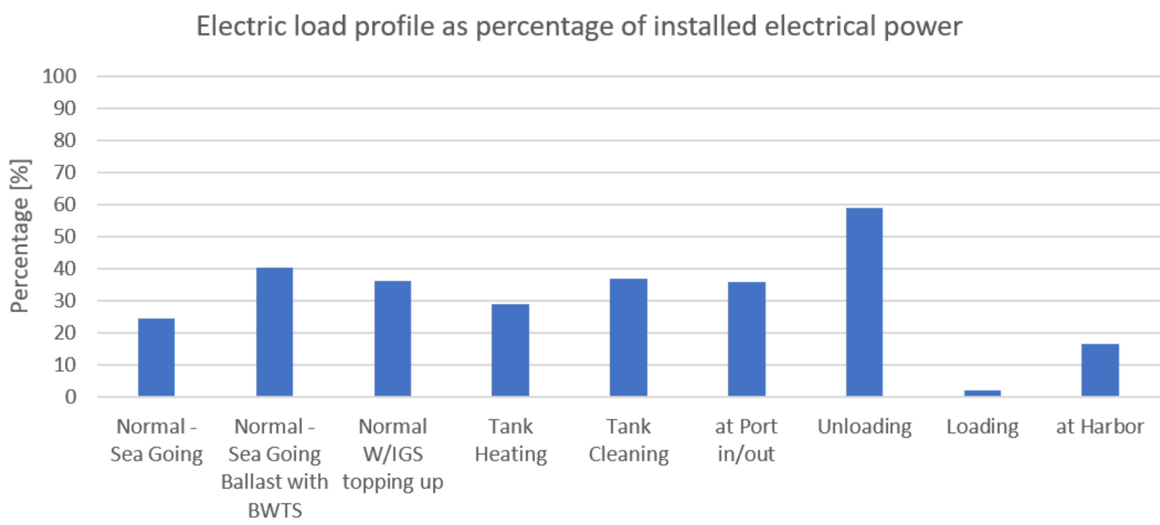

Figure 5.3: Electric load of Suezmax oil tanker as percentage of installed electrical power

Calculating Energy Demand

To include the type of operation of the vessel, the power is calculated combining the installed power of a vesseltype and an assigned load factor for either discharging or loading operations. The range of electrical power that is installed onboard is different for each vessel-type, even for each sub-type of vessels. In Appendix A the boxplots of the installed electrical power onboard of the different subtypes of tankers are shown. For each of the subtypes of vessels that has been defined in this thesis the electrical installed power is determined at the median of the boxplot data. This would give the best estimation of the installed power of a typical vessel which fits inside the deadweight subtype. The constant load factor for determining the power used for loading or discharging, is based on the electric load analyses such as seen in Figure 5.3, and are shown in Table A.1. To find the the at berth power of a ship during an loading or discharging operation, Equation 5.2 is used.

$$P_{ship,n} = lf_{ship,n} * PI_{AE,ship}\ [MW] \tag{5.2}$$

$P_{ship,n}$ = The electrical power demand during operations of operation n [MW]
$lf_{ship,n}$ = Constant load factor of ship and operation n, as specified in TableA.1 [-]
$PI_{AE,ship}$ = Installed electrical auxiliary power median per shiptype, as shown in Figure A.2 [MW]

The electrical power demand of a vessel is therefore only dependent on the installed electrical power onboard of the vessel, and a constant loading factor for either a loading or discharging operation. The systems that do not require electrical energy, such as an auxiliary boiler, are not taken into account in electric load analyses. Auxiliary boilers are used used for generating steam to heat the cargo and power the cargo pumps during unloading, while flue gas from the boiler is scrubbed and used for inerting the cargo tanks [44, 45]. Therefore, the total energy load of a liquid bulk vessel is dependent of the electrical required power and the steam/hydraulic required power.

5.4. Terminals

This section gives a brief overview of the liquid bulk terminals where the liquid bulk vessels load or discharge the cargo. Terminals are designed to transship the cargo from the vessels towards pipelines or to load the vessel from the shore. For the terminals it is important to get insight into the power demand of the vessels at the terminal and the lay-out of the jetties or quay walls.

5.4.1. Visiting fleet

In order to gain insight in the visiting fleet the historical visit data of the terminals in Rotterdam is analysed. For the period of 2011 - 2020, all vessel visits are recorded for each terminal in Rotterdam. Because it would be too much work to combine every individual vessel visit with corresponding vessel data of the specific vessel, the vessels are segmented. Therefore, the vessel visiting data is combined with the specified vesseltype segmentation as presented in Table 5.3. For the terminals, the visiting vessels are divided into the vesselgroups with corresponding energy demands and other operational data.

5.4.2. Lay-out

The lay-out of terminals varies for each specific terminal, as seen in Figure 4.2, 4.3, 4.4 and 4.5. With the variety of terminal designs it is unable to assign a general lay-out for all terminals. Therefore, when assessing the terminals in Rotterdam for shore power systems, the terminal specific layout is used as input.

5.5. Conclusion

To conclude, this section describes the different liquid bulk vessels, which are categorised in 14 subtypes based on deadweight and cargo, which represented at least 95% of the vessels. The found subtypes are shown in Table 5.1. For the subtypes, the typical yearly port visits are estimated based on expert interview and typical voyages, which are shown in Table 5.4.

The berthing strategies of liquid bulk vessels are discussed as well and a vessel will berth in a specific position if an occurring operational demand for berthing occurs. However, there are always situations where the preferred berth is not safe or not desirable, e.g. strong tides. The chance of not berthing in the desired direction is approximated at a maximum of 10%.

The energy demand is calculated as function of the installed power of each vesseltype and a load factor. The installed power is obtained per vesseltype as the total installed electrical auxiliary power and the load factor is based on electrical load balance sheets.

The power demand at the terminals is dependent on the historical vessel visiting data in Rotterdam combined with the vesselgroups data. And the terminal characteristics are to be determined per terminal.

6

Technology Assessment

This chapter discusses all relevant technology that could be part of the shore power systems for liquid bulk vessels. The technology assessment aims to find the technology that is available or new concepts to design a shore power system. The focus on the technology assessment for shore power for tankers is the cable management system of a shore power installation. The found concepts will be briefly reviewed based on criteria and evaluated in a performance matrix.

First, in Section 6.1 the procedure of finding technologies that can be part of the technological solution for shore power is explained. Secondly, in Section 6.2 the criteria to evaluate the technical feasibility are presented and discussed. In Section 6.3 the cable management system solutions are briefly discussed. Finally, a multi criteria performance analysis is conducted in order to give insights in the scores of technical feasible technology that could be implemented in a shore power system for liquid bulk vessels.

6.1. Find technology

This section will describe the methods for finding technological solutions who can be part of the cable management system of a shore power installation. To determine which technical solutions can be used in shore power installations, both operational experience with shore power systems and literature is reviewed. As described in Chapter 4, the shipboard electrical systems as well as the shoreside electrical systems are not interchangeable for other technologies, but a requirement. The focus of the technology assessment is therefore on the cable management system of the shore power installations.

For finding technology that is able to fulfil the functions of the cable management system, various other shore power projects have been reviewed and meetings with third parties have taken place. Various existing concepts were found and conceptual idead for cable management systems were generated, these technical solutions are reviewed using the criteria for feasibility, which will be discussed in the next section.

The focus on finding technology for the cable management system is on the transporting of the cable and the location of the CMS. The cable storage and the controls of the CMS are out of scope, and it is assumed that the cable will be stored on a cable reel.

6.2. Criteria for feasibility

To assess the feasibility of the various technologies for a shore power system, multiple criteria are defined. These criteria will be used to evaluate the feasibility of the technology that is available for shore power systems or that is still in conceptual phase. Other concept development studies used the compatibility and TRL for evaluating the technological solutions, these two criteria are suitable for this evaluation as well [63].

In literature, various criteria are found for evaluating technology concepts for a system, also during meetings with third-parties regarding shore power systems some criteria were discussed. These two sources formed the criteria that are relevant for this feasibility study, which are listed below:

- **Safety**, that a technology must comply with the safety requirements is already mandatory, but this criterion aims for a qualitative analysis of how safe a system is to operate, maybe to analyse possible risks or accidents that could occur. Also the ability to make an emergency disconnection is taken into account here.
- **TRL**, this criterion is to identify in which technological readiness level (TRL) the technology currently is, it ranges from non-proven idea until a full-scale tested system.
- **Easy to use**, this criterion says something about the ease of cooperating with the system. As less manual work is needed, or the systems works without lots of actions, the score is higher.
- **Compatibility**, this criterion states how easy the technology fits into the existing infrastructure onboard or onshore and how easy it is to integrate it with other systems. This criteria is important because it influences the costs of the systems, because hard to integrate systems are often more expensive. For example, a system which needs a new platform installed next to the terminal does not integrate very well in the current infrastructure.

The criteria that are listed above will be assessed on a scale ranging from 1 to 5, with 1 as lowest and 5 as highest. However, the TRL scale is generally scaled from 1 to 9, therefore it will be scaled from 1 to 9 as well in this assessment.

6.3. Cable management systems

This section describes the different technical solutions for the Cable Management System of the shore power system for liquid bulk vessels. These technical concepts are divided into two groups, first the systems near the midship section are discussed and secondly, the systems near the aftship are reviewed.

6.3.1. Midship - Reel on top

This solution was proposed by the Port of Gothenburg in order to find a technical working solution for liquid bulk vessels in the port. The concept is still under development, but the general working concept is already clear.

The concept is based on the fact that almost all liquid bulk vessels have a hose handling crane in the manifold area. This crane is then used to lift the cable from shore to ship. The cable is stored onshore on a reel inside an inerted 20ft container located on an elevated platform at the jetty. As well as the manifold, the shipboard connection box is located both on the portside and starboard of the vessel, to make sure the vessel can berth both ways. The cable runs is routed over the deck in a closed galvanised cable tray to the aftship, where the breaker and transformer are located.

Safety

This solution is placed in the midship area, which has an ATEX-zoning. This means safety measures must be taken in order to use electrical equipment in that area. If all equipment is either ATEX-certified or in an inerted space, than the safety can be guaranteed. However the CMS is still in an ATEX rated zone, therefore the risk of explosive gases is always present and this creates an additional risk when something of the CMS fails for instance. Also, an emergency disconnection is possible, when this is designed in the cable connection but it is difficult in an ATEX zone.

TRL

The design of this system concept is in an early stage and is done by the Port of Gothenborg. The technology concept is formulated, but as of writing this thesis not yet tested. The concept of inerting a confined space with high voltage cables on a reel as well as the connection box, is currently in a very low technology readiness level.

Easy to use
This system uses the hose handling crane of the ship itself, so this one must be operated by the ships crew. The cable can be picked up from the elevated platform in the manifold area of the terminal without any personnel involved. Onboard the connection must be made within an inerted connection box, this involves manual handling of the cable in the manifold area of the ship. Also, the crane of the ship, might be used for cargo operations as well, and it is a disadvantage as these operations have to wait.

Compatibility
This system requires a structure on the terminal side in the manifold area. For jetty structures this might be difficult as the manifold area is often densely packed with the loading arms and other equipment. The cable reel and enclosed storage is located on a platform about 3 meters above the ground level, which makes is slightly easier to fit on tightly packed jetties. The ship side has a inerted connection box which has to fit in the manifolding area and close to the hose handling crane, for tankers without a flush deck this can be difficult, e.g. LNG tankers. Also the cable must be routed to the aft ship where the breaker and transformer is located, which can be complex as well without a relative flush deck.

6.3.2. Midship - Loading arm

The conceptual idea that was proposed during meetings regarding the CMS workshop in march of using a loading arm for transporting the cable from shore to ship. The cable is either in a similar pipe which is used for cargo transport or in a vapour return line on the outside of the construction. As well as the manifold, the shipboard connection box is located both on the portside and starboard of the vessel, to make sure the vessel can berth both ways. The cable runs is routed over the deck in a closed galvanised cable tray to the aftship, where the breaker and transformer are located.

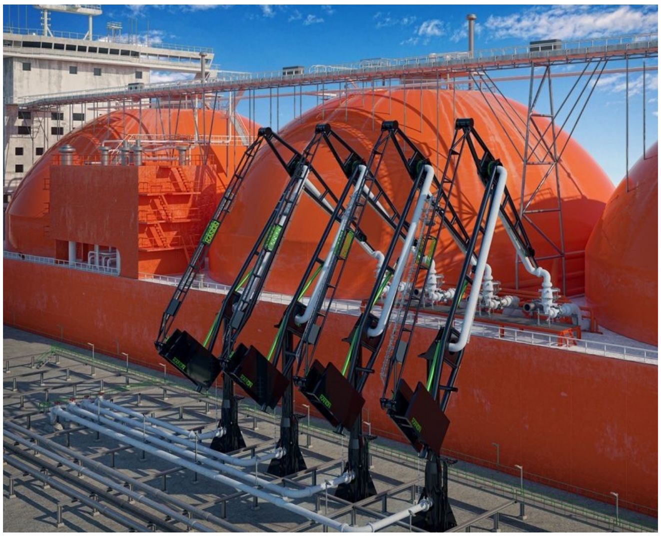

Figure 6.1: Cargo loading arm structure, image from [8]

Safety
This solution is placed in the midship area as well, which has an ATEX-zoning. This means safety measures must be taken in order to use electrical equipment in that area. If all equipment is either ATEX-certified or in an inerted space, than the safety can be guaranteed. However the CMS is still in an ATEX rated zone, therefore the risk of explosive gases is always present and this creates an additional risk when something of the CMS fails for instance. Also, an emergency disconnection is possible, when this is designed in the cable connection but it is difficult in an ATEX zone.

TRL
The use of the loading arm and vapour return line is widely used at liquid bulk terminals, and is therefore TRL 9. Yet the use of the loading arm or vapour return line for shore power cables is new, and must be properly designed. And as this idea is still in the conceptual phase the TRL is 1, because only the basic principles are observed and reported.

Easy to use
This system uses the same working principle as the cargo handling hoses or cargo loading arms, the procedure is therefore not new to the crew of the vessel and the terminal. The connection is made by moving the loading arm towards the receiving point on the vessel, and there the flanges have to be connected. Special attention must be paid to make sure that the connection is done properly and no gases from outside can enter the enclosed piping or hose. The inerting of the hose or pipe also needs to be monitored, as this is an crucial aspect of this solution.

Compatibility
This system requires a rather large structure on the terminal side, because these loading arms require a lot of space on the shoreside. Also the existing loading arms must not be blocked, and since these have a sideways rotation there must be some space in between the loading arms. Often the jetty structures are designed that exactly everything fits on it, so an extra loading arm structure would be too tight to fit. On the vesselside, 2 receiving point have to be installed, either an inerted box or an inerted pipeline. The estimation is that this would not require a lot of space, however this depends of the exact design of the vessel itself. The cable tray from the midship area to the engine room, where the breaker and transformer are located must be integrated on the deck, which will be difficult if the deck is not flush.

6.3.3. Aftship - Floater

The floating concept is based on a floater in the port, which is self propelled and can place itself towards the connection point at the aft of the ship. This conceptual idea was proposed by YaraMarine in a workshop meeting in February, however no further developments have been done. By moving the cable reel to the ship, the shipboard stores crane can pick up the cable with a cable hook. The design of the floater is only in conceptual phase, and is therefore not finished.

Safety
The floating system is floating near the aft of the ship and is self propelled. Because it is located in the water it is outside the hazardous ATEX zones of the vessel and terminal, therefore no satefy restrictions are needed. However another risk is that this floating system could collide with the vessel, and even worse the cable can become entangled with appendages or propeller of the vessel. As the land connected cable must is rather large with a large bending radius, it could form a barrier to freely propel the floater and become a safety hazard.

TRL
The idea of this floating concept was proposed by YaraMarine as an autonomous system, which was scaled down to using the shipboard stores crane. However the concept is not fully worked out and therefore only in in the TRL 1 phase.

Easy to use
When operating this system, the vessels crane at the aft of the ship is used. The cable must be lifted from the floating platform, which can be difficult due to the fact that the cables have to be lifted from an unmanned floating object. The crane must be operated and supervised by someone who looks for the cable. Therefore, the prediction is that it is not easy to use. Unless some sort of gripper makes it more easy to pick up the cables. When transported to the ship the cable must be manually connected to the connection switchboard at the aft of the ship.

Compatibility
The integration in the current lay out of the vessel and port is quite good, because the floating system takes almost no space on the shore side since it is floating. Only for the umbilical cable from the floating buoy to the shore, there should be a little space reserved. And for the vessel, the own crane is used and the electrical equipment that is needed anyway needs to be installed, the breaker, transformer and connection switchboard.

6.3.4. Aftship - Crane and cable reel

This technological concept consits of a crane and cable reel placed onshore, either on the quay or on a platform in case of jetty terminals. This concept is used for cruise vessels and ferries for several years, an example of this concept is shown in Figure 6.2.

Safety

The cable connection is made at the aft of the vessel, thus little to no ATEX related risks are present. Previous shore power systems have been using this system for over years and it is working without any safety risks. Eventually an emergency disconnection is possible, when this is designed in the cable connection. The safety scoring is therefore good.

TRL

The technology is widely used in ferries and cruise vessels. For example, the technology is commercially available by Cavotec etc. and used for the Stenaline ferry in Hoek of Holland [74]. Therefore the technology is not new and tested a lot of times, however near to ATEX zones, some electrical equipment might require additional revisions or needs to be partly redesigned. Therefore, the TRL score of 9 is applicable here.

Easy to use

This system needs a manual handled crane on the shore side, therefore at least one person should operate the crane from the shore. The cable(s) need to be handled when provided to the vessel, at least one person should manually connect the cable(s) coming from the crane.

Compatibility

The solution fits more or less easy on a vessel, since apart from the standard shore power equipment for ships nothing else is needed. The breaker and transformer are mandatory for each shore power system. The connection switchboard is the location where the cable is connected, and not all vessels can be retrofitted that this will fit in the superstructure. For the terminal, there is space needed for the installation of a crane and also the area between the crane and vessel should be clear of any obstructions. In order for the crane to safely transport the cables. When a jetty structure terminal is present, an additional platform should be built to house this crane with the cable reel.

6.3.5. Aftship - Cable reel

The concept of the aftship cable reel is very basic, the cable reel is located on the shore side either on the quay or on a platform. And the shipboard stores crane lifts the cable(s) using a lifting tool. Then the cables are connected on the ship at the connection switchboard. In Figure 6.3 the systems is seen during operation in California.

Safety

The safety scoring is good, since the connection is made at the aft of the vessel little to no ATEX related risks are present. Previous shore power systems have been using this system for over years and it is working without any safety risks. Eventually an emergency disconnection is possible, when this is designed in the cable connection.

TRL

This technology is used in the one operational shore power system for tankers in California. The technology is commercially available at Cavotec and is tested and commissioned for the shore power project in Long Beach, as described in Section 4.5. Therefore, the TRL score of 9 is applicable here.

Easy to use

This system needs a manually handled crane on the vessel, therefore at least one person is needed for the lifting operations. The cable(s) need to be handled when provided to the vessel, at least one person should manually connect the lifting tool with the crane's hook. When the cable(s) is transported to the vessel, it needs to be manually plugged into the connection switchboard. The handling is therefore not very complex, although it involves manual pulling of the cable onboard.

Compatibility

The solution fits more or less easy on a vessel, since apart from the standard shore power equipment for ships only the stores crane is needed, which should be on the vessel itself. If the vessel has a sufficient working stores crane, the use of the vessel crane eliminates the need for a crane on the shore side. The breaker and transformer are mandatory for each shore power system. The connection switchboard is the location where the cable is connected, and not all vessels can be retrofitted that this will fit in the superstructure. For the terminal, there is space needed for the installation of a crane and also the area between the crane and vessel should be clear of any obstructions. In order for the crane to safely transport the cables. When a jetty structure terminal is present, an additional platform should be built to house this crane with the cable reel. For quay walls the system is more compatible than for jetty structures.

Figure 6.2: Aft - crane on shore with integrated cable reel in Hoek van Holland, image from [9]

Figure 6.3: Aft - shore cable reel, the crane lifts the cables towards the onboard cable tray [10]

6.4. Multi criteria performance analysis

This section will perform a multi criteria performance analysis for all the technologies that are found for the cable management system. The results of the technology assessment are shown in the performance matrix in Table 6.1.

Table 6.1: Results of the performance of the different shore power system concepts

	Safety [1-5]	TRL [1-9]	Easy to use [1-5]	Compatibility [1-5]
Midship				
On top container reel	3	2	3	3
Loading arm	3	1	3	3
Aft ship				
Floating solution	3	1	2	4
Shore Crane & Reel	5	9	3	2
Reel on platform	5	9	4	3

As seen in the performance matrix, the midship connections are scoring not very well on the safety and the TRL scale. The aftship concepts using either a shore or onboard crane and cable reel onshore have the overall best scores.

III

Model & Case Results

7
Model Design

This chapter elaborates on the design of the models which are used for the evaluation of the shore power concepts for the vessel and terminal. This chapter follows the first steps of a concept exploration phase, by setting up a model that can assess whether different shore power concepts are feasible or not. The feasibility exploration is based on the economics of shore power systems and the power utilisation.

In section 7.1 the requirements for the model and the simplified synthesis of the model is elaborated. In Section 7.2, the design of the ship model is explained. Thereafter, in Section 7.3 the composition of the terminal model is briefly explained. In Section 7.4, the verification, uncertainties and the sensitivity of both models is elaborated. Thereafter, in Section 7.5, the model scenarios are discussed including the base case and alternative scenarios. Finally, in section 7.6 the conclusion on the model design and scenarios is presented.

7.1. Model Synthesis

This section elaborates on the requirements which form the guidelines of the model and discusses the outlook of the model in general. First, the requirements and guidelines for the model design are presented. And secondly the synthesis of the ship and terminal model is discussed.

The requirements for the model consist of the requirements by the Port of Rotterdam and the resulting requirements from the research scope in Chapter 2. The requirements for the model are briefly described below and form the guidelines for constructing the model, and indicates how the requirements will be implemented in the model. The model requirements are listed below:

- System decision: an input field is created where specific scenarios can be recreated. Such as terminaltypes, terminal layout and physical terminals in the Port of Rotterdam as well. The selected shore power system can be chosen to gain insight in the emissions, economics and constraints that are involved.
- Economical: Model contains databases of different cost factors for realising a shore power system for both the terminal and vessel. It also holds an option for assigning a price for emissions.
- Emissions: Database for emission factors of both the electricity grid in the Netherlands and from MGO in an auxiliary engine expressed in grams/kWh. The difference in emissions per kWh forms the emissions reduction potential.
- Constraints: a set of constraints through which it becomes possible to assess whether a scenario is feasible or not.
- Applicability: The model must be created in a way that it is transparent and flexible, for example it should be able to use the model for different vessel types and different terminals. Also it should be easy to update newer cost estimations, other emission factors or other possible shore power

technology. The output must generate a total amount of emissions saved during a scenario and the costs per kWh shore power must be presented.

7.1.1. Outlook of the models

For the synthesis of the model, the decision of two separate models is made because the terminal and vessel both have different ways of operating and different technical parameters which must be separated. The general outlook of the model is presented in Figure 7.1, for the ship model as well as the terminal model. This simplified model outlook shows which parameters are important for both models in red and which determines the economic and utilisation outcome of the models. First, the ship model synthesis will be briefly discussed and thereafter the terminal will be shortly summarised.

The ship model is based upon the investment and operational expenses for a shipside shore power system, which have to be paid back by the lower costs of electricity per kWh. This can only be the case, if the electricity is sold at a lower cost per kWh compared to using MGO for electricity generation on board. The ship model is based upon the fact that it makes a economical consideration whether the system will payback within the lifetime of the system, which is 20 years. The system total costs of owner ship must be earned back by making profit with using electricity from shore instead of fuel for the diesel generators. It is therefore important what the MGO price is and what the electricity selling price at the terminal is. Also, the ship is modelled with a shore power system of choice installed and the shore power utilisation depends on the amount of shore power port visits. Since the exact visits for large groups of tankers are not known, the amount of SP port visits are an input value, and the estimated yearly port visits per shiptype form the top boundary for this value. With the amount of shore power used, the yearly emission reduction is estimated, using the emission factors. The parameters and calculations will be further discussed in Section 7.2.

The terminal model is based upon the investment and operational expenses the terminal makes, which have to be paid back by selling electricity to the ships. The amount of electricity that can be sold, depends on the ships that visit the terminal, if these ships are shore power ready and if the chosen shore power system can cover all vessels in terms of usage. The historical ship visits of the terminals in Rotterdam have been used to generate a historical visiting profile for each terminal. And by using this data, the energy demand can be calculated and the fleet coverage for each system can be determined. The parameters and calculation of the terminal model are further discussed in Section 7.3.

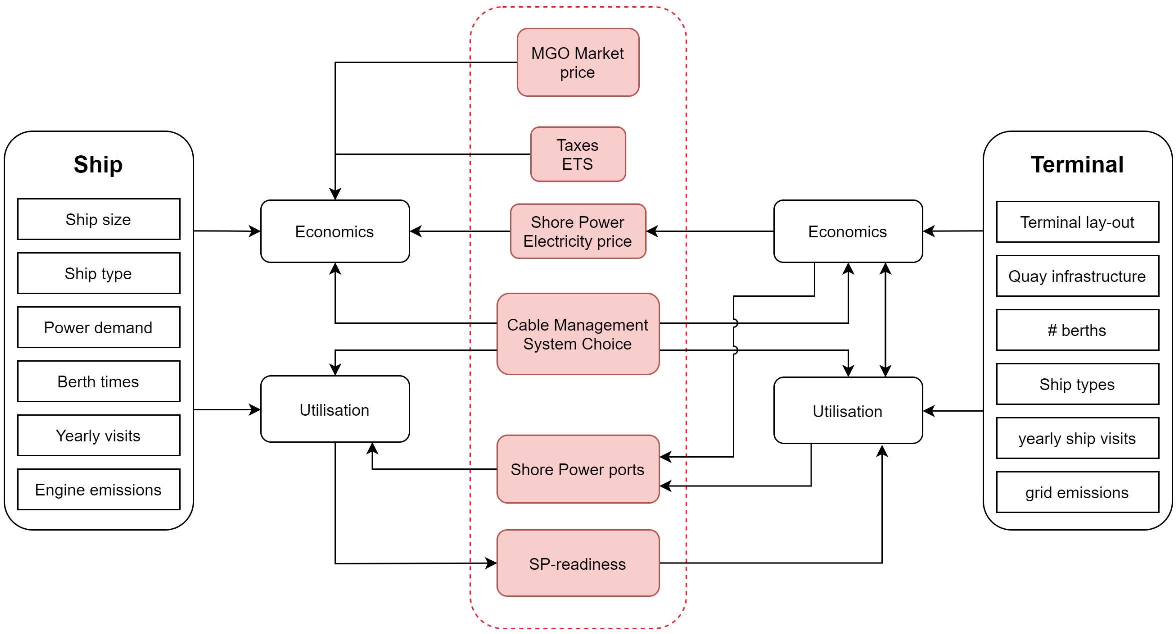

Figure 7.1: Simplified overview of the ship model and shore model

7.2. Ship model

This section aims to provide a structured overview of the design of the ship model. The ship model uses an input page, which contain the input parameters as shown in the first subsection. Thereafter, the calculation of the economical factors and shore power usage is elaborated. Then, the power demand calculations are explained. Finally, the output of the model is presented where the LCOE and profit are shown.

7.2.1. Input parameters

The input parameters for the ship model are listed in the Table 7.1.

Table 7.1: Input parameter for the Ship model

Parameter	Unit	Range of input
General parameters		
Shore Power System	-	Mid - On top / Mid - loading arm / aft - floating buoy / aft - Crane and reel / aft - cable reel
System lifetime	years	15-20 [54]
Interest rate	%	4-8 [51]
Electricity Mix Year	-	2020/2030/2050/Green [13]
Vessel parameters		
Cargotype	-	Oil/Gas/Chemical/Special
Sizetype	-	
Cranes available	-	Yes/no
Newbuild	-	Newbuild/retrofit
Cost parameters		
MGO price	€/ton	200 - 700 [47]
Electricity price	€/MWh	70 - 200 Depends on price terminal [48]
Bunker levy	€/ton fuel	0 - 150 [75]
ETS	€/ton CO2	0- 100 [75] (2030 Forecast is up to 90 €/ton for EU ETS)

7.2.2. Ship costs

The shore power system costs for the ship consists of the investment costs and the operational costs following the LCC method [51]. First, the capital costs are discussed and thereafter the operational expenses. The costs are estimated by assessing different literature, estimations from other companies and estimations from the Port of Rotterdam.

Total Capital Costs

The costs for the installation of a shore power system is based upon the costs for standard shore power equipment that is required and the costs for a specific CMS. The standard shore power equipment consist of a transformer, breaker and adjustments on the electrical equipment. The Total capital cost of ownership is shown in Equation 7.1, and is expresses in euro. The annualised costs are calculated with Equation 7.2.

$$TCC = C_{breaker}(P_{ship,1}) + C_{trafo}(P_{ship,1}) + C_{adjust} + C_{CMS,x} \qquad [€] \tag{7.1}$$

where,

TCC = Total capital expenses [€]
$C_{breaker}$ = Costs for onboard breaker as function of maximum discharge power [€]
C_{trafo} = Costs for onboard transformer as function of maximum discharge power [€]
C_{adjust} = Costs for adjustment of ship switchboard in order to use shore power [€]
C_{CMS} = Costs of all compartments of the CMS as specified in Appendix C [€]

$$C_{cap,a} = \frac{TCC * CRF}{T} \qquad [€/yr] \tag{7.2}$$

where,

$C_{cap,a}$ = annualised value of the total capital cost [€]
CRF = Capital Recovery Factor as function of interest rate of investment [51] [-]
T = Lifetime of the system [years]

Operational expenses

The operational expenses include the maintenance costs of the shore power system, the fixed costs per shore power connection in the port and the saved costs of reduced auxiliary engine usage. The cost of maintenance for the shore power systems is rather low according to studies [54]. The total cost of operating and maintaining a shore power system onboard of a vessel is estimated at 1000 €/year. The direct costs per call are estimated at €100 [59]. The estimation of the engine maintenance is found at 1,80 €/hr of operating the auxiliary engine [54]. Other maintenance estimations by TNO are dependent of the exact engine power, which is in the same order of magnitude as the estimation by Green Cruise Port.

Table 7.2: Operational expenses for the ship

Expense	Value	Frequency	Source
Visits based costs	€100	per use	[59]
Maintenance SP-system	€1,000	per year	[54]
Reduced AE maintenance	€ -1.80	per engine hour	[54]

In Equation 7.3, the equation for calculating the yearly operations and maintenance costs is shown.

$$C_{OM} = C_{call} * \sum_{n=1}^{2} ops_n + C_{m,SP} - C_{m,AE} * n_e * t_{berth,ship} \sum_{n=1}^{2} ops_n \qquad [€/yr] \tag{7.3}$$

where,

C_{OM} = yearly costs of operations and maintenance of shore power system onboard [€/yr]
C_{call} = costs per shore power call [€]
ops_n = The yearly amount of operation n, where n is either discharging or loading [-]
$C_{m,SP}$ = Yearly maintenance costs of a shore power system onboard [€/yr]
$C_{m,AE}$ = Engine maintenance costs per running hour [€/hr]
n_e = Amount of engines which runs during port operations [-]
$t_{berth,ship}$ = The historical average of time at berth in Rotterdam of vesseltype $ship$ [hr]

Fuel prices

From an economical point of view, the shore power prices are compared to the fuel price for the ship's auxiliary engines. For converting the fuel price from €/ton to €/MWh the specific fuel consumption of the engine and the efficiency of the diesel generator set is needed. The fuel cost (C_{fuel}) is expressed in [€/MWh].

$$C_{fuel} = price_{fuel} * \frac{\frac{SFC_{AE}}{1{,}000}}{\eta_{gen}} \qquad [€/MWh] \tag{7.4}$$

(7.5)

The resulting profit from the use of shore power is calculated by subtracting the shore power price from the higher fuel price. By using shore power as electricity supplier rather than running the diesel engines, a profit can be made if the shore power has a lower price per MWh than MGO.

$$Revenue = C_{fuel} - C_{SP} \qquad [€/MWh] \tag{7.6}$$

7.2.3. Ship shore power usage

The shore power usage is a function of the amount of SP-ports that the ship visits in a year, the port operation, the average power demand per operation, the average berth time and the connection time of the shore power system. In Equation 7.7, the yearly shore power usage is calculated. The electrical power demand is split up into an average loading and discharging value, which is then multiplied with the amount of loading operations and discharging operations per year. The ops_n indicates the amount loading or discharging operations in a port with shore power, thus the operations in ports without shore power are not considered in this equation.

$$P_{SP,ship} = \sum_{n=1}^{2} P_{ship,n} * ops_{n,ship} * (t_{berth,ship} - 2 * t_c(x)) * b_d \qquad [MWh/yr] \tag{7.7}$$

where,

$P_{SP,ship}$ = The ships total yearly shore power demand [MWh/yr]
$P_{ship,n}$ = The electrical power demand of operation n [MW]
$ops_{n,ship}$ = The yearly amount of operation n of a ship [-]
$t_{berth,ship}$ = The historical average of time at berth in Rotterdam of vesseltype i [hr]
$t_c(x)$ = The estimated time for connecting shore power system x [hr]
b_d = Berthing direction factor, ranges from 0 to 1 [-][1]

Emissions

The yearly emission abatement is calculated by multiplying the difference in emission factors with the yearly shore power demand of the vessel, $P_{SP,ship}$. The emission factors difference is calculated by subtracting the emission factors from the electricity grid from the MGO emission factors from an auxiliary engine [7]. The emission abatement calculation is shown in Equation 7.8. Both the emission factors for the pollutants can be found in Table 5.2 and Table 4.2.

$$ER_p = P_{SP,ship} * (EF_{p,AE} - EF_{p,SP}) \qquad [ton] \tag{7.8}$$

where,

ER_p = The yearly emission reduction of pollutant p [ton/year]
$EF_{p,AE}$ = The MGO emission factor of an Auxiliary engine for pollutant p [g/kWh]
$EF_{p,SP}$ = The electricity grid emission factor in the Netherlands for pollutant p [g/kWh]

7.2.4. Ship output

The output of the ship model presents the resulting LCOE of the shore power installation for a specific ship as well as the total demand of shore power using a selected shore power system. The amount of shore power used can thereafter be expressed in reduced emissions.

LCOE

The LCOE is calculated using Equation 7.9. However to calculate the resulting LCOE, the profit per amount of power is calculated. The profit is thereafter calculated by subtracting the LCOE from the revenue from using electricity, and is calculated in €/MWh as shown in Equation 7.10.

$$LCOE = \frac{C_{cap,a} + C_{OM}}{P_{total,a}} \quad [€/MWh] \tag{7.9}$$

$$Profit = Revenue - LCOE \quad [€/MWh] \tag{7.10}$$

The output table is shown in Figure 7.2 and shows the LCOE of the chosen CMS concept, the revenue of the electricity price vs the MGO price and the resulting profit.

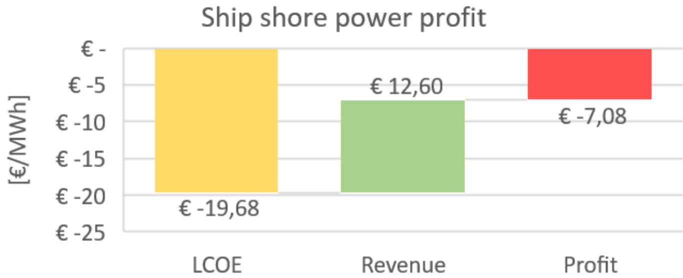

Figure 7.2: Economical output graph with LCOE, revenue of using SP and profit

Shore power demand and emission abatement

The yearly shore power demand of the vessel in the ports is calculated using Equation 7.7. The output visualisation for the amount of shore power used per year is shown in Figure 7.3. The emission abatement at berth for the vessel is shown in Figure 7.4.

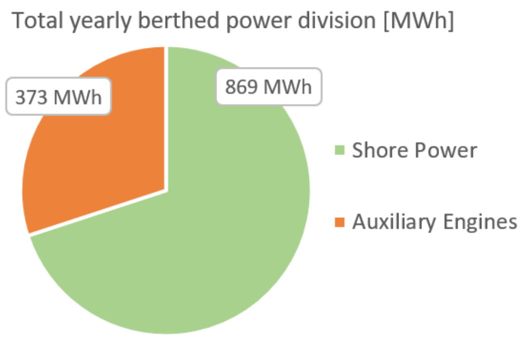

Figure 7.3: At berth shore power utilisation of the vessel

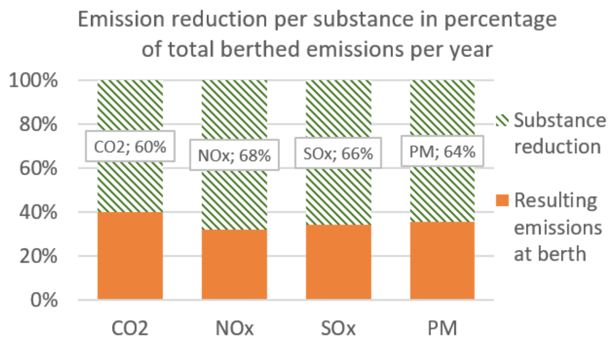

Figure 7.4: Total emission abatement of the vessel using shore power

7.3. Terminal model

This section describes the synthesis of the terminal model. First, the input of the model is discussed. Secondly, the economical assessment equations are presented and thereafter the power demand equations.

7.3.1. Input

The input for the terminal model is based upon the terminal parameters and electrical parameters. The terminal parameters define for which terminal the model is used together with technical and operational characteristics of the terminal. The electrical parameters define the design power of the shore power system and the shore power readiness of the ships.

Table 7.3: Input parameter for the Terminal model

Parameter	Unit	Range of input
Terminal parameters		
Terminal	-	Specify the terminal at the Port of Rotterdam
Amount of (desired) SP-berths	-	1 - #Berths at terminal
Jetty terminal	-	Yes/no
Free space near manifold	-	Yes/no/not sure
Shore Power System	-	Mid - On top / Mid - loading arm / Aft - floating buoy / Aft - Crane and reel / Aft - cable reel
System lifetime	years	15 - 25
Electrical parameters		
Installed power of SP installation (P_{inst})	MW	1 - 20MW
Shore power readiness ships	-	0 - 1
Electricity Mix Year	-	2020 / 2030 / 2050 / Green
Shore power price	€/MWh	70 - 200

7.3.2. Terminal costs

TCC

The Total Capital Cost (TCC) of the terminal shore power installation is a function of the installed power, the jetty structure, lay-out of the terminal and the amount of cable management systems installed. The total capital cost is calculated in euro in Equation 7.11.

$$TCC = C_{grid}(P_{inst}) + C_{Ehouse}(P_{inst}) + C_{Cables} + C_{CMS,x} + C_{Eng}(TCC) \tag{7.11}$$

where,

TCC = Total Capital Cost [MWh/yr]
C_{grid} = Costs of a connection to the HV-grid [€]
C_{Ehouse} = Costs of the Ehouse with transformers and frequency converter [€]
C_{Cables} = Costs of the HV cables, to quays and Ehouse [€]
$C_{CMS,x}$ = Costs of CMS system x, as specified in Appendix D [€]
C_{Eng} = Engineering cost as function of MW and total costs [€]

The TCC is divided by the amount of years in which the systems is depreciated, and multiplied by the Capital Recovery Factor [51]. This results in the annualised value of the total capital cost as shown in Equation 7.2, which also applies for the ship model.

Operational expenses

The operational expenses of the terminal are shown in Table 7.4, and consist of the maintenance of the installation and the yearly electricity transport costs. The transport costs are a function of the total installed power, and the monthly maximum power use. The costs per call are directly charged to the vessel who is using the shore power system.

The value of $P_{max,m}$ (MW) is important, because it depends on the maximum power utilisation. The maximum monthly power usage costs are paid for the maximum demanded power when demanded for at least 10 minutes per month. Thus when two rather large SP-ready vessels berth at the same time, the power output to these vessels is higher than when two small SP-ready vessels are berthing at the same time. To illustrate the problem, Figure 7.5 shows the simplified power demand over time of berthed vessels.

Table 7.4: Terminal operational expenses for shore power systems

Expense	**Value**	**Frequency**	**Source**
Shore Ehouse	2000	per year	[59]
Shore CMS	2000	per year	[59]
Fixed Transport costs	2,760	€/year	Stedin [76]
Installed power transport costs	23,000	€/MW/year	Stedin [76]
Max power usage transport costs	2460*$\sum_{m=1}^{12} P_{max,m}$	€/year	Stedin [76]

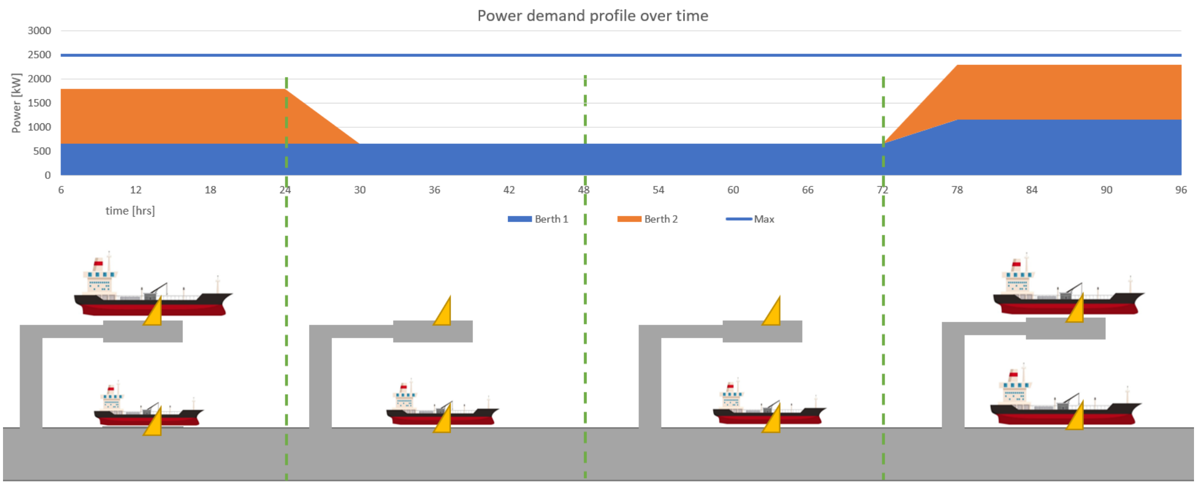

Figure 7.5: The simplified average power demand illustrated over 4 days, with each day different vessels in size and numbers (own figure)

To simulate this max power demand in a month in the model, it uses maximum power scenarios which is based on the amount of shore power vessels and the maximum power demand of the visiting vessels at the terminal. In the model, four scenarios are set up, high, mid, low and minimal. As seen in Figure 7.5, the maximum installed power is not always required, especially not when the event of two large vessels almost never occurs.

Table 7.5: Maximum monthly power usage scenarios

Scenario	100%	75%	50%	25%
High	8	4	0	0
Mid	2	8	2	0
Low	0	4	8	0
Minimal	0	0	6	6

7.3.3. Terminal total power demand

The total power demand of all the vessels that are visiting a specific terminal is determined by the amount of visits, average power demand, average berth time and estimated connection time. The amount of visits are separated into the loading and discharging visits per type of vessel, because in the operational analysis it was found that the type of operations affects the ship's average power demand. Therefore, the power demand per vesseltype is also separated into loading and discharging power demand. The equation for determining the yearly total power demand of all visiting vessels at a terminal is shown in Equation 7.12.

$$P_{total} = \sum_{n=1}^{2} \sum_{ship=1}^{14} ops_{ship,n} * P_{n,ship} * (t_{berth,ship} - 2 * t_c(x)) \ [MWh/yr] \tag{7.12}$$

where,

P_{total} = The total yearly electrical power demand from all visiting vessels[MWh/yr]
$ops_{ship,n}$ = The yearly amount of operation n of vesseltype $ship$ [-]
$P_{n,ship}$ = The electrical power demand during operation n of vesseltype $ship$ [MW]
$t_{berth,ship}$ = The historical average of time at berth in Rotterdam of vesseltype $ship$ [hr]
$t_c(x)$ = The estimated time for connecting shore power system x [hr]

The amount of loading and discharging operations are found by analysing the historical visit data from the Port of Rotterdam. This data set contained all the liquid bulk ships that visited the port, segmented by the terminals and cargoes. The loading and discharging power demand per type of vessel are estimated in Chapter 5. The berth times are estimated by taking the average berth time of a vesseltype, using the berth time data from the Port of Rotterdam from 2019 and 2020. For the average berth times per vessel type, no distinction in loading and unloading was possible. The connection time are determined for each shore power system and it is assumed that the disconnection takes as long as the connection, therefore it must be subtracted twice.

System Power Utilisation
The shore power utilisation of the chosen shore power system is calculated by multiplying the total terminal power demand with the shore power readiness factor of the vessels and the fleet coverage factor of the CMS concept as seen in Equation 7.13

$$P_{SP-sys} = P_{total} * R_{f,SP} * Cof_{SP} \ [MWh/yr] \tag{7.13}$$

where,

P_{SP-sys} = The yearly power that the Shore Power system delivers
$R_{f,SP}$ = Shore power Readiness of the fleet that visits the terminal
$Cof_{f,SP}$ = The fleet coverage of the shore power system

Fleet coverage
The fleet coverage of a shore power system defines the percentage of ships that can theoretically be provided with shore power, assuming the ship is operating the same shore power system. For the midship and floating shore power systems it is assumed that their fleet coverage is 100%, thus regardless of what vessel is visiting. However, the aftship systems have the disadvantage of a fixed crane length, which reduces the fleet coverage of the system since some CMS systems are out of reach of the crane. To calculate the fleet coverage for these aftship systems, the following equation is used:

$$Cof_{SP} = \frac{\sum P_{x=x_{optimal}}}{P_{total}} * b_d \qquad [-] \tag{7.14}$$

where,

Cof_{SP} = The fleet coverage of the shore power system [-]
$P_{x=x_{optimal}}$ = Shore power demand from ships with CMS in range of the used crane or reel [MWh/year]
b_d = Berthing direction factor, ranges from 0 to 1 [-][2]

The optimal power demand that a CMS system can deliver depends on the placement of the fixed crane. In the case of a cable management system located in the manifold area, the optimal power demand is the same as the total power demand, thus a factor of 1.

Installed power

In order to calculate the operational and investment costs, the total installed electrical power of the shore power system must be determined. This is done using the weighted average power demand of the visiting vessel fleet, as shown in Equation 7.15.

$$P_{inst} = \#CMS * \frac{\sum_{ship=1}^{14} \sum_{n=1}^{2} P_{ship,n} * ops_{n,ship}}{\sum_{ship=1}^{14} (ops_{loa,ship} + ops_{dis,ship})} \tag{7.15}$$

Calculating the installed power with the weighted average, reduced the total installed power and lowers the line as shown in Figure 7.5. The method of weighted average, ensures that the installed power is not determined by only a few large vessels. But, it estimates a installed power that is more tailored to the majority of visiting vessels at a terminal. And by using the weighted average estimation of the installed power instead of the largest vessel power demand times the amount of berths, the installed power is reduced. The reduction of installed power, also reduces the electrical equipment costs and the electrical transports costs which are both dependent on the installed power. Yet, this could lead to a specific situation where each berth location has the largest vessel visited. In that specific case, the shore power installation is not able to power all the ships, if and only if all vessels demand shore power as well.

LCOE and profit

The levelised cost of energy for the terminal is calculated using Equation 7.16, with the purchase price of electricity included (C_{elec}).

$$LCOE_{terminal} = \frac{C_{cap,a} + C_{OM,a}}{P_{SP-sys}} + C_{elec} \qquad [€/MWh] \tag{7.16}$$

The profit of shore power systems is determined as shown in Equation 7.17

$$Profit = Price_{SP} - LCOE_{terminal} \qquad [€/MWh] \tag{7.17}$$

7.3.4. Output

The output of the model presents the resulting LCOE of the shore power installation for a specific terminal as well as the total amount of shore power that can be delivered to the vessel using a selected shore power system. The amount of shore power used can thereafter be expressed in reduced emissions.

LCOE

The resulting LCOE is calculated by subtracting the annualised yearly costs included with the electricity purchase price from the shore power sales sales, and is calculated in €/MWh. The output table is shown in Figure 7.6.

Shore power delivered

The amount of shore power that is provided to the vessels in a year is expressed in MWh per year. This is calculated using Equation 7.13. The output for the amount of shore power per year is shown in Figure 7.7 and in Figure 7.8 the top visiting vessels of the terminal are shown.

[2] According to port pilots, as discussed in Chapter 5

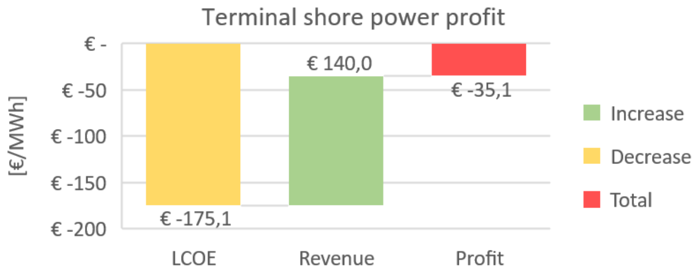

Figure 7.6: Economical output graph with LCOE, revenue of SP sales and profit

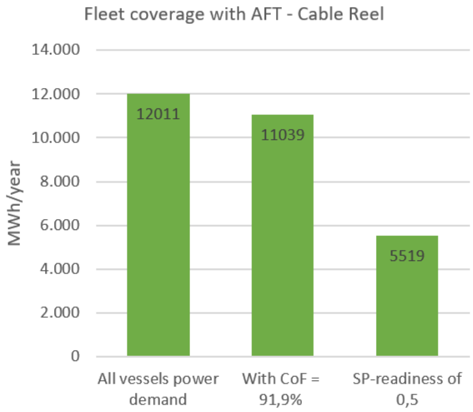

Figure 7.7: Fleet coverage and SP-readiness for the shore power system

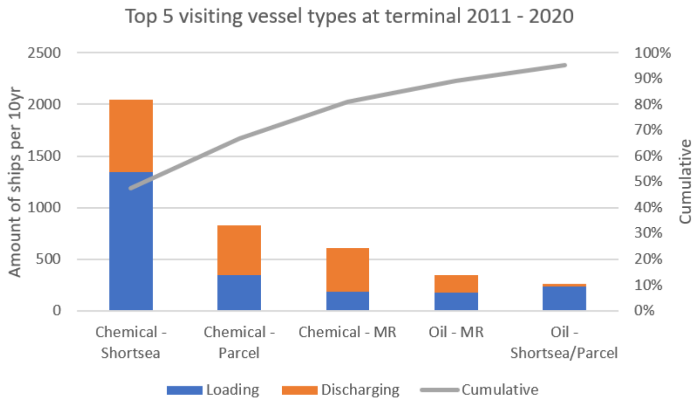

Figure 7.8: Terminal top visiting ships output figure from the dashboard

Limitations of CMS

The insights in limitations of each shore power concept are one of the outputs of the terminal model. Midship located systems have the advantage of a fleet coverage factor of 1, because all vessels can be reached with the midship crane or loading arm. However, for an aftship located terminal crane, the limitation is shown by a graphical representation of the ships and the crane outer limits. This is shown in Figure 7.9, which shows the ships from midship to aft as simplified bars.

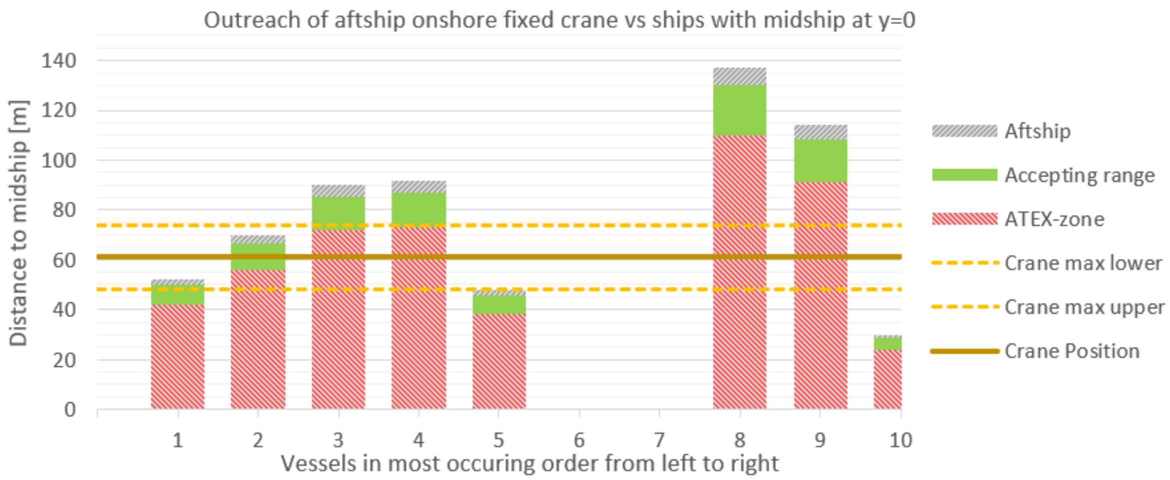

Figure 7.9: Graphical representation of the terminal crane outreach limit, for a optimised crane position

7.4. Model verification & sensitivity

This section focuses on the verification of the models and discusses the uncertainties of the models. For both the models the verification of the equations is performed to assure that the equations are implemented as described in this chapter. An detailed verification of the models is given in Appendix B.

7.4.1. Uncertainties sensitivity

The model uses some approximated or interpolated values for parameters for which no value could be found in literature or in databases. These approximations were made using different sources, such as literature regarding a similar subject or an experts view on the subject. The model is therefore not an description of the real world, but an description with assumptions.

The connection times for the different CMS concepts are estimated based on the easy to use score of the concepts. To see whether the model is sensitive to changing the connection times of the various concepts, the power demand sensitivity for the connection time is shown for the terminal in Figure 7.11 and for the ship in Figure 7.10. It shows that the power demand sensitivity for the connection time changes is rather small.

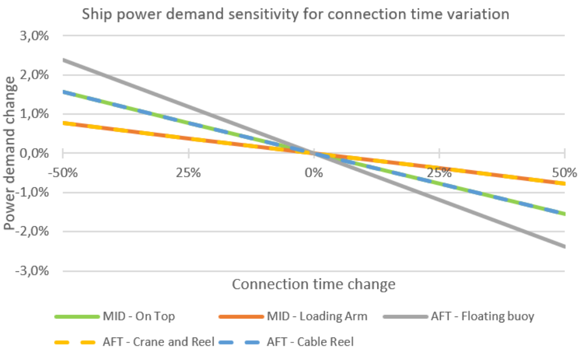

Figure 7.10: Power demand sensitivity for the CMS concepts connection times for the ships

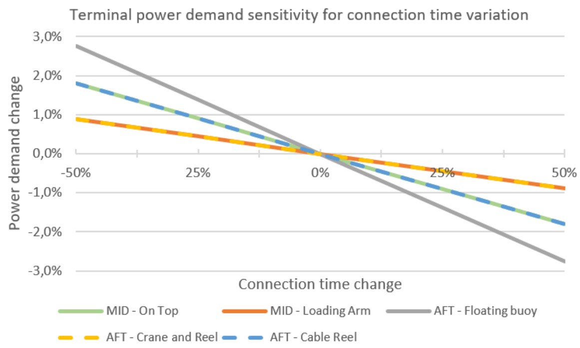

Figure 7.11: Power demand sensitivity for the CMS concepts connection times for the terminals

The berth direction factor (b_d), which defines the chance of a ship berthing in the desired position for a shore power system, is assumed after meetings with experts between 0.9 and 0.95. The influence of the berth direction factor is shown in Figure 7.12 for the ship, and in Figure 7.12 for the terminal. When this parameters reduces, due to various reasons, the LCOE of the two fixed aft systems is increased. And below 0.8, the ship LCOE of the aft crane and reel concept is larger than the midship concepts. For the terminal, the LCOE is becoming much larger below a b_d factor of 0.8.

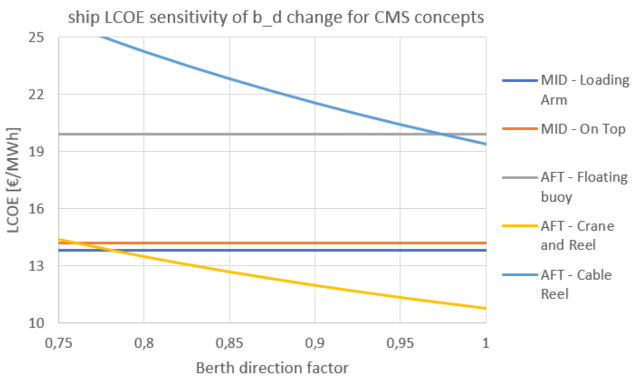

Figure 7.12: Power demand sensitivity for the CMS concepts berth direction factor for the terminals

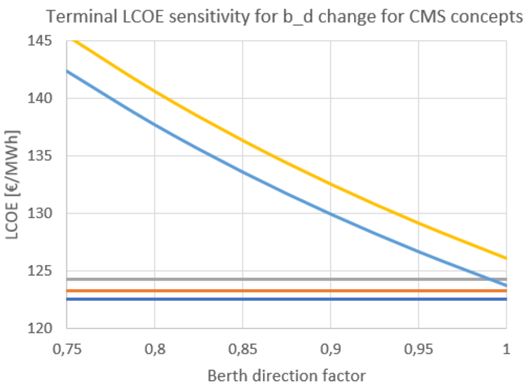

Figure 7.13: Power demand sensitivity for the CMS concepts berth direction factor for the ships

7.4.2. Sensitivity

In this section the sensitivity of the output will be discussed, in order to obtain an overview for which parameters the ship model is sensitive and for which parameters the terminal model is sensitive.

Ship sensitivity

The ships outputs are the costs and the shore power demand. For the financial sensitivity, the MGO price and the shore power price are highly influencing the LCOE of the ship model. As is seen in Figure 7.14, for a vessel with 50% shore power port visits the levelised cost of energy is higher than when 70% of the ports has shore power. The levelised cost of energy is not dependent on the price of fuel, and is therefore constant is this graph. The profit when buying shore power instead of MGO, is increasing with the increasing fuel price. And where the horizontal LCOE lines are crossing the diagonal shore power lines, the investment can be paid back within 20 years.

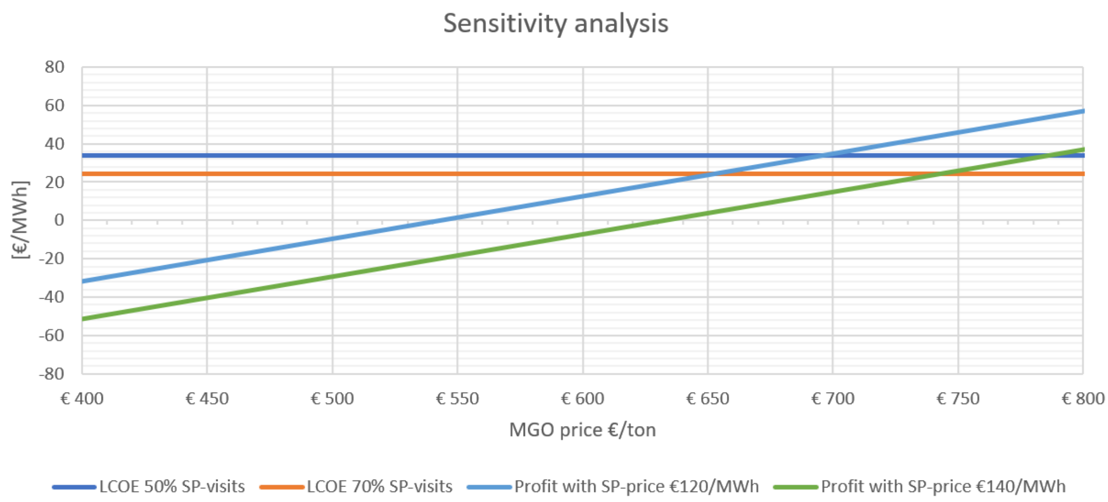

Figure 7.14: Sensitivity of profit of choosing electricity over MGO, as function of MGO, combined with the LCOE for 50% and 70% SP-visits per year

The sensitivity for the power demand of the vessels in the vessel model is shown in Figure 7.15. The power is increased to 150% or decreased to 50% of the original ship's power demand estimate. This variation in power demand only has a large effect when the yearly amount of shore power visits is low. A 20% reduction in power demand at berth, can have really negative consequences if the vessel rarely visits shore power ports in a year. But when the vessel visits a lot of shore power ports, the effects will be less severe. This is because the yearly annualised costs have to be paid back by the total amount of shore power used. The shore power utilisation is highly dependent on the amount of shore power port visits and less on the change in power demand as seen in Equation 7.7.

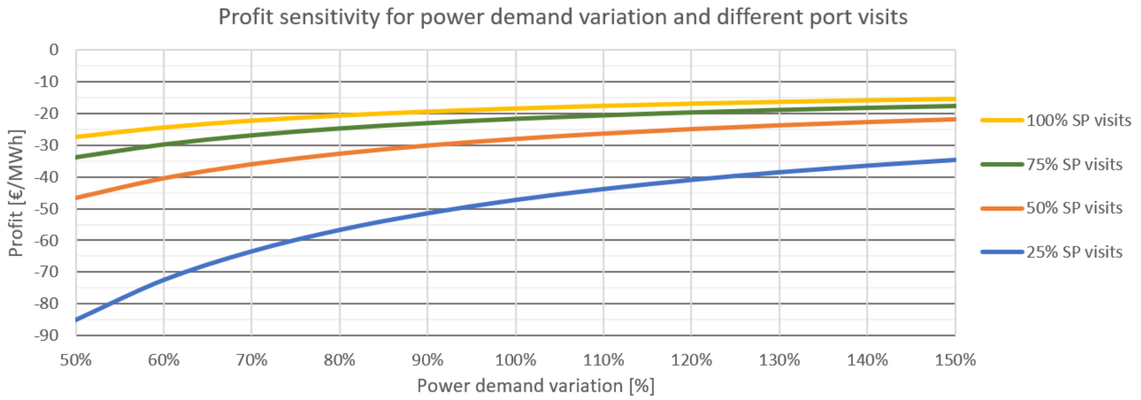

Figure 7.15: Ship sensitivity of profit for power demand variation with 100% as the current power demand, for each SP-visit scenario

Terminal sensitivity

The terminal model is dependent on the ships, with an compatible shore power system, that visit the terminal, also called the shore power readiness of the (visiting) fleet. In Figure 7.16 it is clearly visible that the terminal model is highly dependent on the shore power readiness of the fleet, which is logical because it has influence on the shore power usage.

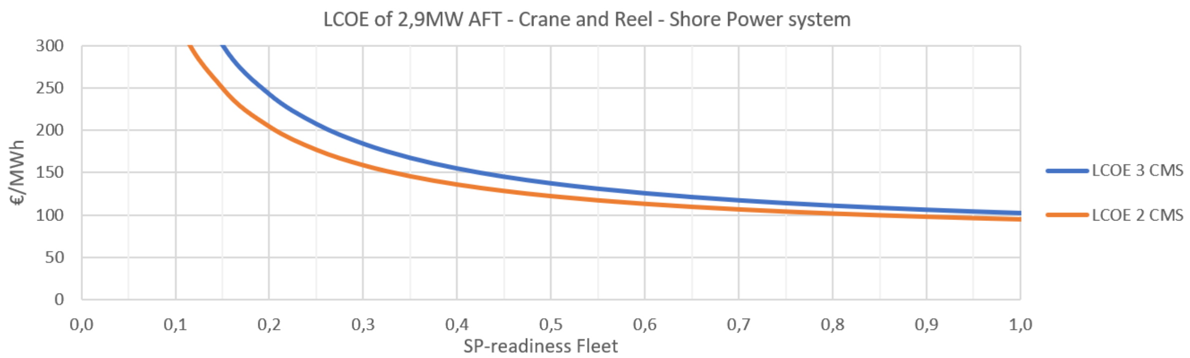

Figure 7.16: Sensitivity of the LCOE as function of the SP-readiness of the fleet and the amount of CMS installed at berth

The terminal pays for the installation and the operational expenses of the installation. The costs for using a fixed amount of power are a large factor of the yearly operational expenses. A shore power installation with a higher installed power, has higher operational expenses. And the amount of operational expenses can either make the business case positive of negative in most cases. Therefore, it is very important to reduce the amount of power installed to a certain amount which can fulfil the power demand of most of the vessels. In Figure 7.17, the installed power of an shore power installation is plotted versus the total capital costs of a system with one to four CMS at berth. As seen in the figure, the costs are gradually increasing before 10 MW and afterwards a more steep curve is observed due to a higher grid connection fee for installations over 10MW. In Figure 7.18, the yearly operational expenses for each utilisation scenario are shown as function of the installed power of the shore power system.

The sensitivity of the levelised cost of energy is shown in Figure 7.19 for changing all the parameters for calculating the LCOE of the terminal according to Equation 7.16. In Figure 7.19, the sensitivity of the LCOE is shown for three terminals in the port to indicate the range of sensitivity for the parameters. The sensitivity slightly changes with 1-2% for each terminal, but remains in the same order of magnitude. The most important parameter is the price for electricity, if the electricity price for industrial use increases with 20%, the LCOE for shore power will most likely increase with 11-14%.

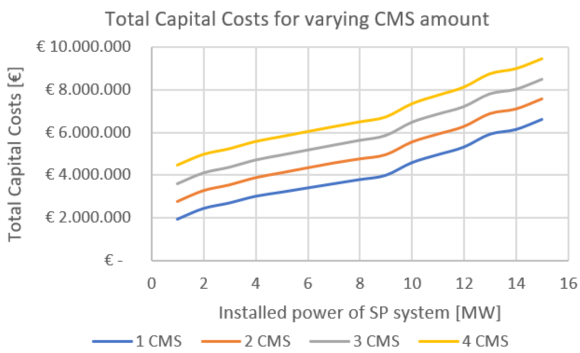

Figure 7.17: Terminal sensitivity of TCC for the installed power of the shore power system

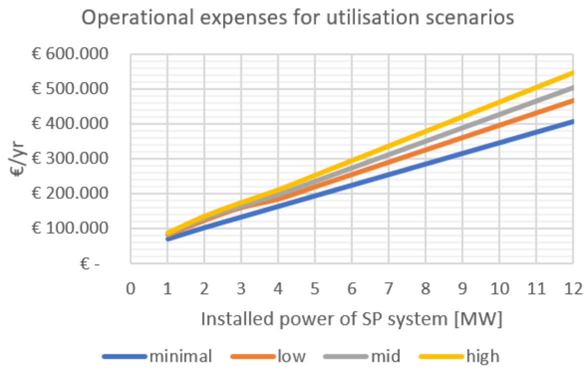

Figure 7.18: Terminal sensitivity of operational expenses for power utilisation scenario and installed power

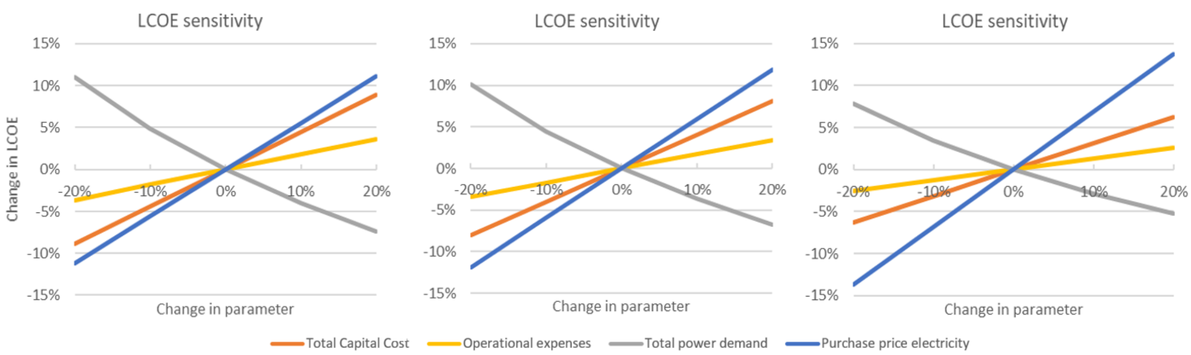

Figure 7.19: Change in LCOE for each change in parameter

7.5. Scenario Design

This section is elaborating the use of a base case for the two models and different scenarios by varying different parameters. The use of a base case scenario and alternative scenarios is also done for other comparative analyses on sustainable technologies [63, 77]. First, the base case for both the terminal model and the ship model is elaborated and the results are shown. Secondly, the alternative scenarios on the base cases are discussed.

7.5.1. Base case

This section describes the first scenario, the base case and present the results of the first base case. The base case is made for both the terminal model and the vessel model, and the found shore power price of the terminal model will be used for the vessel model.

Terminal base case

The base case for the terminal model consists of a terminal in the botlek area, with 274 yearly ship visits. Which will have the currently existing shore power system installed, the aftship shore based cable reel, on the two berth locations. The aftship cable reel must be installed on separate platforms in the aftship area at the berth places. The total installed power is set at the total expected maximum power if each berth is occupied with the largest visiting ship, resulting in a 2.3MW installation. The investment is depreciated in 20 years with an interest of 6%, which results in a CRF of 8.72%. For the base case it is assumed that 50% of the vessel visits is done by a ship that is shore power ready with a compatible system. The monthly maximum power utilisation scenario is set at high.

The total investment costs of installing shore power for this terminal is €3,101,482 and the operational expenses are 123,899 €/yr. If 50% of the vessel visits is a shore power ready ship, the resulting total power demand is 3,038 MWh/year. However, with an aftship system with a limited crane outreach and berthing direction factor set at 0.95, the total power demand that can be delivered is 2,885 MWh/year. To earn back the investment with this vessel power demand, a shore power price of at least 169 €/MWh is required.

For all other terminals, the shore power price when only 50% of the vessels are SP-ready varies between 140 and 340 €/MWh, as seen in the terminal model results.

Ship base case
The base case for the ship model consists of a newbuild chemical vessel in the shortsea range. Using the current MGO fuel price of 500 €/ton and a shore power price of 169 €/MWh, which came out as a suitable price for the terminal base case. The amount of shore power visits per year is assumed at 40 yearly visits, this is 50% of the estimated yearly port visits for a chemical shortsea tanker. The port operations are as much loading operations as discharging operations, resulting in 20 loading operations and 20 discharging operations in ports.

The total investment cost for a aftship cable reel system consists of installing two crane and the electrical equipment adjustments required for receiving shore power. This results in a investment of €533,138 and the operational expenses at €1,184. When using the shore power price of €/MWh for the vessel, using shore power of 169 €/MWh is more expensive than using MGO at 110 €/MWh. Thus, under the current circumstances shore power is not financial profitable for a chemical vessel. The yearly amount of shore power that is used in the ports is 569MWh for this base case, which is 45.7 % of the vessels estimated total yearly berthed power demand.

Analyse results
A shore power price of 169 €/MWh is calculated for the base case of the terminal, assuming that half of the yearly vessel visits use shore power at the terminal, which is a positive assumption. Yet, this shore power price is not competitive with the current MGO prices for the ships. Therefore shore power is still too expensive to use under the current market. As seen in Figure 7.16, the shore power price has to be higher when the utilisation is lower. Figure 7.16 also makes clear that the shore power price could converge to a LCOE under the MGO price, but only when the utilisation is near the maximum. In order to reduce the high shore power price and increase the utilisation and thus obtain the environmental benefits of shore power, the following parameters can be changed to find a positive business case.

- Use CO_2 price for shipping
- Subsidy for terminal investment
- Subsidy for ship investment
- More shore power ready vessels
- More shore power ports/terminals

7.5.2. Alternative scenarios
In order to find scenarios for liquid bulk vessels and terminals which are feasible, variations on the input parameters are made which are based in the analysis of the results of the base case. The main variation in this thesis is the Cable Management System, of which all five concepts will be evaluated in the alternative scenarios. The variations for other parameters that are used are listed in this subsection, first for the terminal and thereafter for the ship.

Terminal
For the terminal model, the sensitivity is largest for the shore power price, shore power readiness and subsidies, as seen in Section 7.4. With these parameters variations on the base case are made in order to obtain alternative scenarios for the terminal model outcomes.

- Shore power price
- Shore power readiness
- Subsidy for investment

To increase the profit of selling shore power, the price of selling shore power is dominant in determining if profit is made, therefore the price is an important parameter. The LCOE is mainly determined by the costs and the utilisation. The costs are more constant than the utilisation, which depends on the visits of shore power ready vessels. Therefore, it is important to see for different shore power readiness factors the impact on the power utilisation and thus the LCOE of the system. To reduce costs and thus the LCOE at a low shore power readiness level, subsidy for the terminal can offer a reduced total capital cost.

Ship
The ship model is very sensitive for the shore power price and the shore power visits, as seen in Section 7.4. With these parameters the alternative scenarios for the ship model are constructed in order to find other outcomes of the ship model.

- Shore power visits
- CO_2 price
- Shore power price

First, the amount of yearly shore power visits has directly influence on the power utilisation per year. Which determines how much shore power is used, and thus influences the levelised cost of energy. And the emission reduction is directly dependent on the amount of shore power used. Secondly, to make profit of using shore power instead of MGO for the diesel engines, the price of shore power should be lower than the price of MGO per MWh. Therefore, different prices for shore power should be used in order to analyse when the vessel can make profit with shore power. As well as analysing alternative scenarios where the MGO price is increased by a CO_2 price, this is done by presenting the required CO_2 price in order to make profit.

7.6. Conclusion

This chapter has described the design of the model to evaluate the economical and power utilisation feasibility of various Cable Management Systems for both the ships and terminals. As discussed, the base case results of the ship model and terminal are both not financially feasible, under the described circumstances. In order to find under which circumstances the shore power concepts can be feasible, alternative scenarios are presented, which are discussed in the previous section as well. Using these alternative scenarios, the best performing shore power concept for the terminal and the ships will be found.

8 Case Study

This chapter describes the relevance for a case study, the choice of vesseltype for the case study and set up of the shore power case study. In this chapter all parameters that are required as input in the model are discussed for the chosen liquid bulk submarket.

First, the case study relevance is discussed on why it is important that a liquid bulk submarket is chosen for a shore power case study. Secondly, the choice criteria for the case study are discussed and the choice of vessel type is elaborated. Thereafter, the general set up of the case study is discussed, which consists of information of the vessels and terminals and other European ports. Finally, in Section 8.4 the vessel parameters are discussed and in Section 8.5 the terminal parameters are elaborated.

8.1. Case study relevance

This section describes the relevance of the case study. As discussed in the problem analysis in Chapter 2, there is no technical solution that is the standard for using shore power in the liquid bulk industry. To overcome this problem, the five technologies which are proposed in Chapter 6 are evaluated in the model for a specific liquid bulk submarket. Instead of modelling all types of vessels and terminals, this case study zooms in on a liquid bulk submarket that has the highest potential of a positive business case for shore power, as well for the terminals as the shiptype. If insights on a certain technology can be given in terms of economics and emissions for a liquid bulk submarket, with positive results for the shore power case, this liquid bulk market can be used as a pilot. As stated by Stolper, pilots help to overcome or fully remove all market entry or operational barriers such as interdepency, reliability, regulations or mindset barriers [78].

8.2. Vesseltype choice

This sections provides the arguments for the choice of a vesseltype for the shore power case study. This section aims to find a liquid bulk submarket, consisting of vessels and related ports, which has a high potential for shore power. First, the criteria for the vessel choice are elaborated and thereafter the choice of vessel is presented. The liquid bulk sub market and corresponding vessels with the highest potential for a positive shore power case is based the following aspects:

- Visit numbers Rotterdam
- Shore power potential
- Trade region

The visit numbers in Rotterdam are important, because in the previous chapter it was shown that the sensitivity for the utilisation of the shore power systems is high. And the utilisation is higher, when a vessel visits Rotterdam more often. The shore power potential is based on the typical power demand of a vessel and the equipment onboard. The trade region and typical shipping routes are of importance, since local trade lanes in the EU can be better regulated by EU emission plans than worldwide trade.

8.2.1. Top visitors Rotterdam

The top visitors in Rotterdam are found using the historical port visit data from the Port of Rotterdam over a period from 2010 to 2020. This data contained the UCRN numbers of each visit and specific terminal visits. The UCRN, the Unique port Call Reference Number, is a number that is assigned to each unique port visit that a specific ship makes. Therefore, each UCRN number per ship is counted and divided by the typical yearly port visits of a shiptype, as shown in Equation 8.1.

$$UCRN_{relative} = \frac{\#UCRN}{V_t} \tag{8.1}$$

where,

$UCRN_{relative}$ = Percentage of typical yearly UCRN visits in Rotterdam [-]
$\#UCRN$ = Yearly averaged UCRN count per vessel over a period 2010-2020 [#visits]
V_t = Yearly typical port visits per vesseltype [#visits]

When sorting the vessels with the highest $UCRN_{relative}$, the vessels that most often visit Rotterdam are found. The most frequent visitors were found to be the chemical shortsea tankers and chemical parcel tankers, with slightly over 20% of the typical port visits in Rotterdam.

8.2.2. Shore power potential

The shore power potential is related to the most frequent visitors of the port. However, the shore power potential is as well dependent on the vessels power demand and average berth times, as seen in Equation 7.12. The Port of Rotterdam has estimated the emissions related to berthed vessels in the port. The results of this for the year 2020 is shown in Table 8.1. As seen in the Table, the chemical tankers have the largest share in the total berthed emissions of all tankers in the port. This is due to the frequent visits of a lot small chemical tankers, as for the oil tankers most of the tankers are large and visiting infrequently.

Table 8.1: Total estimated berthed emissions per ship type in the Port of Rotterdam in 2019

Ships	CO_2 [t]	NO_x [t]	SO_x [t]	PM_x [t]
Chemical tanker	77,308	1,195.3	98.2	19.7
Oil tanker	49,528	757.6	62.9	12.6
Gas tanker	6,048	92.7	7.7	1.6
Other tankers	2,560	42.7	3.2	0.7
Total	135,444	2088.3	172	34.6

Therefore, by solving the shore power case for the chemical tankers, the highest reduction can be achieved per subtype of vessel.

8.2.3. Trade Region

As discussed in the introduction, the regulations for shipping are not always covering the whole world and as shipping is an international business, regulation implementation can be difficult. For example, a nationwide Emission Trading System (ETS), is not applied to shipping because the seagoing ships sail at sea and not inland. However, as said in the introduction, the European Union has plans to implement the shipping in the EU ETS, and the ships that are mostly affected are the coastal shipping liners. In addition to that, the regional shipping also sails smaller distances compared to intercontinental shipping, therefore their yearly time in port is relative large compared to the sailing time. Therefore, the choice for an regional liquid bulk market is made upon the fact that the EU ETS would have the most effect on such a regional market.

8.2.4. Choice of vessel

Considering the above three aspects, the small chemical tankers score the best on all three. Using the visiting data, the small chemical tankers visited the most times per year, both absolute and relative to their typical amount of trips per year. Secondly, the shore power potential, as shown in Table 8.1, is highest for all chemical tankers in Rotterdam. This is of course due to the higher visiting numbers, but also to the relative long berth times and power demand. Finally, the trade region of the small chemical vessels is mainly located in Europe, this can be confirmed when the actual visiting data of the vessels is analysed. Concluding, the vesseltype choice are the chemical shortsea and chemical parcel tankers, as specified in Table 5.1.

The amount of vessels that are analysed for retrieving the port visit data of the is set at 45. Out of the 6,411 unique liquid bulk vessels that visited Rotterdam in the last ten years, about 45 vessels visited Rotterdam at least 20% of their typical port visits related to the vesseltype. The vessels are all under 20,000 dwt and the technical parameters are shown in Table 8.2

8.3. Case study set-up

This section briefly describes the set-up of the case study. First, by discussing the data of the vesseltypes that have been chosen. Secondly, the terminals in Rotterdam that have the most chemical vessel visits are presented with the share of the case study tankers. Thereafter, the ports that these vessels are visiting outside of Rotterdam are presented with a analysis of the terminal lay outs.

8.3.1. Vessel data

For the group of 45 vessels that are frequent visitor in the Port of Rotterdam, the technical parameters can be more specifically determined, since this sample group is smaller. Using the Clarkson database, and the vessels MMSI numbers, the new technical data is determined using the average of the parameter of this sample group. This data is shown in Table 8.2.

Table 8.2: Case study vesseltypes technical parameters.

Parameter	Chemical shortsea	Chemical parcel	Source
Deadweight [dwt]	0 < dwt < 10,000	10,000 < dwt < 20,000	[6]
Length [m]	99	140	[6]
Discharge power [kW]	660	1,155	[6]
Loading power [kW]	470	825	[6]
Berth times [hrs]	27.5	33	PoR berth times, see Appendix F
Crane aftship	No	No	Vessel images
Crane midship	Yes	Yes	Vessel images

Preferential Solution

The chemical vessel owners have a slight preference for connection in the aftship area, this was stated by vessel owners in the workshop in March. Due to safety reasons, the midship connections are not in favour by the vessel owners. The aftship connections have the preference due to short distance to the engine room and electrical switchboard.

The chemical tankers for the case study, are designed for shortsea shipping and are rather small compared to large oil or gas tankers, therefore the aftship is often very crowded with both the funnel and safety equipment as seen in Figure 8.1 and 8.2. During an analysis of small chemical vessels, it was noticed that most of the vessels have a falling life boat systems at the aft ship. Either the aftship has a emergency fallboat on the starboard side or portside. Mostly, a davit crane with a smaller lifeboat is present on the opposite side of the fallboat. Out of safety considerations, this crane is highly likely not going to be used for transporting and holding a shore power cable. The large funnel from the engine room, also reduced the available space on the aftship for a crane for shore power cables.

Figure 8.1: A 5,700 dwt chemical vessel, where the aftship is very crowded

Figure 8.2: A 44,000 dwt chemical vessel, where the aftship is slightly more spaceous.

Due to the midship ATEX zoning and the aftship shortest path to the switchboard, the preference of the shipowners is therefore an aftship connection. But, with limited crane space and low availability of emergency cranes, preference is to use a shore crane which transports the cable from shore to land. Yet, the placement of the fixed shore crane is hereby moved on to the terminal, which might not cover all visiting vessels with a fixed shore crane.

8.3.2. Terminal data Rotterdam

The chemical terminals in Rotterdam have to be determined for this case study. As the liquid bulk terminals often have a wide variety of visiting vessels, it is not evident which terminal is a typical chemical terminal. However, by combining the total vessel visiting data with the 45 case vessels visiting data, a list of mainly chemical terminals is found. At these terminals the most chemical vessels are berthing, both in absolute and relative numbers. As well as the most visits from case study vessels, to obtain a list of terminals where the case study vessels are often visiting. In Table 8.3 the terminals, without names, with the highest chemical tanker visits per berth location are shown.

Table 8.3: Terminal data with the yearly visits of chemical shortsea/parcel tankers, the amount of berth places and the amount of yearly visits by the 45 case study vessels

Terminal	Total visits	Chemical tanker visits	Berths	Case vessel visits
A	467	204	4	161
B	876	631	7	109
C	329	229	4	111
D	430	288	4	93
E	274	239	2	82
F	564	304	2	90
G	503	334	3	86
H	361	267	3	59
I	472	273	6	52
J	276	162	3	48
K	200	136	3	42
L	378	210	4	46

What is noticed in the visiting numbers of the different terminals in Rotterdam, is that a few vessels visits more than twice a month a specific terminal, suggesting that there are a few liner services along the vessel visits. However, the amount of liner services should be higher in order to have a positive business case with sufficient visiting vessels that would have shore power. Terminals with large visit numbers from case vessels, thus have a relative small group of vessels responsible for a large share of the yearly visits.

Terminal lay-outs

Terminal lay-outs in Rotterdam do not follow a standard design, but are tailored to the terminal that has the jetties or quay walls installed. According to the Port of Rotterdam, terminal design also follows current trends in terminal design and is therefore changing over the years. It is thus hard to include all terminal lay outs with one analysis. Yet, most terminals in Rotterdam have a jetty structure stretching out in the waterway, the size of the jetty is varying per terminal or even within one terminal. Only a few terminals have a quay wall where only small vessels can berth.

Preferential solution

The terminals in Rotterdam often have a jetty structure where the chemical vessels are berthing, however some have a quay or a rather large jetty. The preferential solution for the terminals depends on two factors, safety and costs. If the shore power concept does not create additional safety hazards when in operation, the midship connection has the most economical potential. Because, as stated in Chapter 5, the liquid bulk vessels are aligning their midship manifold with the terminal manifold. Therefore the midship area of the vessel is always in the same place as the manifold area of the terminal, making this a almost perfect solution regarding shore power utilisation.

Terminals have operational flexibility as a high value in their operations, vessels should not wait on ships at berths when another berth spot is already free. Therefore, most of the terminals have manifolds that can handle almost all the goods that are transshipped at the terminal. Thus, when only one shore power system is in operation, it could occur that a SP-ready vessels is waiting before the shore power berth is free. Terminals like to have either all berths fitted with shore power or none, because in between all and none is the chance of not using the installations due to occupied jetties or empty jetties.

8.3.3. European chemical ports

The other visited chemical ports that are found with the Port of Rotterdam vessel calls database, are counted for each unique vesselvisit based on the UCRN number. The resulting visited ports were counted in total and the share of each port for the chemical vessel group was calculated. Eventually, ports who cooperate, such as HaRoPa[1] were combined into one port. The result of port (coalition) visits is shown in Figure 8.3, and it can be noted that the first 5 ports are responsible for more than 50% of all visits. And in addition to that the next 9 ports are responsible for the next 20% of all visits.

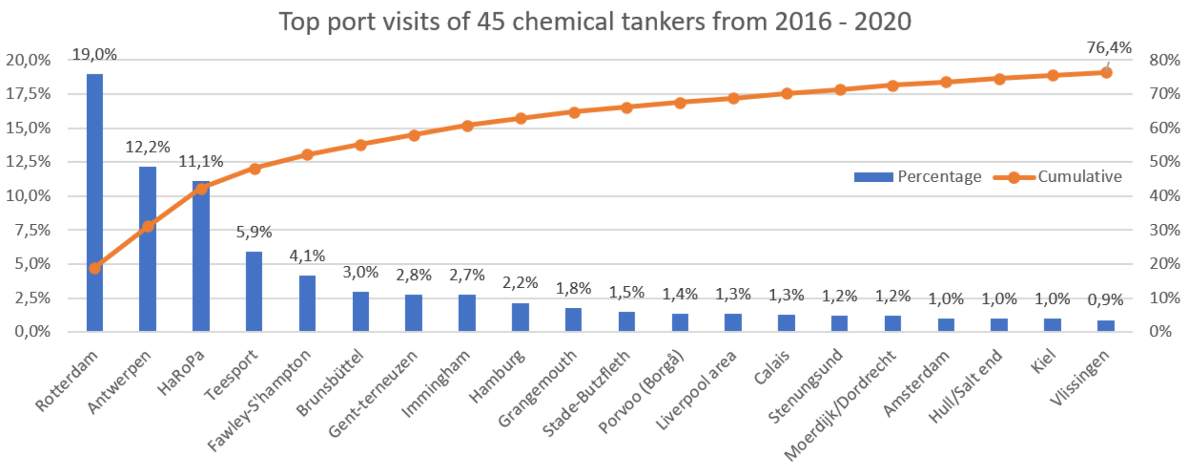

Figure 8.3: Top 20 port visits of the 45 case study vessels from 2016 - 2020

These ports are all located in Europe and show minor similarities in terminal design, however there is no leading terminal design. What is noticable, is that a large amount jetties are located upstream along

[1]HaRoPa consists of Le Havre, Rouen and Paris as seen on their website https://www.haropaports.com/en

the river, which makes the berthing procedure vulnerable for strong tides or currents. This could have an impact on the berthing direction requirement for the shore power systems which are located on the aft.

8.3.4. Solving the loop

This section describes how to solve the loop of finding the shore power solution for the vessels and terminals, as various parameters have influence on both models as seen in Figure 7.1. To solve the case study loop, the group of chemical tankers that are frequent visitors is again analysed for typical technical and operational parameters, which are then updated in the ship model. Also, for the terminal model it is assumed that the terminals in Rotterdam represent other European terminals in terms of vessel visits as well. For both the ship and terminal model, all five CMS concepts will be evaluated.

Then, the alternative scenarios vary the shore power price and the shore power visits, as steps from the european chemical ports, the CMS solutions are evaluated for costs and utilisation. This includes the MGO price and emission tax at which the shore power becomes profitable for this group of tankers. The results for the ships are presented for the system choice as well as 4 size steps in the shore power port visits. As seen in Figure 8.3, Rotterdam takes 19% of the yearly ports visits from the chemical tanker group, this will be the first step for evaluating the vessel economics for the CMS concepts. The next step is at 50% of shore power visits, consisting of the first 5 ports, and thereafter 70% and 100%. As 100% is only happening if all ports are participating, which is highly unlikely in the upcoming 10 years.

1. **Find vessel group**
   This vessel group for a liquid bulk market is the starting point for the case study and are described in Section 8.2.
2. **Find corresponding port visits**
   The corresponding port visits are important to identify how many ports are needed for what percentage of the port visits. These ports are presented in Figure 8.3. First scenario is only visiting in Rotterdam, second scenario visiting the first 5 ports, third scenario visiting the first 14 ports and the fourth all ports.
3. **Evaluate terminal model for system choice**
   Analysing the terminal model output for the different CMS concepts with different shore power prices and find what utilisation is required to make profit. Also, find the possible effectiveness of subsidies on the profit of terminals.
4. **Evaluate Vessel model for system choice**
   Analysing the vessel output for different CMS concepts with different shore power prices and different shore power port visits.
5. **Evaluate best solutions for other ports**
   Evaluate the CMS concepts for ships and terminals, and find the best performing solution for shore power in liquid bulk. Also, assess whether the found solution for Rotterdam can also have a positive economical and utilisation output in other ports in Europe. Assume that ship visits in the European chemical terminals are similar to Rotterdam.

8.4. Vessel Parameters

The detailed vessel parameters that are used for the case study are shown in Table 8.4, these parameters are assumed constant for the case study. The choice for newbuild vessels is made because retrofit have an higher investment cost due to the installation on an existing ship, which is more expensive [25]. In addition to that, the depreciation time is also shorter which means the investment is annualised over less years as seen in Equation 7.2. In the base case it was already clear that the base case was not even positive for 20 years depreciation time under the current circumstances, therefore the case study is done for newbuild vessels.

Table 8.4: General input vessel parameters used for the case study

Parameters	Value	Explanation
Years	20	Depreciation of system in 20 years [54]
Interest rate (CRF)	6	Interest used for capital recovery factor calculation [51]
Electricity mix	2030	Since, shore power will probably not be implemented before 2030. Therefore the emission reduction forecasts of 2030 are used, to compare with MGO
Cargotype	Chemical	Case study is on chemical vessels
Vesseltype	Shortsea/parcel	Either shortsea or parcel
Newbuild	Newbuild	For this thesis the newbuild option is considered, due to higher costs of retrofitting and shorter system lifetime [25, 29]

The technical and operational constant parameters used for the vessel in this case study are shown in Table 8.5.

Table 8.5: Technical vessel parameters used for the case study

Parameters	Value	Explanation
P_{loa}	470 kW 825 kW	Loading power determined by Clarkson database per shiptype with loading factor of 0.5
P_{dis}	659 kW 1,155 kW	Discharging power determined by Clarkson database per ship-type with discharging factor of 0.7
Port visits	105 79	Average yearly port visits from chemical shortsea and chemical parcel, respectively
Berthtimes	27.5 hr 33 hr	Average berth times per vesseltype in Rotterdam from database 2019 and 2020 for chemical shortsea and chemical parcel respectively
SFC_{AE}	210	SFC of high speed diesel engine used as auxiliary engine [7, 67]
η_{gen}	0.95	Generator efficiency which turns mechanical rotation into electricity [68]
n_e	2	Almost all ships have three AE configuration of which most likely 2 engines are used in port operations [6] (Figure 5.3)
b_d	0.95	Set at 0.95, as estimated by Pilots in the Port of Rotterdam
Outreach aft cranes	15 m	Estimation based on shipboard cranes and other shore power projects

For the alternative scenario's, the parameters in Table 8.6 are considered to make variations on the base case and the range of variation is shown. The upper bound for the shore power price is 160 €/MWh and set by the vessel, for which the MGO must exceed 750 €/ton. The lower bound is determined by the terminals, the LCOE of terminals with full utilisation does not converge to a point below 120 €/MWh. The shore power visits lower bound is determined by the case vessel visits from Figure 8.3, where Rotterdam has a 20% share. The upper bound is the maximum amount of shore power visits as stated in Table 8.5.

Table 8.6: Ship changing parameters

Parameter	Lower bound	Upper bound
SP-Price	120 €/MWh	160 €/MWh
SP-Visits	19%	100%

8.5. Terminal Parameters

The detailed terminal parameters that are used for the case study are shown in Table 8.7, these parameters are assumed constant for the case study. The choice is made to show the results for terminal E in the next chapter, and evaluate the results of all terminals from Table 8.3 in the Appendix. It is assumed that all the berths will have a CMS concept installed, which depends on the amount of berths per terminal.

Table 8.7: General input vessel parameters used for the case study

Parameter	Input	Explanation
Terminal	Chemical terminals	Terminal E is used for showing results, but other terminals will be evaluated as well
#CMS	Max	Amount of CMS concepts installed, as much as berth places of specific terminal
Jetty terminal	Yes/No	Depends on terminal specific lay-out, most terminals have a jetty
Manifold space	Yes	Most jetty structures have some additional space for a midship placed CMS
CMS concept	[all]	all CMS concepts are evaluated by KPI economics and utilisation
Years	20	Years before the system is depreciated, is set at 20 years, which is found in literature [54]
Power capacity (P_sys)	#CMS * $\sum P_{ship,wa}$	Terminal specific, equals the amount of CMS * weighted average power demand of the chemical vessels
Electricity mix	2030	Since shore power will probably not be implemented before 2030. Therefore the emission reduction forecasts of 2030 are used, to compare with MGO
Scenario power utilisation	High	The installed power is scaled down using the weighted average power demand of the vessels, so the use of power will be close to the installed power

In Table 8.8, the constant terminal parameters are shown, which are not input parameters in the model.

Table 8.8: Constant terminal specific values used in the model the case study

Parameter	Input	Explanation
Electricity price	66.8 (€/MWh)	Price which the terminal pays to the electricity provider for the electricity, 3yr average [48]. Excluded from tax, as stated by the dutch government [41]
Shore power cables	1	3 cables are used for 10MVA ship system at 6.6kV. Power demand under 3MVA can be fulfilled with 1 cable. [5, 10]
b_d	0.95	Berth direction factor is set at 0.95, as stated by Pilots in the Port of Rotterdam
Distance jetties	400 m	Estimation of average cable distance from terminal based E-house to jetties with CMS. Influences cable and excavation cost
Distance HV grid	1500 m	Estimation of distance from HV grid to Ehouse on terminal, based on HV network of Stedin in the port [79]. 1500m seems a reasonable distance for all terminals
Brownfield complexity	1.2 (low)	Estimation of increased excavation costs of cable trenches on the terminal.
Outreach aft cranes	15 m	Estimation based on shipboard cranes and other shore power projects

For the alternative scenario's, the parameters in Table 8.9 are considered to make variations on the terminal base case and the range of variation is shown.

Table 8.9: Terminal changing parameters

Parameter	Lower bound	Upper bound
SP-Price	€120	€180
SP-readiness	20%	100%
Subsidy	0	100%

9
Case Study Results

This chapter presents the results for the case study as described in the previous chapter. The chapter will evaluate the five CMS concepts on the costs, power utilisation and cost-effectiveness, both for the terminal and vessels from the case study.

First, the results for the terminals are presented and secondly, the results for the case vessels are presented. The results are presented by first discussing the economics, than the shore power utilisation and thereafter the levelised cost of energy. At last, the pricing results for making profit are presented. The best performing systems are evaluated for the whole chemical market in Europe by assessing other port lay-outs and locations. Thereafter, a roadmap is presented for gradually using shore power for the regional chemical bulk market in the upcoming years. Finally, with the insights and results from the case study, a brief analysis of shore power implementation for the other liquid bulk vessels is given.

9.1. Terminal model results

This section presents the results of the various CMS for the terminals. First, the preferential shore power concept solution for the terminals is discussed. Secondly, the economic results of the different shore power systems are presented and thereafter the utilisation of the different systems is discussed.

9.1.1. Economics

The terminals that invest in shore power have to do a rather large investment in order to provide shore power to the vessels who visit their terminal. To quantify the Total Capital Costs (TCC) differences of each CMS concept, the costs are shown in Figure 9.1 for a 1.4MW installation and 2 CMS concepts installed.

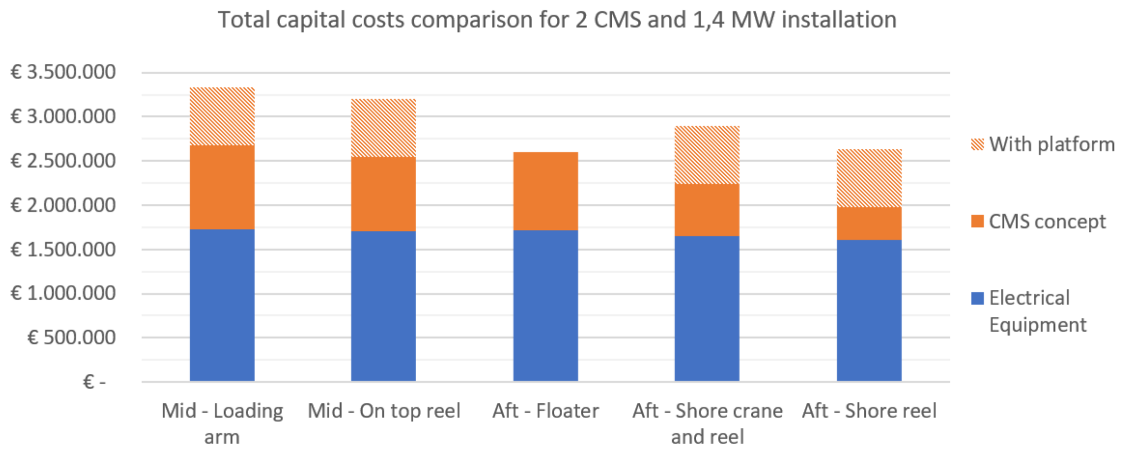

Figure 9.1: Total capital costs of different shore power installation of 1.4MW with two CMS installed

The explanation for the differences in TCC between the different systems, is that the systems that are installed in the midship area have additional costs for inerting systems to comply with the ATEX regulations. The floater is self propelled and therefore rather expensive, but does not rely on existing jetty infrastructure. Both land based midship and aftship systems can be placed on existing infrastructure if these provide enough clear space for such systems. If not, than an additional platform should be constructed which has a high cost as seen in the figure. Placing something on existing infrastructure is therefore required to make the solution cost effective. However, as discussed before all terminals have different layouts, thus no one size fits all can be found here. The terminal that was analysed in this figure has both a quay wall berth and a jetty berth, with both enough space in the midship area. Therefore, the midship solutions have no need for a platform and only one of the aftship solutions requires an additional platform. When the terminals manifold area at midship is too crowded, the midship solutions need a platform as well which results in that the aftship systems are cheaper to install.

In order to provide insights in the yearly expenses of both the capital costs and the operational costs, both are shown in Figure 9.2 and 9.3, respectively. The operational expenses do not vary per CMS concept, as these are dependent on the amount of power installed, amount of power delivered and the amount of CMS installed. Therefore, the operational expenses are not relevant for evaluation per CMS concept. The yearly operational expenses for the terminal is shown in Figure 9.3.

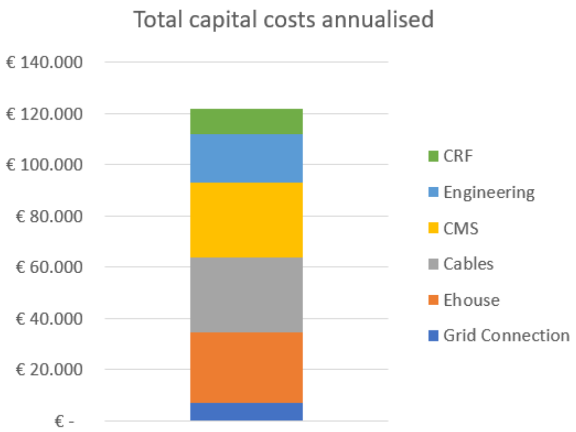

Figure 9.2: Total capital costs annualised of the terminal with two CMS installed

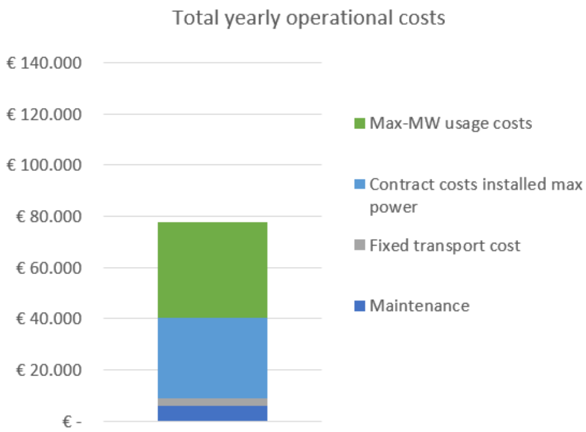

Figure 9.3: Yearly operational costs of the terminal with two CMS installed

9.1.2. Utilisation

The shore power utilisation of the different CMS concepts varies per concept, as each concept has slightly different connection times and as some have different fleet coverage levels. As stated in Section 7.3, the yearly shore power demand of a terminal is dependent on the shore power readiness ($R_{f,SP}$) and the fleet coverage factor ($Cof_{f,SP}$) and the connection times ($t_c(x)$). In Figure 9.4, the average shore power utilisation for the first five chemical terminals from Table 8.3. The average value only has a deviation of 0.1%, and therefore this graph can represent all the chemical terminals. The shore power utilisation is expressed in percentage of the total yearly shore power demand at the terminal, as for each terminal this demand is dependent on the visiting vessels.

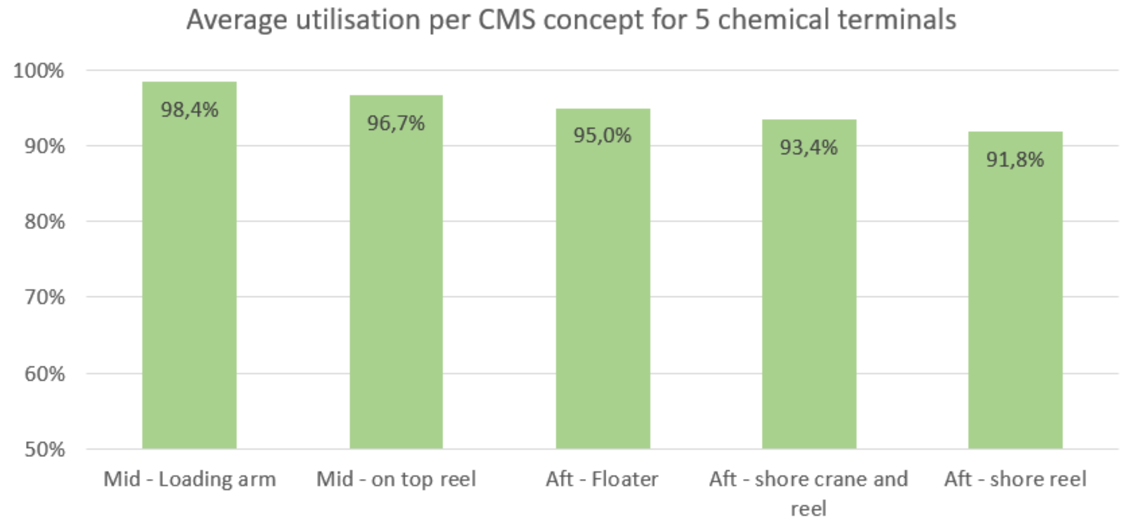

Figure 9.4: Utilisation; fleet coverage of the CMS concepts as percentage of the total yearly berthed power demand of chemical vessels under 20,000 DWT

Because the chemical vessels in this case study are within the range of an aftship fixed crane, these systems only have a reduced fleet coverage due to the berthing factor (b_d). The berthing direction factor is set at 0.95, because of the opposite berthing direction of vessels due to safety reasons. The aftship systems are performing rather good, considered these systems have a fixed outreach of the crane.

Emissions

The terminals can effectively reduce the emissions of the visiting chemical tankers by using shore power. In Table 9.1 the emission reduction is shown for using different systems.

Table 9.1: Emissions reduced for chemical terminal E

	Mid - Loading arm	Mid - On top reel	Aft - floater	Aft - shore crane	Aft - shore reel
CO_2 [t]	2,458	2,502	2,413	2,377	2,355
NO_x [t]	32.7	33.3	32.1	31.6	31.1
SO_2 [t]	1.09	1.11	1.07	1.05	1.04
PM_x [t]	1.07	1.09	1.05	1.03	1.02

9.1.3. LCOE

The LCOE for the terminal is calculated using Equation 7.16.

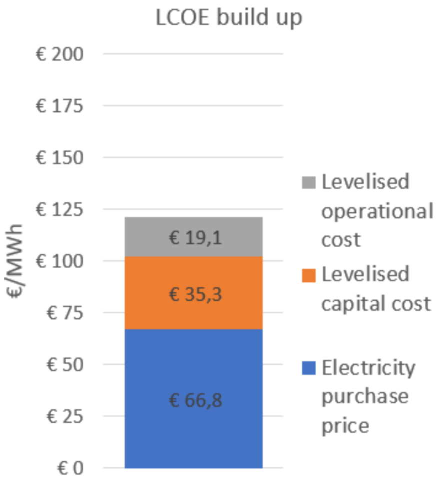

Figure 9.5: LCOE fractions at 100% SP-visits from the chemical case vessels for the aft - cable reel system with 1.4MW

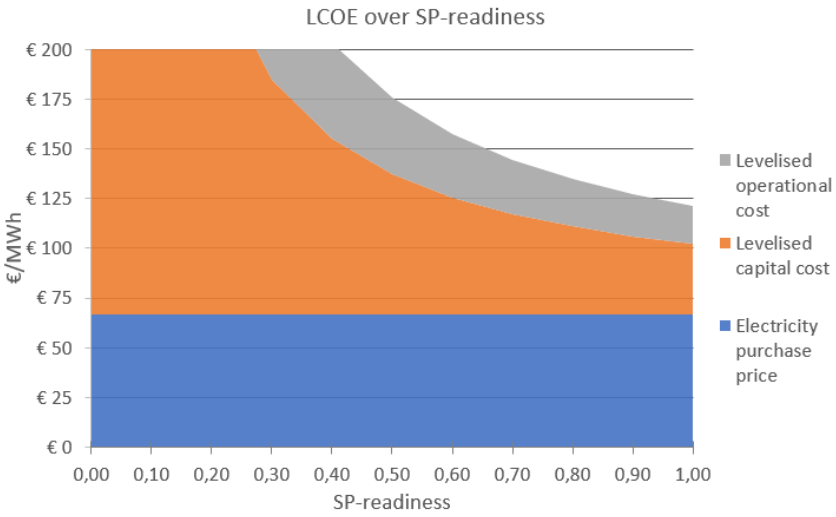

Figure 9.6: LCOE as function of the shore power visits of vessels at the terminal for the aft - cable reel system with 1.4MW

The LCOE is varying per CMS concept because the costs are varying per CMS concept and the yearly power utilisation changes. This results in different LCOE values over the amount of shore power visits. In Figure 9.7, the differences in the LCOE of the CMS concepts are shown. Comparing the most expensive one with the cheaper one, the difference at low SP-readiness is 11 €/MWh and at high SP-readiness 6 €/MWh.

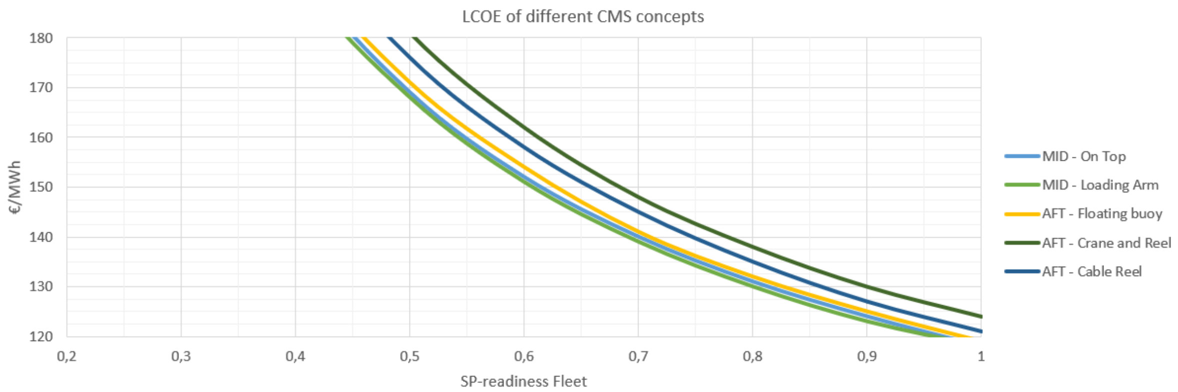

Figure 9.7: LCOE of different CMS concepts as function of SP-readiness of visiting fleet

What is clearly visible, is that the main influential factor on the LCOE is the SP-readiness of the visiting fleet at the terminal. The choice of CMS concept has a limited influence on the LCOE of shore power for the terminal.

9.1.4. Terminal scenarios

The alternative scenarios for the terminal are the shore power price, shore power readiness and subsidy on the investment. The terminal earns back the investment, by selling the shore power to the vessels for at least the LCOE price. Thus, it is important to have insights under which circumstances which shore power price is needed to be able to pay back the investment. Filling in the input parameters from Table 8.7 and 8.8, the pricing results are shown in Figure 9.8. The figure belongs to a terminal with 238 yearly visits from chemical tankers under 20,000 dwt, who are responsible for a power demand of 4,428 MWh. This is therefore the theoretical maximum of power utilisation that can be required in order to earn back the investment. A power demand over this theoretical maximum power demand of the terminal, is not possible.

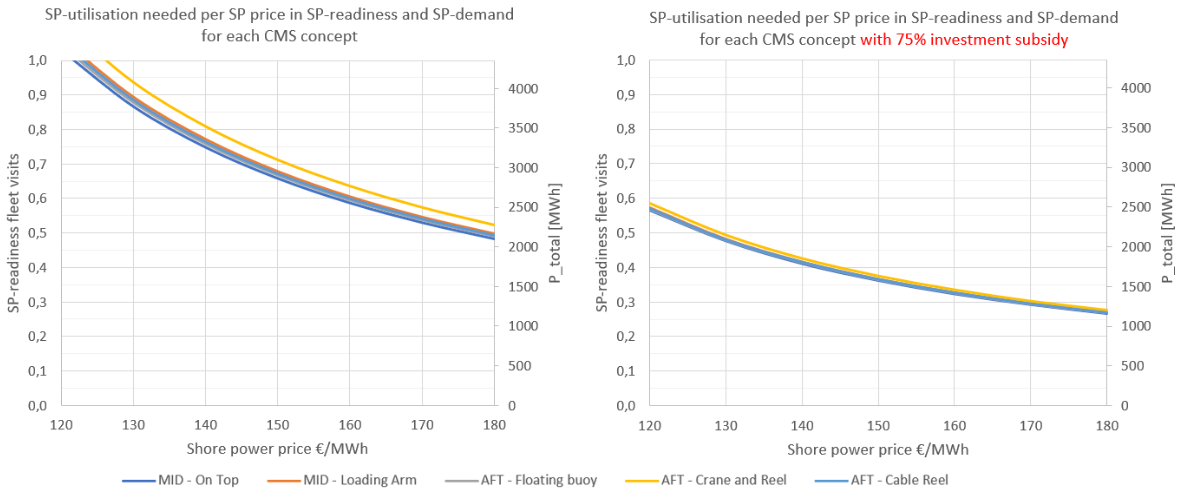

Figure 9.8: Shore power utilisation needed at terminal for each shore power price, left figure: without subsidy, right figure: with subsidy of 75% of investment costs

At the lowest utilisation of 0,5 in the left figure, the terminal is not able to make profit on shore power unless it sell the shore power at 180 €/MWh. When the capital costs are subsidised by 75%, the required SP-readiness of the vessels drastically decreases and the terminal can make profit on the same utilisation of 0,5 when selling shore power at 130 €/MWh. This is important as during the introduction of using shore power for liquid bulk vessels, not all vessels are SP-ready yet a low SP-price is desired. When the capital costs are subsidised, the differences in CMS concept choice also reduces significantly, since the capital costs are less dominant in the LCOE equation. In Figure 9.9, the effect of different capital cost subsidies is shown for the terminal. The price differences per CMS concept are negligible for high subsidy and therefore removed from the graph for clarity.

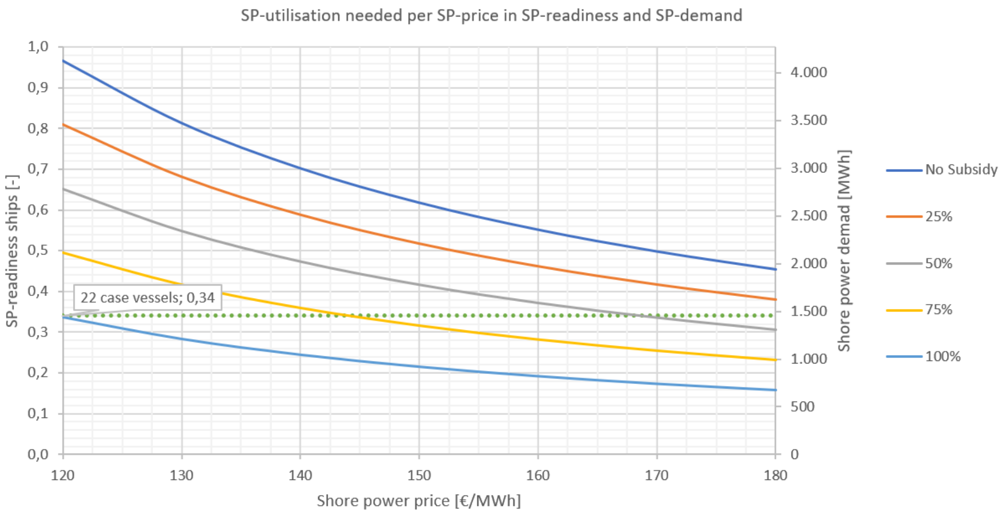

Figure 9.9: Shore power utilisation needed per shore power selling price at the terminal, median of the CMS systems shown for each level of capital costs subsidy

In the above figure, the dotted line represents the power demand of the group of case vessels at this terminal. That means that with shore power ready 45 case vessels and full subsidy on the capital costs, a shore power price of 120 €/MWh can be realised. For this specific terminal, the use of shore power can be economically feasible for the small case study vessel group if the investment is subsidised. This is the minimal viable product for the terminal. When fully subsidised the choice of CMS is irrelevant for the business case, because the differences in costs for each CMS concept are fade out.

In Appendix G, the utilisation that is required per shore power price and subsidy level is shown for all the 12 terminals. It can be concluded that the terminals require different utilisation levels per shore power price and require different subsidy amounts to make shore power economically feasible for low shore power prices.

9.1.5. Terminal result

Any CMS concept that is discussed in this thesis, is in theory economically feasible for the terminals if all visiting vessels use shore power. However, the amount of visiting vessels that is able to use shore power is the bottleneck. Thus, the yearly power demand from the vessels must be high enough to sell the shore power to the ships for a reasonable price. At the base case it was clear that an shore power price of 180 €/MWh is too high for the ships to make profit.

For most chemical terminals in Rotterdam, the total amount of ships that visit can in theory be enough to earn back the investment for any shore power CMS concept. The liquid bulk vessels and terminals have a high priority on safety, therefore the innovative ideas on connecting the vessel on the midship seems to contradict this safety priority. Although, the midship systems will be better integrated in the current terminal infrastructure, a dedicated platform for an aftship landbased system is the overall best solution for realising shore power.

However, the terminals in Rotterdam often have a jetty structure, and the midship systems often could be placed near the existing cargo manifold. Making the midship systems slightly less expensive than the aftship systems. When the terminals have to crowded manifold areas and midship solutions need a platform as well, the aftship systems are cheaper to install.

9.2. Ship model results

This section describes the results of the the various shore power concepts for the case study vessels, the shortsea chemical tankers and the parcel chemical tanker. First, the preferential solution for the vessels is discussed on why the vessel owners have a preference for a certain solution.

9.2.1. Economics

The investment costs and the operational expenses of installing different CMS systems onboard of the vessels are shown in this paragraph. In Table 9.2 the total capical cost (TCC) and the operational expenses are shown for a chemical shortsea tankers and chemical parcel tankers, respectively.

Table 9.2: Investment (TCC) and operational costs (C_{OM}) of a chemical shortsea and parcel tanker when shore power is used in all visiting ports

	Chemical Shortsea Tanker			Chemical Parcel Tanker		
	TCC [€]		C_{OM}	TCC [€]		C_{OM}
CMS concept	Electrical	CMS related	[€/yr]	Electrical	CMS related	[€/yr]
Mid - Loading Arm	159,400	223,400	1,294	197,000	228,520	-215
Mid - On Top	159,400	223,400	1,483	197,000	228,520	-89
Aft - Floating buoy	159,400	373,740	1,672	197,000	378,540	37
Aft - Crane and Reel	159,400	133,740	1,294	197,000	138,540	-215
Aft - Cable Reel	159,400	373,740	1,483	197,000	378,540	-89

What is clear, is that the CMS related costs are very dominant in the total capital costs for the ships. Thus the choice of CMS concept is important for the economic outcomes of the ship model. Also, the negative operational costs for the chemical parcel tanker indicate that the engine maintenance savings are higher than the shore power system maintenance and shore power call costs.

9.2.2. Utilisation

The evaluated concepts for the Cable Management System do not show large differences in the utilisation of shore power. The utilisation of the concepts for the chemical shortsea tankers and the chemical parcel tankers are shown in Figure 9.10 and Figure 9.11 respectively.

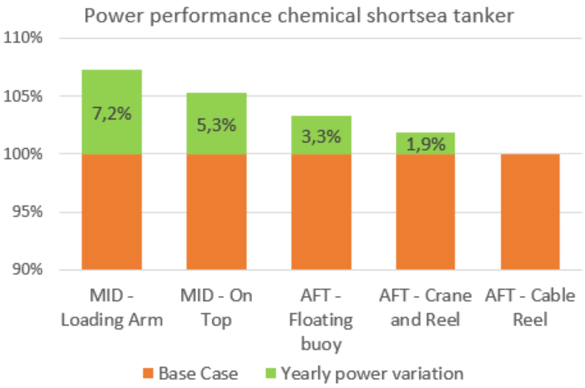

Figure 9.10: Yearly shore power utilisation of a chemical shortsea tanker as percentage of the total yearly berthed power demand

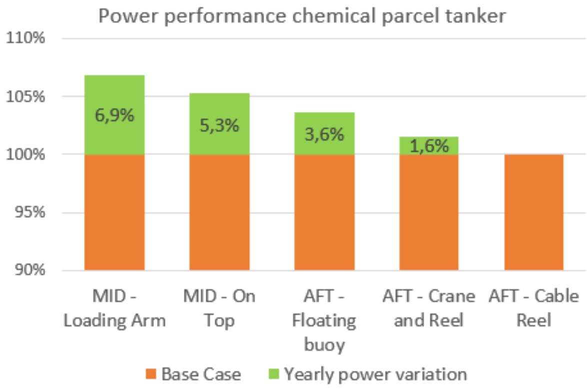

Figure 9.11: Yearly shore power utilisation of a chemical parcel tanker as percentage of the total yearly berthed power demand

As seen in Figure 9.10 and 9.11, the amount of shore power that is used by the vessels is slightly dependent on the choice of CMS concept. The vessels yearly power demand is dependent on port operations, the loading or discharging power demand, time at berth, CMS connection time and the berth direction factor (Eq. 7.7). By changing the CMS concept, the connection time and the berth direction factor are varying. The values for connecting times of a CMS concept are based on the easy to use criteria in Chapter 6. Thus, the utilisation per CMS concept does not vary much, only the amount of yearly shore power visits has a significant impact on the shore power usage.

Emission abatement

As stated in the introduction, the main reason for using shore power is the significant local air quality and noise improvement in and near ports. The chemical shortsea tankers and parcel tankers can reduce about 80 to 90% of all at berth emissions in a year, if all port visits provide shore power and the grid emissions are in the same order of magnitude as in the Netherlands (4.2). The absolute yearly reduction of CO_2 for an shortsea tanker is 895 ton and for a parcel tanker, 1,268 ton. The chemical shortsea vessels can reduce up to 8.4% of the total CO_2 emissions per year, and the chemical parcel tankers can reduce the total yearly emission can by up to 6.2% [18, 19]. Extended emission results are shown in Appendix H.

9.2.3. LCOE

Combining the yearly costs and the utilisation of shore power, forms the LCOE of the ships investment. The LCOE for the chemical shortsea and parcel tanker is plotted for each different CMS concept over the amount of shore power visits per year. In Figure 9.12 and 9.13 the LCOE is shown for the shortsea chemical tanker and the parcel chemical tanker, respectively.

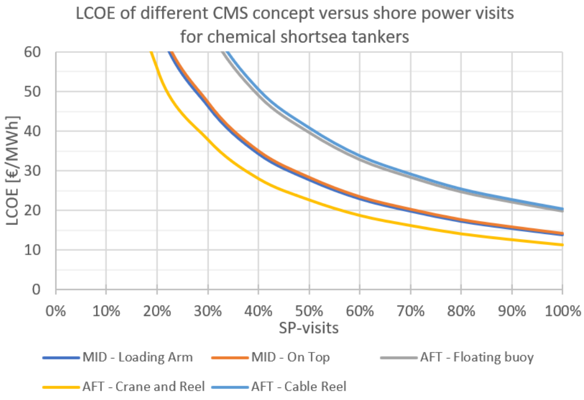

Figure 9.12: Chemical shortsea tanker LCOE per CMS concepts over shore power visits

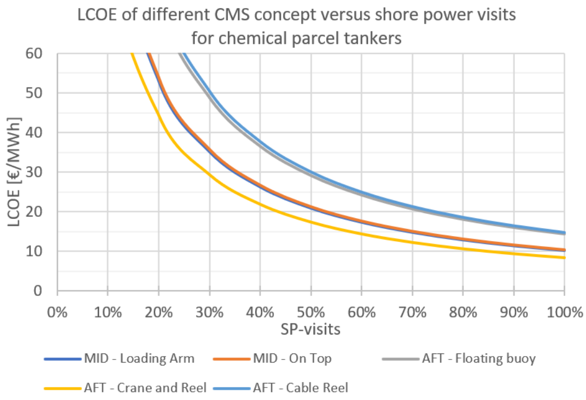

Figure 9.13: Chemical parcel tanker LCOE per CMS concepts over shore power visits

In this figure, the amount of shore power visits is dependent on the average yearly visits, as shown in Table 8.5. At 100% all yearly port visits provide shore power and the vessel uses the shore power. The figure shows that the aftship crane and reel system has the lowest LCOE for both chemical vessels.

9.2.4. Ship scenarios

The ship alternative scenarios are described in the previous chapter as, varying the shore power price and varying the amount of shore power visits. The fuel price is not considered in the alternative scenarios, due to the volatility and the fact that only a high fuel price will be feasible for shore power. The current fuel price in the Port of Rotterdam is 500 €/ton MGO and the world average is slightly higher and as stated in Chapter 2 is varying heavily over time [47]. In Table 9.3, the low, median and high values of the MGO price are given.

Table 9.3: MGO prices range

Fuel type	Low	Median	High	Source
$price_{MGO}$ [€/ton]	170	500	600	[47]
C_{MGO} [€/MWh]	37.5	110	132.8	[67, 68]

In Table 9.4 the price range for shore power electricity at the terminal is shown. When referring to shore power price, the price that the ship pays to the shore power provider (terminal) is meant. The lower limit of the shore power price is determined by the positive scenario's of the terminal, for maximum utilisation or high subsidy a shore power price of 120 €/MWh is possible. And the upper limit of the shore power price is determined by the vessel, which needs a MGO price of at least 750 €/ton to compete.

Table 9.4: Shore power price range for vessels, upper limit is determined by the vessel, lower limit by the terminal

Electricity	Low	Mid	High	Source
Shore power [€/MWh]	120	140	160	From Terminal & Ship model

The cost of MGO (C_{MGO}) should be higher than the price for MGO, otherwise the ship is not able to earn back the investment. As seen in Table 9.3, the median MGO price much lower than the average shore power price the terminal would require, in the most positive case. Therefore, either the shore power price should be reduced or the MGO price should be increased.

To determine what the effect of the different prices is, the revenue of using shore power instead of fuel is shown in Figure 9.14 and 9.15. The two dotted lines represent the revenue per MWh, when using a MGO price of 600 €/ton and a shore power price of 120 €/MWh and 130 €/MWh. The ship earns back the investment if the LCOE line crosses the revenue dotted lines. are plotted over the amount of SP-visits of a ship per year.

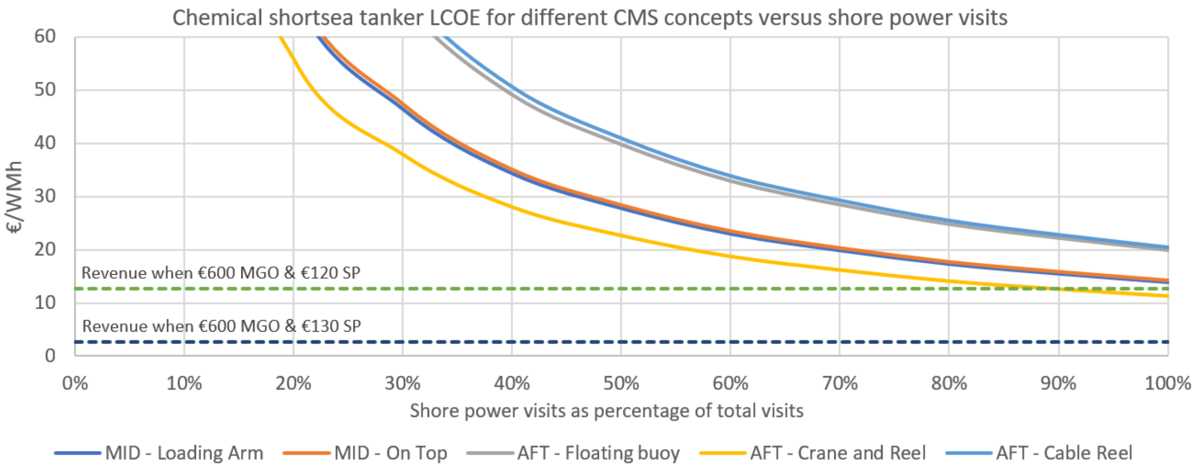

Figure 9.14: Chemical shortsea tanker LCOE of CMS concepts combined with the revenue of high MGO price vs low shore power over the amount of shore power visits

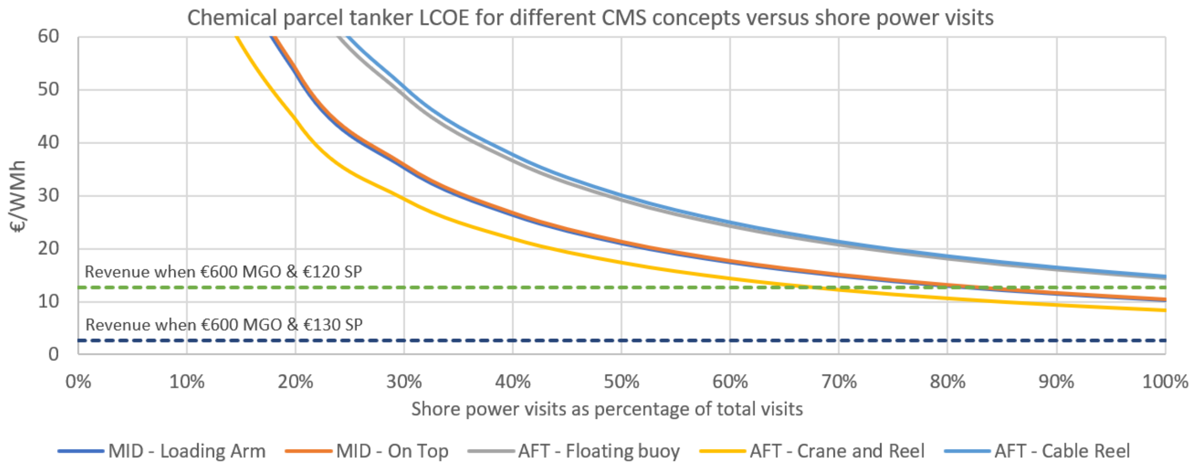

Figure 9.15: Chemical parcel tanker LCOE of CMS concepts combined with the revenue of high MGO price vs low shore power over the amount of shore power visits

When using the highest market-driven fuel price, and the lowest shore power prices at the terminal, only one of the two revenue lines cross the LCOE lines at a high shore power visit percentage. Which means, that only if the fuel price is high and shore power price is low, shore power is economically feasible for ships.

To overcome the LCOE of the shore power system it is important to analyse the shore power prices in combination with the MGO prices. As seen in Figure 9.14 and 9.15, the high MGO estimate is not large enough with shore power prices above 120 €/MWh. In order to further increase the MGO price, CO_2 tax can be used to artificially increased the MGO price. If an CO_2 tax is applied, it increases the MGO price as function of reduced carbon emissions. To quantify what CO_2 price is required to make a CMS concept feasible for both tanker types, Figure 9.16 and 9.17 show the required CO_2 prices. In the two Figures the median MGO price is used from Table 9.3, and the CO_2 price is shown which is required to make profit for a certain CMS concept with an certain shore power price.

CO2 price needed for 50% SP-visits Chemical shortsea

SP-price [€/MWh]	MID - Loading Arm	MID - On Top	AFT - Floater	AFT - Crane & Reel	AFT - Cable Reel
120	€ 58	€ 59	€ 79	€ 50	€ 81
140	€ 91	€ 92	€ 112	€ 84	€ 114
160	€ 125	€ 126	€ 146	€ 117	€ 147

CO2 price needed for 70% SP-visits Chemical shortsea

SP-price [€/MWh]	MID - Loading Arm	MID - On Top	AFT - Floater	AFT - Crane & Reel	AFT - Cable Reel
120	€ 46	€ 47	€ 61	€ 41	€ 62
140	€ 79	€ 80	€ 94	€ 74	€ 96
160	€ 113	€ 113	€ 128	€ 107	€ 129

CO2 price needed if 100% SP-visits Chemical shortsea tanker

SP-price [€/MWh]	MID - Loading Arm	MID - On Top	AFT - Floater	AFT - Crane & Reel	AFT - Cable Reel
120	€ 37	€ 37	€ 47	€ 33	€ 48
140	€ 70	€ 71	€ 81	€ 66	€ 82
160	€ 104	€ 104	€ 114	€ 100	€ 115

Figure 9.16: CO_2 price needed for shortsea tanker per CMS concept and different shore power prices

CO2 price needed for 50% SP-visits Chemical parcel

SP-price [€/MWh]	MID - Loading Arm	MID - On Top	AFT - Floater	AFT - Crane & Reel	AFT - Cable Reel
120	€ 48	€ 48	€ 62	€ 42	€ 63
140	€ 81	€ 81	€ 95	€ 76	€ 97
160	€ 114	€ 115	€ 128	€ 109	€ 130

CO2 price needed for 70% SP-visits Chemical parcel

SP-price [€/MWh]	MID - Loading Arm	MID - On Top	AFT - Floater	AFT - Crane & Reel	AFT - Cable Reel
120	€ 38	€ 39	€ 48	€ 34	€ 50
140	€ 72	€ 72	€ 82	€ 68	€ 83
160	€ 105	€ 105	€ 115	€ 101	€ 116

CO2 price needed if 100% SP-visits Chemical parcel tanker

SP-price [€/MWh]	MID - Loading Arm	MID - On Top	AFT - Floater	AFT - Crane & Reel	AFT - Cable Reel
120	€ 31	€ 32	€ 38	€ 29	€ 39
140	€ 65	€ 65	€ 72	€ 62	€ 72
160	€ 98	€ 98	€ 105	€ 95	€ 106

Figure 9.17: CO_2 price needed for parcel tanker per CMS concept and different shore power prices

As seen in the above figures, the scenario of a shore power price of 160 €/MWh is requiring large CO_2 prices. These price ranges are larger than the forecast of the EU ETS price of up to 89 €/ton in 2030, and therefore unfeasible. As seen in both figures, the best cost-effective solution is the aftship shore crane and reel. This is due to the fact that most of the small chemical tankers do not have a crane on the aftship and for both the aft floater and aft shore reel systems, two cranes should be installed on the ship. There are two cranes needed because the vessel should be able to berth along portside and starboard. When the shore power CMS concept provides a crane on the shoreside, which is also the case for ferries, there are no cranes needed on all the vessels. Which seems a more logical option from the point of view of the vessel, as these cranes would not be used during sailing.

9.2.5. Ship result

For the ships, a cable connection on the aftship is the preferential solution as discussed before in this section. Considering the technology assessment in Chapter 6, the aftship shore crane performs best on all criteria. When the economics of the CMS concepts is considered, the aftship shore crane and reel is obviously the best scoring in the economical evaluation, due to the crane investment on the shore side. When analysing the utilisation performance of the various CMS concepts, the midship located systems have the best power utilisation performance. However, the utilisation differences with the aftship located systems is small, with the berth direction factor set at 0.95, which relates to how much of the vessel can berth with the aftship at the right location. Only at a berth direction factor below 0.8, the LCOE of the midship systems will be lower than the aftship crane and reel.

The cost-effectiveness, the LCOE, of the aftship shore crane and reel is therefore the best for the chemical vessels in this case study, under the given circumstances. When using shore power in 50% of the ports, a CO_2 reduction of 444 ton can be realised. This LCOE equals an emission abatement price of 38 €/ton CO_2 when considering the LCOE versus the emission factor reduction for CO_2. This does not form any baseline for the CO_2-price required to earn back the investment.

The scenarios for which ETS CO_2 price the shore power concepts are feasible are shown in Figure 9.16 and 9.16. The forecast for the EU ETS CO_2 prices in 2030 range from 32 to 89 €/ton, thus the scenario should not be exceeding this limit [80]. Considering 50% shore power visits, the aft shore crane and reel is the only feasible option.

9.3. Evaluation of Solution

In order to choose a CMS concept that works for both the terminal and the vessel, the main driver is the vessel economics. Because, the CMS costs share is largest for the vessel, and the main cost drivers for the terminal is the shore based electrical equipment. Whereas the terminal benefits if more vessels would install shore power because the shore power utilisation at the terminal will increase.

Shore power becomes only profitable at a higher fuel price for vessels, thus needs a Emission Trading System with a CO_2 price which is applicable for shipping in the EU. Considering the lowest required CO_2 price, best performing solution for the vessel in operational, economical and utilisation aspect is the aftship shore based crane and reel.

However, this solution does only perform better when the berth direction factor is at least 0.8, as seen in the sensitivity analysis. The European chemical ports are mainly located alongside riverbanks, which makes them vulnerable for tides and strong currents. This could affect the berthing strategy, as discussed in Chapter 5. The berthing of vessels can deviate from the standard protocol if a strong current arises, which translates into not being able to use an aftship shore power system when berthed opposite to the shore power installation. In Figure 9.18, the berthing direction problem that could occur for the aft shore crane solution is visualised. If the ship is unable to berth in the shown direction, the shore power system can not be used. And for rivers it could occur that due to strong tides the vessel is unable to berth in a certain position, yet exact estimations and forecasts are not present for other countries.

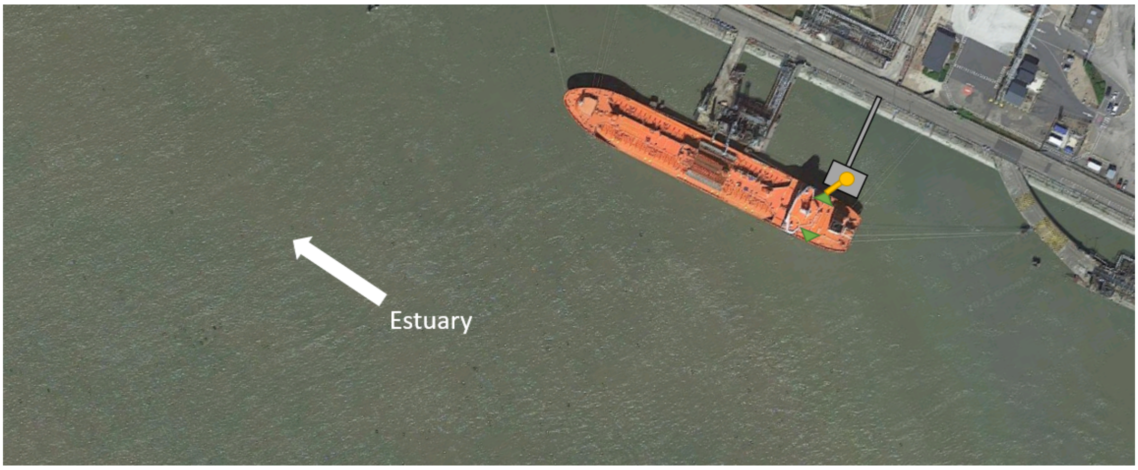

Figure 9.18: Terminal alongside river in Le Havre with direction of estuary shown and an Aft - Crane and reel concept drawing (Source: Google Maps)

The berthing direction factor is of high importance for the positive results of the aftship located CMS concepts. In Rotterdam it was estimated at 0.9 to 0.95, but this is no certainty and especially not for other ports with different geographical lay-outs and hydrodynamic differences such as stronger tides.

9.4. Roadmap Chemical market

This section describes the roadmap that is created in order to give a future outlook on how to convert the conventional use of auxiliaries in ports towards a more sustainable shore power energy system. As innovation is not done overnight, a roadmap is constructed to view the phases in which the shore power transition for the chemical market should happen. The road map is briefly summarised below.

Phase 0 - Collaboration

- Start collaboration with first five chemical ports in Europe.
- Identify large chemical companies and chemical terminals in ports.
- Identify long term time chartered vessels.
- Present possible positive economic outcomes and emission reduction to the whole logistic chain.

Before doing realising pilot projects with vessels and ports, collaborations with other ports in the chemical logistics chain and vessels are needed. All involved parties, should be convinced that shore power is a cost-effective emission reduction option in the ports. With willingness to invest in local emission reduction and more detailed information ships and terminals, the first step for realising pilot projects is made.

Phase 1 - Pilot

- Pilot projects with frequent visiting vessels, and terminals (liners).
- The vessel group is about the size of the case study group, 45 vessels, but preferably more vessels.
- The first five ports install shore power to provide an average of 50% shore power visits for the chemical case vessels (Rotterdam - Antwerp - HaRoPa - Teesport - Fawley&Southhampton) .
- The MGO price should be at least 600 €/ton otherwise the CO_2-price should be able to top up the price.
- Vessels should get discount on port fee when using shore power in the port, this could reduce the vessel LCOE by 3 to 6 €/MWh. Which can be significant for the smaller chemical vessels.
- Lower shore power price to 120 €/MWh, as the amount of shore power ports is low, the shore power price for the vessels should be kept artificially lower by subsidising the terminal investment costs. Because in the starting phase only a relative small group of vessels are equipped with shore power and the terminals have too high expenses for the few shore power visits.

For chemical shortsea vessels, that visit Rotterdam 20 times a year, the difference between the shore power price and MGO price must be rather large to earn back the investment. The current MGO price of 500 €/ton should be artificially increased up to 650 €/ton with a emission tax for CO_2 of 55 €/ton CO_2 in order to have a profitable business case for a shore power price of 120 €/MWh. As seen in Figure 9.16 and 9.17, the vessels business case is highly sensitive to the amount of port visits where shore power is available.

Phase 2 - Chemical Market adaption

- More chemical vessels using shore power and can visit more shore power ports, thus there is less need for the lowest shore power price. This means that the terminals require less subsidies to keep the price of shore power at 140 €/MWh or lower.
- More terminals investing in shore power, thus more shore power port and that increases the amount of shore power visits for vessels which increases the economic feasibility for the vessels and more vessels join.

For the European chemical shipping market, the potential of realising shore power is the highest. Furthermore, the first steps should be collaborate with the other ports in the chemical shortsea chain. Only if a certain amount of ports is willing to collaborate in the shore power projects, the vessel owners will trust the future port developments and will consider shore power as feasible emission abatement option.

However, the downside is that for only connecting the chemical market, it can be unfeasible to install shore power on all the berth locations of a terminal. This is because only a share of the terminal visitors, the chemical vessels, is using the shore power.

9.5. General liquid bulk adaptation

To complete the results of using shore power for liquid bulk vessels, this paragraph briefly discusses the insights that are applicable for all liquid bulk vessels. First of all, the emission reduction potential of shore power in ports is high if all visiting vessels are using shore power. Most European electricity grid emissions are substantially lower than the MGO emissions from the shipboard diesel generators, therefore emission abatement is substantial.

To review the important factors for the shore power case for other vessel types, the berth times, port visits and power demands are important.

As the ship size increases, longer routes are sailed in general and thus less shore power time is available each year. However, larger ships tend to stay longer in ports at terminals compared to smaller vessels, hence this difference is small compared to the port visits difference.

Shortsea vessels which sail short distances in Europe requires only the large European ports to invest in shore power, which have the possibility to attract European funds to subsidise the investment. Longer sailing distances require ships to rely on the worldwide shore power implementation in order to use shore power. When the logistic chain is smaller, the implementation of shore power will be easier because the ports network is smaller and less ports should provide shore power in order to have enough.

When reviewing the case study, for the shortsea and parcel chemical tankers under 20,000 DWT, it was found that the medium range oil- and chemical tankers also visited quite often. Adding these vessels to the shore power ready fleet could have a positive influence on the power utilisation for the terminals. Using the crane limitation as seen in Figure 7.9, the medium range vessels could in theory be covered by aft based systems. Therefore, the aft based crane shore power system will perform really well on chemical terminals with medium range oil or chemical vessels visiting as well.

Using the terminal model, larger terminals with only Suezmax or VLCC visits have also potential for shore power systems. Because most of these large vessels are discharging in Rotterdam and are all about the same size. Yet, the problem is that a lot of unique vessels are visiting. Due to the fact that large oil vessels make longer trips and crude is more a spot market, so less liner services. Which requires a rather large group of vessels to make shore power economically feasible for the terminal.

IV

Conclusion & Discussion

10
Conclusion

This section draws the main conclusions of this research on the feasibility of shore power concepts for the liquid bulk industry. First, a brief answer is given to the research questions as formulated in Chapter 2, as well as the main research question. Thereafter, the recommendations for further research and development of shore power for liquid bulk vessels and terminals are presented. Finally, general insights are presented for using shore power both for the ships and the terminals.

10.1. Research questions

1. *"What is the current state of shore power systems for liquid bulk vessels; which research has been conducted already and how have similar questions been answered?"*

The shore power system has been studied and analysed and the functions and requirements of its subsystems are found. The onshore power supply should provide the desired voltage for transporting and provide the frequency that is used on board. Also, the equipment to do this is placed on the terminal side in a sub station. The desired voltage and frequency should then be provided to the CMS. The CMS placement should be aligned with the ship connection point and not obstruct other port operations. The CMS placement should be chosen such that most vessels could connect to the shore power system if available. The cable should be safely stored on land in order to provide the cable from shore to ship. Also, as part of the CMS, sufficient grounding of the system should be done, if that is not yet done for a vessel and terminal. The onboard connection subsystem has to provide a connection between the shore power cable and the vessels receiving point without spark hazards. It should provide a voltage transformation from the incoming 6.6 kV to the desired onboard voltage level in order to connect with the main switchboard. Also, it should provide a synchronisation of the power supplies before switching off the generators. The cable run on board should be as short as possible.

Research in the field of concept design, often use Key Performance Indicators (KPI's) to determine the performance of a new system. The KPI's of a shore power system for liquid bulk vessels are:

- **Costs**, the total annualised costs of owning and operating the shore power system as well for the terminal as the ship.
- **Power utilisation**, amount of shore power used, where each MWh of shore power has an constant emission reduction factor.

2. *"How to categorise the various liquid bulk vessels in archetypes?"*

The liquid bulk vessels are segmented into the four cargo categories as discussed in Chapter 5, and thereafter into a total of 14 subcategories based on cargotype and sizetype. This segmentation was done based on the Clarkson database containing all commercial vessel information. The table consisting of all the liquid buik vessel archetypes that are used in this thesis is shown in Table 5.1. The segmentation output is based on creating the archetypes which consist of a large group of vessels, while still have some certainty that technical parameters are within an acceptable range.

3. *”Which operational and technical requirements are relevant for connecting a liquid bulk vessel to shore power from the vessels perspective?”*

This question is answered in Chapter 5. The technical requirements and parameters are shown in Table 5.3. Also, the estimation of the loading and discharging power demands of the various archetypes is made. In order to have insights in the average power demand of each vesseltype and how much shore power is required to power vessels at the terminal. Also, the berth direction factor is important for aftship shore power systems.

4. *”What are the criteria by which to assess technical feasibility of solutions for the shore power systems and which solutions are feasible?”*

In literature, various criteria are found for evaluating technology concepts for a system, also during meetings with third-parties regarding shore power systems some criteria were discussed. These two sources formed the criteria that are relevant for this feasibility study, which are 1) Safety, 2) TRL, 3) Easy to use and 4) Compatibility.

Each solution that is discussed in Chapter 6 is technical feasible because all use already existing principles. Yet, the scoring on each of the criteria is different for each system.

5. *”What is the synthesis of a model which demonstrates the economical and emissions related feasibility of the shore power system for a ship or terminal?”*

This is discussed in Chapter 7, the model is split up in a ship model and a terminal model. Both models are based on the model requirements as specified in the same chapter, which form the basis for calculating the KPI’s and providing insights in the shore power business case.

6. *”How can this model be used to find a high potential shore power case for liquid bulk submarket?”*

The model shows that shore power port visits and shore power ready vessels are important for a feasible business case of shore power systems. Therefore, the most visiting vessels must be found, which are the chemical tankers under 20,000 dwt, also called shortsea and parcel tankers. These vessels have the most potential for realising economical feasible shore power system, due to a large amount of visits in the Port of Rotterdam. Of all liquid bulk vessels in Rotterdam, these tankers have the largest potential of realising shore power in the industry. This is because, most visits to Rotterdam, relative large power demand, short sailing times and lot of port visits and part of the European shortsea chemical market and therefore highly subjected to future EU (ETS) regulation.

7. *How can this model be used to create future scenarios in a case study by which the overall feasibility can be determined?”*

The case study showed that only under a few circumstances shore power concepts are economically feasible. The case study vessels are the best performing group of vessels in terms of port visits and thus the described minimal parameters for future scenarios under which the shore power concept is feasible. The best perfoming CMS concept is the aftship based shore crane and reel, due to the lowest investment for the ship. Also, the power utilisation is only slightly smaller than compared to midship systems. Combining the economics and the utilisation, this system is the most cost-effective concept for the vessel. And the required circumstances for shore power to be economically feasible are:

- Shore power availability at the five largest European chemical ports.
- With five ports, the MGO price should be increased with a CO_2 price of at least 84 €/ton when the shore power price is 140 €/MWh. And for a shore power price of 120 €/MWh a CO_2 price of 50 €/ton is required.

- The terminals need a capital costs subsidy of at least 75%, however this is dependent per terminal. As the terminals have a rather large subsidy, the price differences per CMS concept become negligibly small. Some terminals still have an unfeasible economic outcome with subsidy due to the small case vessel group.

However, this shows that shore power is feasible for only 45 vessels and all the terminals in the European ports. The amount of shore power vessels should and could be increased in order to reduce the subsidy that is required.

Finally, a concluding answer to the main research question of this master thesis is provided:

"Determine the feasibility of conceptual shore power system for berthed liquid bulk vessels, considering the technical, economical and emissions related conditions."

This research has shown that shore power has a good performance on emission abatement, due to no local emissions and 80-90% of MGO emissions are reduced compared to electricity. However, shore power is currently not economically feasible for the liquid bulk industry, the cost-effectiveness is too high at low utilisation of shore power. In addition to that, for ships using MGO for electricity generation is cheaper than using shore power.

The case study showed that for the case vessel group of 45 chemical tankers who have a high shore power potential, the shore power is still not feasible for the terminals, since the group of vessels is too small for the terminal to make profit. However, under a few scenario's shore power concepts could be economically feasible for the chemical tankers and the liquid bulk terminals. First of all, this thesis shows that with an increase in MGO price, either by market or ETS system, shore power becomes economically feasible for the chemical tankers. This requires a CO_2 price of at least 55 €/ton, considering vessels can only use shore power in 50% of the ports. The use of the aftship shore crane and reel requires the lowest CO_2 price of all the CMS concepts, and is therefore the best performing system based on cost-effectiveness. As for the terminals, when selling shore power at a price of maximum 160 €/MWh, the use of shore power for most terminals is only feasible with almost full utilisation and partly subsidies on the investment costs. Since all visiting vessels will not convert to shore power at once, maximum shore power utilisation can not be expected. Therefore, the LCOE should be reduced by requesting subsidies for the investment. As the investment subsidy increases, the LCOE differentiation of the various CMS concepts reduce significantly (Figure 9.8). Up until the point, where from the terminal economical point of view, the choice of CMS does not matter.

When almost all visiting vessels use shore power at the terminals and more ports adapt shore power at the terminals, the utilisation will increase rapidly. This leads to terminals who could offer shore power for 120-140 €/MW, yet still a lot of terminals need 25-50% subsidy for the investment. The required shore power price for the terminal does not converge to a point, where it is below 120 €/MWh. For the vessels, if the MGO price stays 500 €/ton, there is an ETS CO_2 price required of 33-66 €/ton, to cope with the shore power price of 120-140 €/MWh.

10.2. Recommendations

Installing shore power systems in a port and on vessels of the liquid bulk market requires standardisation of the shore power system. But the next step in realising shore power is also, customise the standard shore power concept to the exact requirements of each terminal. Because, almost no terminal layout or jetty design is the exact same, thus installing shore power installations needs detailed studies on the lay-out and structure of the terminals berth places.

In short the recommendations are:

- Collaborate with ports, terminals, shipping companies and oil refinery companies to identify long term trade lanes where part of the chemical market is sailing. When a larger group of chemical tankers, who sail trade lanes is identified, more specific and detailed shore power business cases can be made.

- Terminals require 25-100% subsidy on the capital investments, otherwise shore power is not economically feasible. In order to provide a constant low shore power price to the vessels, subsidy is required to keep the shore power price constant while the shore power utilisation is low.
- Further research into the cost effectiveness of batteries for peak shaving or continuous lower power supply. This will make the power demand smoother over time and reduce the maximum monthly grid costs and the total installed power. The average power demand in a whole year is often 60-70% lower than installed for shore power, a large battery could therefore reduce the installed power significantly. The LCOE for shore power can be reduced by 5 - 20% when a battery is used, assuming battery prices from Zakeri [51].
- In depth study for each terminal, what the time dependent utilisation of the berth places is and what vesseltypes are visiting (or average power demand) these specific berth places. When the total ships power demand over time is obtained a more specific maximum power for the installation can be estimated. And less shore power systems could be installed, if chemical vessels only berth at a limited berth places at the terminal.
- Ships should get a discount on port fees when using shore power, in order to increase the profit for using shore power and to payback the investment. Create a larger financial incentive to invest in shore power.
- The berth direction factor for the aft ship systems has a large influence on the power utilisation of the system. Assessing whether a factor above 0.85 is realistic for all terminals is important, otherwise the loss in efficiency is too large for the aftship systems.
- For the afthip based systems the crane outreach is limited, yet more of the visiting vessels at (mainly) chemical terminals are within the outreach of the aftship based cranes. Thus, aside from the chemical shortsea and parcel tankers, the MR chemical and oil vessels up to MR are able to be serviced.

10.3. Insights

This section briefly describes some insights in the operations, technical parameters and costs of the vessels and terminals.

Ship insights

- Oil tankers have more concentrated distribution of the length, which gives certainty but also larger differences between tankertypes.
- Oil and gas tankers larger than 60,000 dwt usually have steam turbines who drive the cargo pumps.
- Chemical tankers have a more evenly distributed length, which gives uncertainty but a smoother gradient between other sizetypes.
- Chemical tankers and gas tankers have a higher electrical power demand than oil tankers.
- Not all vessels have usable cranes on the aft deck, or if a crane is present, it is designated to transporting a life boat.

Terminal insights

- Costs are rapidly increasing when the installed power exceeds 10MW, due to increasing grid connection cost above 10MW.
- The investment costs and operational expenses are sensitive to the increase or decrease of the installed power of the shore power system. Lowering the total installed power is recommended if only a small group of vessels demands this.
- Maintenance has a little effect on the MWh price, however yearly electricity prices have a large effect, thus the focus on improving the installed power estimation at the terminal.

- The grid tariffs take a large part of the operational costs per year, these increase with the power increase of the installation.
- Terminals with higher vessel per berths place have a higher potential for shore power.
- Smaller terminals in the Botlek area could cooperate, to slightly reduce the costs for grid connection and excavation costs towards the HV-grid. Yet, only if the total installation power is under 10MW, see the first bullet point.
- The distance to a grid connection point has a substantial influence on the total costs due to the high costs for the cable and excavation/installation. As this is easily 1 to 2 kilometers, the total capital costs for cable and excavation are exceeding €300,000.

11 Discussion

This chapter provides relevant discussion topics about this research and also addresses some uncertainties that were found in analysing all the used data.

- Both the models need information or outcomes from the other model, yet this is an infinite loop and can not be solved entirely. The interdependence is done by using the alternative scenario's for the ship visits and the shore power ports for example.
- The CO_2 price is calculated using the prospected CO_2 reduction when burning a ton of fuel versus using shore power, which depends on the future grid emissions. If the Dutch grid emissions are lower than the EU forecast of 2030, than the required CO_2 price will increase vice versa.
- The case study is performed for chemical vessels under 20,000 ton dwt, and thus the limited crane outreach of aft systems is no disadvantage as 'all' vessel can be covered by the crane. Yet, the chemical terminals do have other, larger, vessels visiting, thus the aftship located cranes could not reach vessels that are quite larger.
- For better tailored results: more specific information of the berth places is needed. At the abstract level from this thesis, the average total visits can give a good indication what vessels typically arrive at that terminal. However, there might be an certain distinction between various berth places, due to cargo pipelines which are solely designated for specific products. In that case, for at least all berth places the CMS must be installed in order to provide shore power to all ships.
- The model does take into account the specific country electricity prices and electricity transport costs in each country, since for a vessel it is unknown in which country it visits exactly. The electricity price in France is the same as in the Netherlands, but in Belgium and the UK the electricity price is 15% to 20% higher [54]. However, mainly due to taxes and transport costs, which could be exempted by the government to promote shore power.

11.1. Uncertainties

The work in this thesis is subjected to a lot of uncertainties, either small or large. Uncertainties occur in the economical assumptions, some operational parameters, the future forecasts and database segmentation. The uncertainties are discussed below,

Operational uncertainties

- The median of the power and length of each vesseltype is often representing the fleet very well, but some vesseltypes have a broad distribution of length and power. Therefore, real life outcomes for costs and power utilisation can be deviate from the model results.
- The average loading or discharging power demand of a vessel type is dependent of the median and a loading/discharging factor that is used. The actual average power demand during a port

visit can be different than that is used in this model.

- For the aft-ship systems, the water gap from shore to vessel is estimated at 7.5 meter based on average measured length at the Botlek. However, especially for large vessels the curvature at the aft-ship can increase the water gap significantly.
- The yearly averaged vessel visits are not an actual representation of the future vessel visits, but it gives an indication of yearly average if the terminal vessel visits are in the same order of magnitude as the past 10 years.

Economical uncertainties

- The costs estimations of the different CMS concepts are based on costs of similar existed technologies, but especially with low TRL of concepts, these costs have a large uncertainty.
- The electricity price for industrial consumers is taken constant at a 3-year average. The price trend was slightly downwards, but this does not provide a guarantee for price of electricity in the upcoming years.
- The costs of the electrical infrastructure are dependent on the supplier and installation company, and are subjected to small uncertainties.
- The installation of a platform, or the excavation of the cables at the terminal are dependent of the average construction costs in the country of installation, this research is based on costs estimated by dutch standards. Therefore, it can't be assumed that the costs for construction and operation are exactly equivalent in other countries.
- The price per reduced tonne of CO_2 depends on the forecast of the CO_2 price and the absolute reduced CO_2. The forecast of the grid emission factors is sensitive to the future renewable energy plans of different EU countries for electricity production.

Database segmentation

- When segmenting data in groups, in order to make a more organised vesseltype structure, some vessels will fall outside of a certain upper limit or outer limit of all groups. The goal was to minimise the amount of vessels not represent in a group, while still having small enough groups such that the median data could still be a representative value for the whole group. However, this is not possible in the real world and especially not with the worldwide tanker fleet, it is simply not possible to fit all vessels in an amount of segments that contain more than 1 vessel.

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Appendices

A

Shipping Data

This chapter presents additional data from the shipping data of the Clarkson database [6].

This paragraph explains the manual exclusion of vessels in the Clarksons database where some vessels have been manually deleted from the database for this research. All ships that were build before 1975 do not have to comply with the SOLAS regulation that was introduced in November 1974. Therefore the decision was made to exclude these vessels in the data research, because they do not comply with safety regulations. Also vessels that have less than 1000 ton deadweight are not included, because in the past 10 years only 2 vessels with a deadweight below 1000 ton have called the Port of Rotterdam[1]. And the ships that do not have a deadweight tonnage specified are removed as well from the data set. All of the vessels that complies with one or more of the above properties do not have any other relevant information for the data analysis. Furthermore, most of these vessels will not sail in Europe and are even smaller than inland tankers in the Netherlands. The older vessels are most of the times rather small and do not provide information that is useful for the analysis of the technical aspects of the ships either.

The boxplots in Figure A.1 and A.2 consist of the 10th percentile, the median and the 90th percentile, this is chosen because it shows 80% of the ships instead of 50% of the regular boxplots. By plotting 80% of the vessels in a boxplot, the distibution of the power over the different vessels is made clear.

[1]According to the liquid bulk port call list

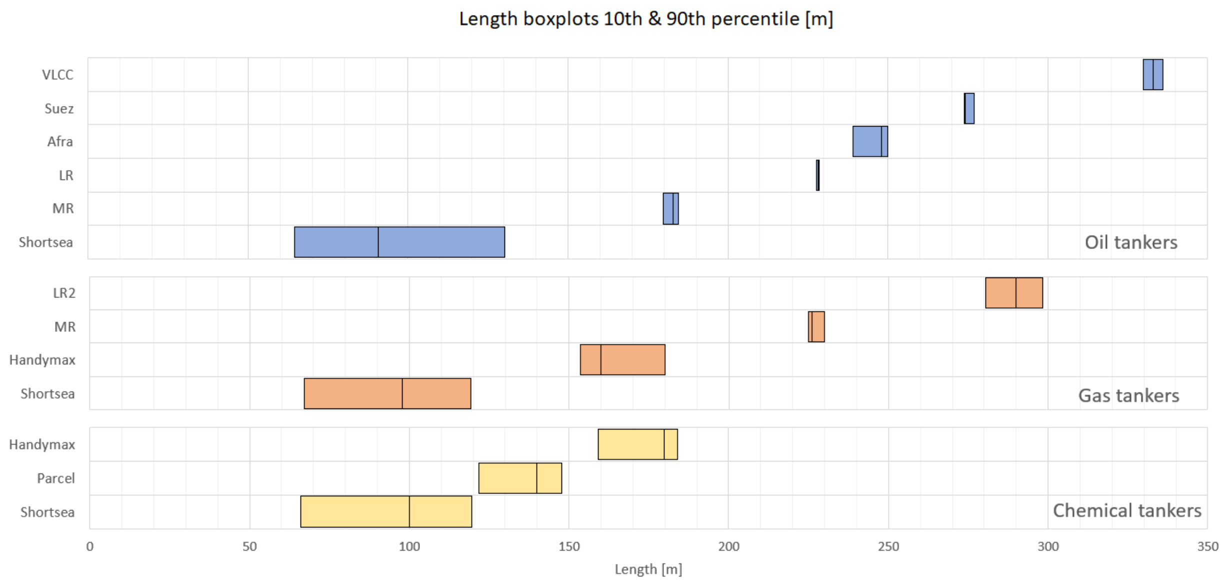

Figure A.1: Vesseltype length boxplots derived from the Clarkson database [6]

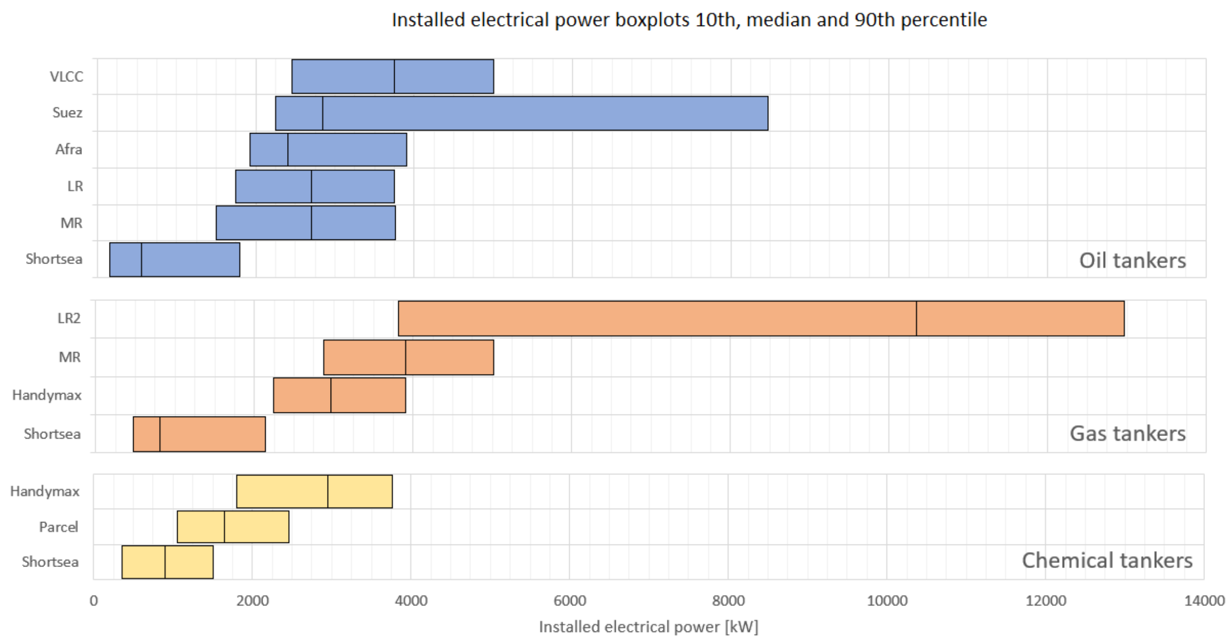

Figure A.2: Vesseltype installed electrical power boxplots derived from the Clarkson database [6]

Frequencies of liquid bulk vessels

Power estimation of liquid bulk vessels

The load factors for determining the loading and discharging power demands are based on electric load analyses of specific vessels and Browning [17]. In Table A.1, the obtained load factor values are shown.

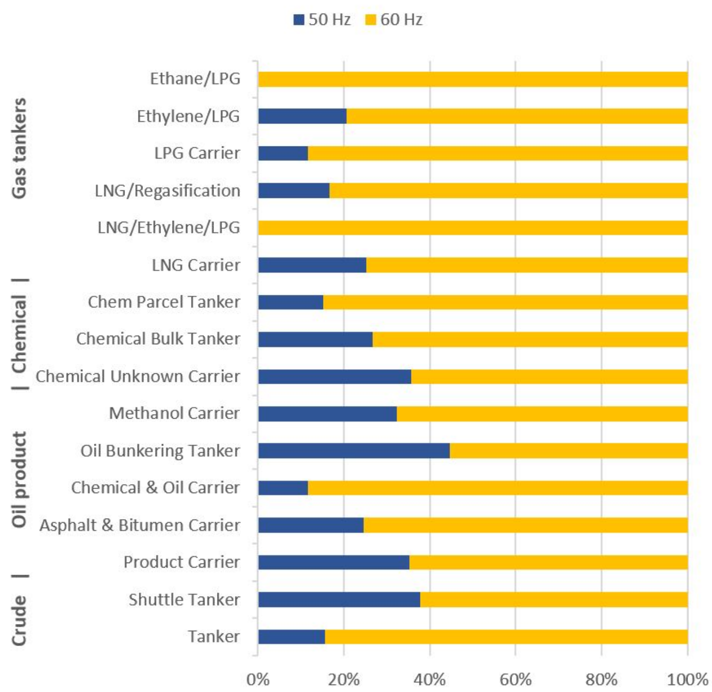

Figure A.3: Voltage frequencies used onboard per shipstype, obtained from Clarkson database [6].

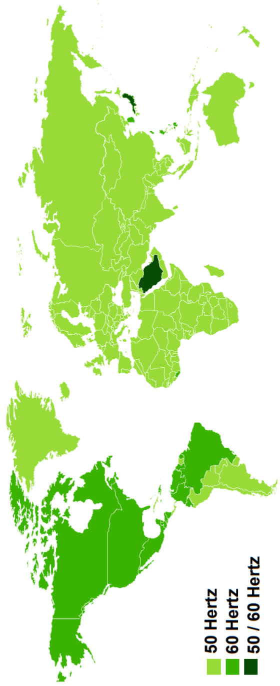

Figure A.4: Frequencies of voltages used worldwide [11], also endorsed by [12]

Ship	Loading - load factor	Discharging - load factor
Oil tankers	0.25	0.7
Gas tankers	0.25	0.7
Chemical tankers	0.5	0.7

Table A.1: Power load factor for different tanker vessels [17].

B Model Verification

The detailed verification of the terminal model and terminal model is described in this chapter. The ship model in Table B.1, and the terminal model in Table B.2.

Parameter	Value	Equation	Output	Value	Explanation
TCC (capex)	€1	7.2	$C_{cap,a}$	€0/yr	works as expected
TCC (capex)	€2,000,000	7.2	$C_{cap,a}$	€108,718/yr	works as expected
Years (T)	1	7.2	$C_{cap,a}$	€3,657,692/yr	works as expected
Years (T)	40	7.2	$C_{cap,a}$	€9,144/yr	works as expected
Interest (CRF)	0	7.2	$C_{cap,a}$	€17,672/yr	works as expected
Interest (CRF)	12	7.2	$C_{cap,a}$	€19,074/yr	works as expected
SFC	1	7.4	C_{fuel}	€0.5/MWh	works as expected
SFC	400	7.4	C_{fuel}	€200/MWh	works as expected
η_{gen}	0.5	7.4	C_{fuel}	€1,050/MWh	works as expected
η_{gen}	1.5	7.4	C_{fuel}	€55.5/MWh	works as expected
t_{berth}	1 hr	7.7	$P_{SP,ship}$	56.4 MWh/yr	works as expected
t_{berth}	64 hr	7.7	$P_{SP,ship}$	3611.5 MWh/yr	works as expected
ops_n	1	7.7	$P_{SP,ship}$	30.6 MWh/yr	works as expected
ops_n	120	7.7	$P_{SP,ship}$	3679 MWh/yr	works as expected
P_{ship}	1kW	7.7	$P_{SP,ship}$	1.8 MWh/yr	works as expected
P_{ship}	1900kW	7.7	$P_{SP,ship}$	3530 MWh/yr	works as expected

Table B.1: Ship model verification of changing parameters

Parameter	Value	Equation	Output	Value	Explanation
TCC (capex)	€1	7.2	$C_{cap,a}$	€0 /yr	works as expected
TCC (capex)	€12,000,000	7.2	$C_{cap,a}$	€650,000 /yr	works as expected
Years (T)	1	7.2	$C_{cap,a}$	€14,120,508 /yr	works as expected
Years (T)	40	7.2	$C_{cap,a}$	€182,755 /yr	works as expected
Interest (CRF)	0	7.2	$C_{cap,a}$	€17,672/yr	works as expected
Interest (CRF)	12	7.2	$C_{cap,a}$	€19,074/yr	works as expected
t_{berth}	-90%	7.12	P_{total}	56.4 MWh/yr	works as expected
t_{berth}	+90%	7.12	P_{total}	56.4 MWh/yr	works as expected
$P_{n,ship}$	-90 %	7.12	P_{total}	56.4 MWh/yr	works as expected
$P_{n,ship}$	+90%	7.12	P_{total}	56.4 MWh/yr	works as expected
R_{sf}	1kW	7.13	P_{SP-sys}	1.8 MWh/yr	works as expected
R_{sf}	1kW	7.13	P_{SP-sys}	1.8 MWh/yr	works as expected
b_d	0	7.14	Cof_{SP}	0	works as expected
b_d	1	7.14	Cof_{SP}	1	works as expected

Table B.2: Terminal model verification of changing parameters

C

Costs Data Ship

The costs for the ship are divided into electrical equipment costs and CMS related costs (Equation 7.1). The electrical costs are based on prices for the breaker and the transformer, which are dependent on the maximum power demand and thus increasing over size of the vessel. The fixed cost in the table consists of the electrical costs and the fixed installation cost. The CMS related costs are estimated for the five different CMS concepts, and based on the equipment required. With the cable length as function of the vessel size. The costs are evaluated with other cost approximations from literature, and are within the range of expectation [25, 29, 81]

Table C.1: Costs estimations for shore power equipment on liquid bulk vessel

Cargo type	Size type	Fixed Cost	AFT - Cable Reel	AFT - Floating buoy	AFT - Crane and Reel	MID - On Top	MID - Loading Arm
Oil	Shortsea	€ 132.800	€ 132.685	€ 132.685	€ 132.685	€ 213.920	€ 213.920
	MR	€ 200.480	€ 144.180	€ 144.180	€ 144.180	€ 226.535	€ 226.535
	LR1	€ 200.480	€ 150.151	€ 150.151	€ 150.151	€ 233.088	€ 233.088
	Aframax	€ 167.360	€ 152.769	€ 152.769	€ 152.769	€ 235.960	€ 235.960
	Suez	€ 200.480	€ 156.240	€ 156.240	€ 156.240	€ 239.769	€ 239.769
	VLCC	€ 200.480	€ 164.000	€ 164.000	€ 164.000	€ 248.285	€ 248.285
Gas	Shortsea	€ 132.800	€ 133.200	€ 133.200	€ 133.200	€ 214.486	€ 214.486
	Handymax	€ 200.480	€ 141.140	€ 141.140	€ 141.140	€ 223.199	€ 223.199
	MR	€ 232.160	€ 149.862	€ 149.862	€ 149.862	€ 232.770	€ 232.770
	Afra	€ 344.480	€ 158.318	€ 158.318	€ 158.318	€ 242.050	€ 242.050
Chemical	Shortsea	€ 132.800	€ 133.689	€ 133.689	€ 133.689	€ 215.022	€ 215.022
	Parcel	€ 167.360	€ 138.492	€ 138.492	€ 138.492	€ 220.293	€ 220.293
	MR	€ 200.480	€ 143.764	€ 143.764	€ 143.764	€ 226.078	€ 226.078
Special	Shortsea	€ 132.800	€ 127.928	€ 127.928	€ 127.928	€ 208.700	€ 208.700

D

Costs Data Terminal

The costs for the terminal are divided into the electrical equipment costs and the CMS related costs. The electrical equipment costs are based on the costs for the grid connection, the HV cables, transformers, frequency converter, filters and the Ehouse construction. The costs are based on internal cost estimations from the Port of Rotterdam for similar shore power projects and in the same order of magnitude as reviewed in literature [29, 81]. The electrical equipment costs as function of the installed power are shown in Figure D.1.

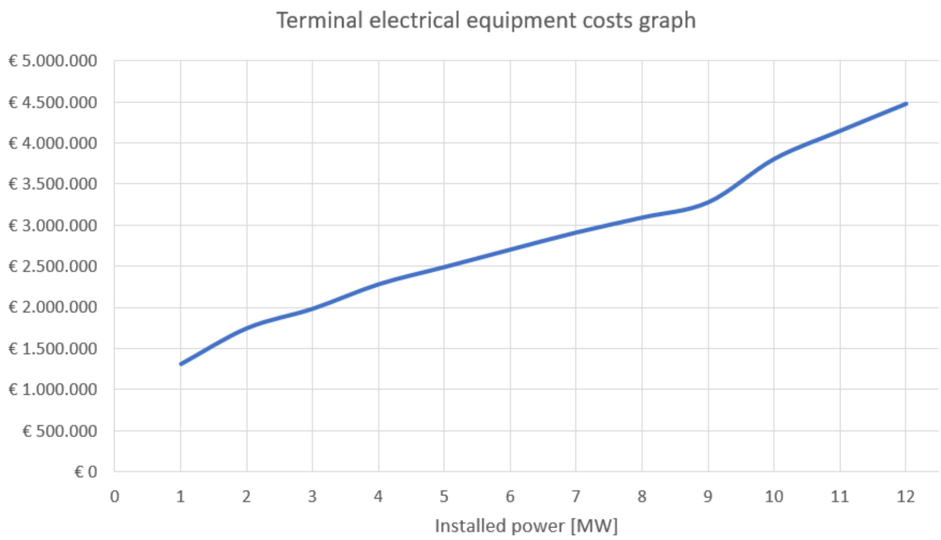

Figure D.1: Terminal electrical equipment costs as function of the installed power

The CMS related costs are based on the estimated costs for each subsystem of the CMS concept. This based on similar subsystems pricing from literature or assumptions [54, 76, 82]. In Table D.1, the costs for the CMS concepts are shown.

Table D.1: The basic breakdown of the costs of Cable Management System concepts

MID - on Top				
What	**Amount**	**Cost**	**Price**	**Source/Note**
Elevated container	1	€ 150.000	€ 150.000	Steel construction assumption
Inerted Box	1	€ 75.000	€ 75.000	Large volume [83]
Cable Reel	1	€ 150.000	€ 150.000	[82]
Cable	50	€ 100	€ 5.000	Stedin
Control cable	50	€ 20	€ 1.000	Stedin
Additional Platform	1	€ 250.000	€ 250.000	PoR AM estimation
			€ 381.000	
		no space	€ 631.000	
MID - Loading arm				
What	**Amount**	**Cost**	**Price**	**Source/Note**
Loading Arm	1	€ 250.000	€ 250.000	Based on B2Bmarine quotation
Inerting mechanism	1	€ 25.000	€ 25.000	Small volume [83]
Cable Reel	1	€ 150.000	€ 150.000	[82]
HV Cable	50	€ 100	€ 5.000	Stedin
Control cable	50	€ 20	€ 1.000	Stedin
Additional Platform	1	€ 250.000	€ 250.000	PoR AM estimation
			€ 431.000	
		no space	€ 681.000	
AFT - Floating Buoy				
What	**Amount**	**Cost**	**Price**	**Source/Note**
Floater	1	€ 250.000	€ 250.000	Assumption
Hook system	1	€ 25.000	€ 25.000	Assumption
Submerged cable	200	€ 100	€ 20.000	Stedin
Cable Reel in floater	1	€ 100.000	€ 100.000	Based on Stehmann/RHDHV data & [82]
HV Cable	50	€ 100	€ 5.000	Stedin
Control cable	50	€ 20	€ 1.000	Stedin
			€ 401.000	
AFT - Crane and Reel				
What	**Amount**	**Cost**	**Price**	**Source/Note**
Cable Reel within crane	1	€ 100.000	€ 100.000	Based on Stehmann/RHDHV data & [82]
Shore Crane	1	€ 160.000	€ 160.000	Based on B2Bmarine quotation
HV Cable	50	€ 100	€ 5.000	Stedin
Control cable	50	€ 20	€ 1.000	Stedin
Platform installation	1	€ 250.000	€ 250.000	PoR AM estimation
			€ 266.000	
		If Jetty	**€ 516.000**	
AFT - Cable Reel				
What	**Amount**	**Cost**	**Price**	**Source/Note**
Cable Reel	1	€ 150.000	€ 150.000	[82]
Cable lifting tool	1	€ 10.000	€ 10.000	Assumption
HV Cable	50	€ 100	€ 5.000	Stedin
Control cable	50	€ 20	€ 1.000	Stedin
Platform installation	1	€ 250.000	€ 250.000	PoR AM estimation
			€ 166.000	
		If jetty	**€ 416.000**	

E

Emissions Data

The emission reduction that is calculated when using shore power is based on the grid emissions of electricity production in the Netherlands.

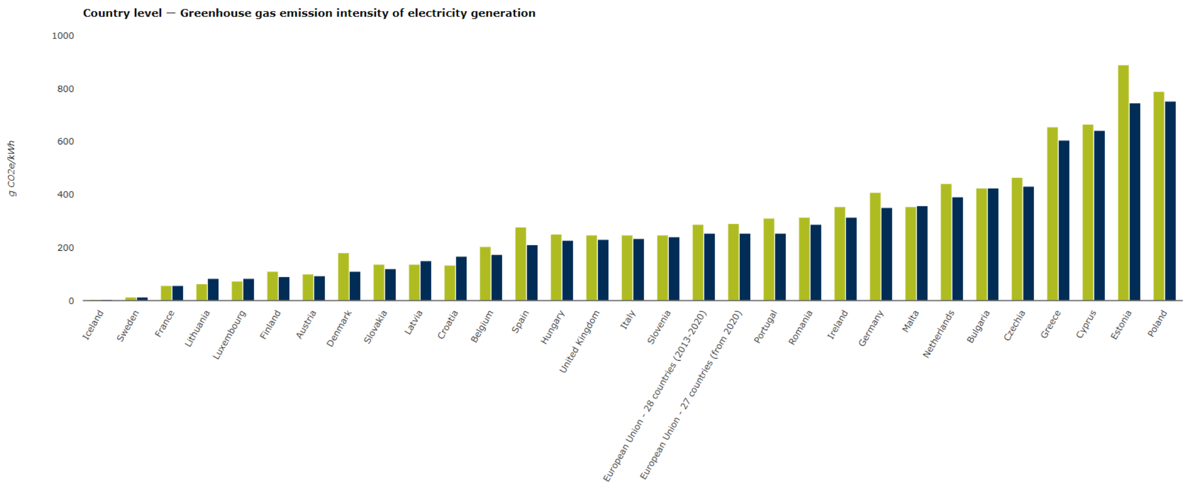

Figure E.1: CO_2 emissions per kWh generated electricity in Europe for 2018 and 2019. [13]

The reduction scenario for 2030 is also found using the data of the European Environment Agency. In Figure E.2, the forecast of the grid emissions is shown. Two scenario's are plotted, the high reduction scenario is at 75.5 g/kWh and the low reduction scenario is at 96.8 g/kWh. For the forecast of the Netherlands, the low reductin scenario is chosen due to the fact that the Netherlands are below the European average.

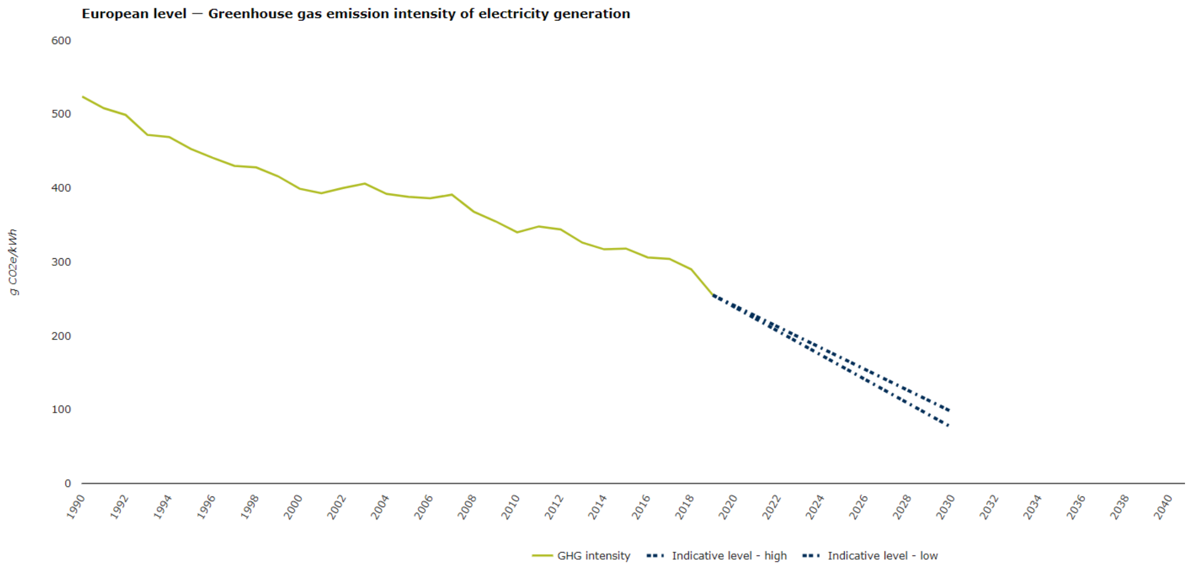

Figure E.2: Forecast of the emission factor of electricity production in the European Union [13]

Note with the figure [13]: "The 2030 values represent indicative intensity levels that would allow the EU to achieve a net 55% reduction in greenhouse gases by 2030, compared with 1990. Greenhouse gas emission intensity (g CO2e/kWh) is calculated as the ratio of CO2e emissions from public electricity production (as a share of CO2 equivalent emissions from public electricity and heat production related to electricity production), and gross electricity production."

F Case Study Berth Times

The berth times probability distributions are shown in the following three figures, based on the berth times in the Port of Rotterdam 2019 - 2020. The berth times distribution are shown for the chemical shortsea, parcel and MR tankers, respectively.

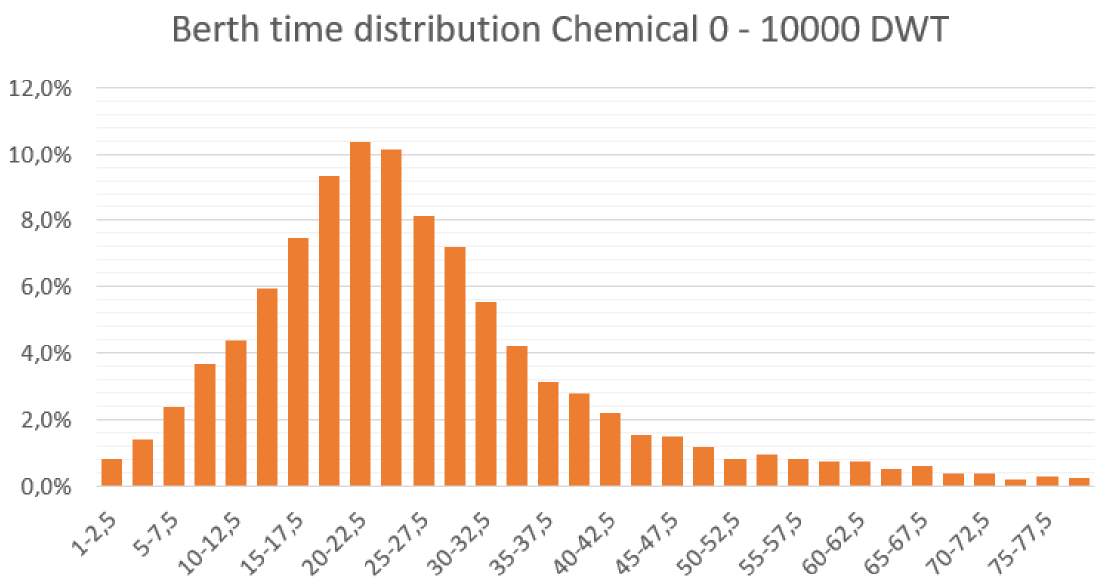

Figure F.1: Berth times probability distribution of chemical tankers below 10,000 DWT

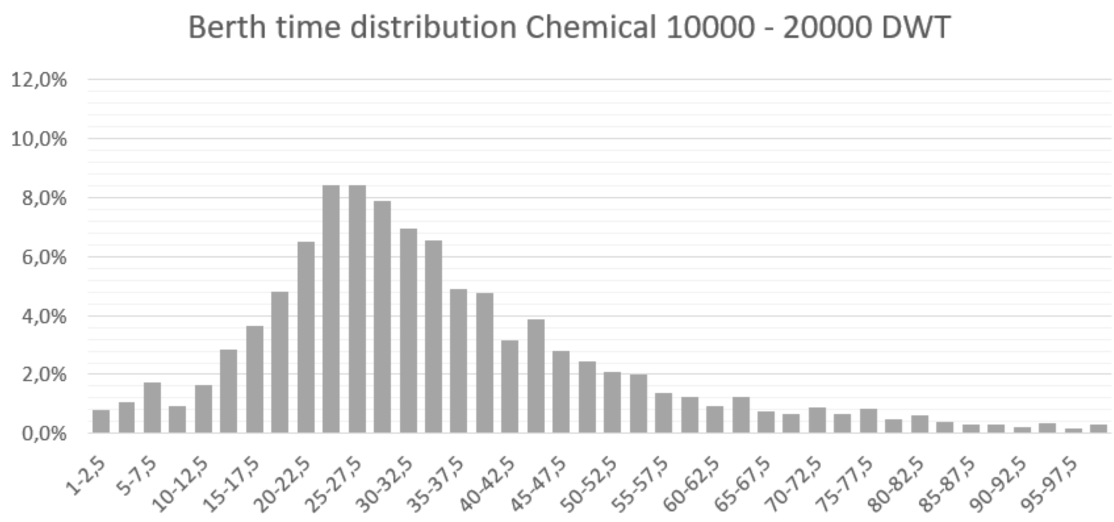

Figure F.2: Berth times probability distribution of chemical tankers between 10,000 and 20,000 DWT

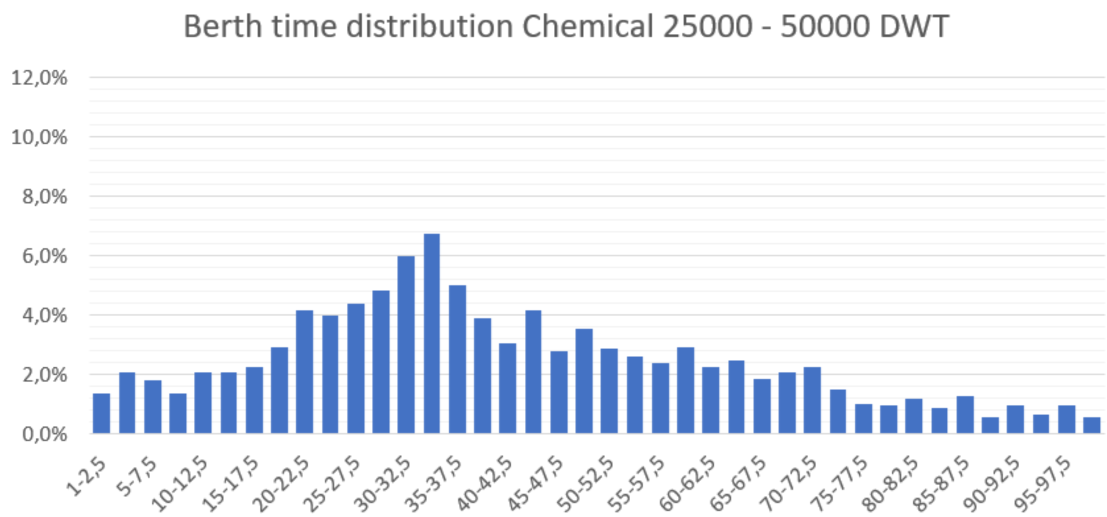

Figure F.3: Berth times probability distribution of chemical tankers between 25,000 and 50,000 DWT

G
Terminal Extended Results

Emissions

The emissions are not exactly related to the terminal operations, however the ships emissions are emitted in the terminal area in the port. Therefore, quantifying the emission reduction of each of the systems contributes to the insights in the emission reduction potential of the various systems. In Figure G.1 and G.2 the relative emission reduction is shown for each emission pollutant as percentage of the total berthed emissions at the terminal. Terminal A does also have a lot of larger oil vessels visiting, therefore the reduction of chemical vessels <20,000 ton is less than expected.

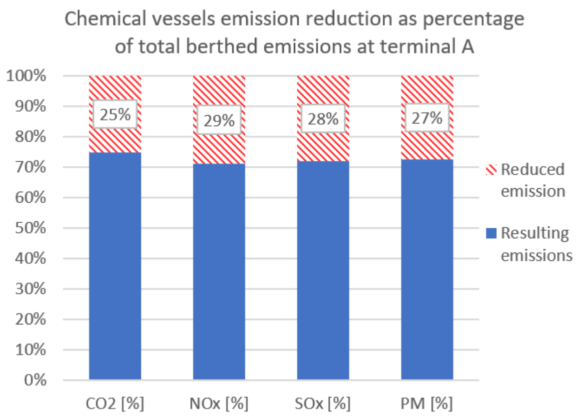

Figure G.1: Total emission reduction potential of chemical tankers <20,000 dwt at terminal A

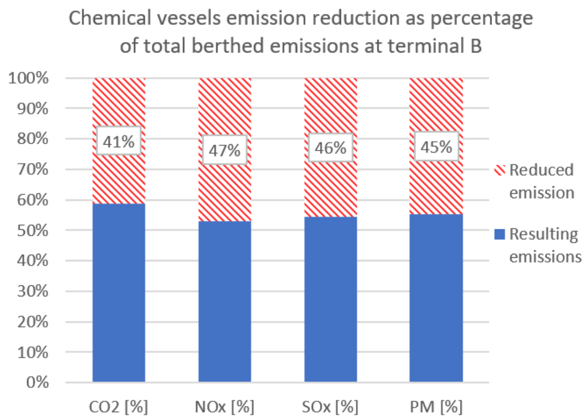

Figure G.2: Total emission reduction potential of chemical tankers <20,000 dwt at terminal B

Utilisation Terminal

The required utilisation of power that each terminal requires is shown in Table G.1. The red cells indicate that the required amount of utilisation is higher than the theoretical total power demand, and thus infeasible. In figure 9.4, the maximum utilisation percentage is shown per CMS concept.

Table G.1: Utilisation required per SP-price and subsidy for all chemical terminals

	Needed utilisation for 120 SP-price					Needed utilisation for 140 SP-price					Needed utilisation for 160 SP-price				
	0% Subsidy	25% Subsidy	50% Subsidy	75% Subsidy	100% Subsidy	0% Subsidy	25% Subsidy	50% Subsidy	75% Subsidy	100% Subsidy	0% Subsidy	25% Subsidy	50% Subsidy	75% Subsidy	100% Subsidy
A	inf.	inf.	inf.	0,94	0,70	inf.	inf.	0,85	0,68	0,51	0,94	0,80	0,67	0,54	0,40
B	inf.	0,86	0,71	0,56	0,41	0,73	0,62	0,52	0,41	0,30	0,58	0,49	0,40	0,32	0,23
C	inf.	inf.	inf.	0,89	0,65	inf.	0,99	0,82	0,64	0,47	0,91	0,78	0,64	0,51	0,37
D	inf.	inf.	0,93	0,72	0,51	0,99	0,83	0,68	0,53	0,37	0,77	0,65	0,53	0,41	0,29
E	0,97	0,81	0,65	0,49	0,34	0,70	0,59	0,47	0,36	0,24	0,55	0,46	0,37	0,28	0,19
F	inf.	0,87	0,70	0,53	0,37	0,75	0,63	0,51	0,39	0,27	0,59	0,49	0,40	0,30	0,21
G	0,95	0,80	0,65	0,50	0,35	0,69	0,58	0,47	0,36	0,25	0,54	0,46	0,37	0,28	0,20
H	inf.	0,96	0,78	0,60	0,42	0,83	0,70	0,57	0,44	0,31	0,65	0,55	0,45	0,34	0,24
I	inf.	inf.	inf.	inf.	0,78	inf.	inf.	inf.	0,79	0,57	inf.	0,96	0,79	0,62	0,44
J	inf.	inf.	inf.	0,91	0,68	inf.	1,00	0,83	0,66	0,50	0,91	0,78	0,65	0,52	0,39
K	inf.	inf.	inf.	inf.	0,84	inf.	inf.	inf.	0,85	0,61	inf.	inf.	0,86	0,67	0,48
L	inf.	inf.	inf.	0,87	0,66	inf.	0,94	0,79	0,63	0,48	0,86	0,74	0,62	0,50	0,38
Sum	2	5	6	10	12	6	9	10	12	12	10	11	12	12	12

H Vessel Extended Results

For a chemical tanker, the yearly reduced emissions are calculated using Equation 7.8. These are compared to the total yearly emissions without shore power, thus electricity generation by using the auxiliary engines. To compare the emissions reduction of using shore power systems in ports, the total yearly emissions of the chemical tankers has been reviewed in other literature. The total yearly CO_2 emissions estimates were found, including sailing and in port emissions. Both emission estimates are heavily dependent on the actual size, engines, and operational profile of the vessel, but it gives an indication of the yearly CO_2 emissions. In Table H.1 the interpolated total yearly CO_2 emissions of both chemical tanker types are shown.

Chemical tanker	DWT	CO_2 emission [t/yr]	Source
Shortsea	dwt <10,000	11,085 ±40%	[18, 19]
Parcel	10,000 < dwt < 20,000	21,262 ±25%	[18, 19]

Table H.1: The interpolated estimated total yearly CO_2 emissions of a chemical tanker [18, 19]

As seen in Figure H.1, shore power is an effective measure for at berth emissions, if the electricity grid does provide cleaner energy. For this outcome, 105 shore power visits a year were assumed, an average of 27 hours at berth and future grid emissions in the Netherlands of 2030. The total yearly CO_2 emissions of a chemical shortsea tanker can be reduced by 8.4%, as seen in Figure H.2. That is a significant amount of reduction given that during sailing the main engine is responsible for a large share in the CO_2 emissions. An explanation, is that a chemical shortsea tanker is during a year, on average 30% of it's time in port.

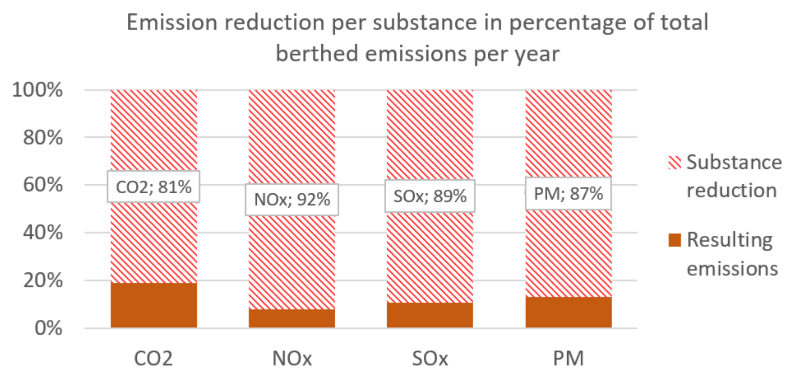

Figure H.1: Yearly at berth emission reduction of chemical shortsea tankers

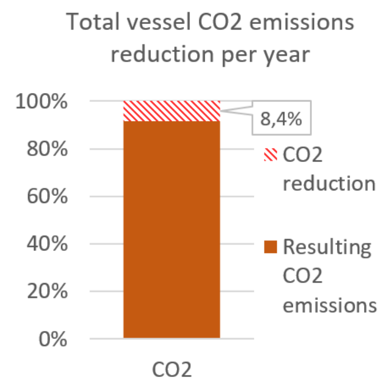

Figure H.2: CO_2 reduction as percentage of yearly CO_2 emissions of a chemical shortsea tanker

The chemical parcel tankers also can reduce about 80 - 90% of its at berth emissions in a year, if all port visits provide shore power and the grid emissions are in the same order of magnitude as in the Netherlands (4.2). As seen in Figure H.3, shore power is an effective measure for at berth emissions of chemical parcel tankers as well. The yearly total reduced CO_2 emissions have a slightly smaller share in the total CO_2 emissions of a chemical parcel tanker in a year.

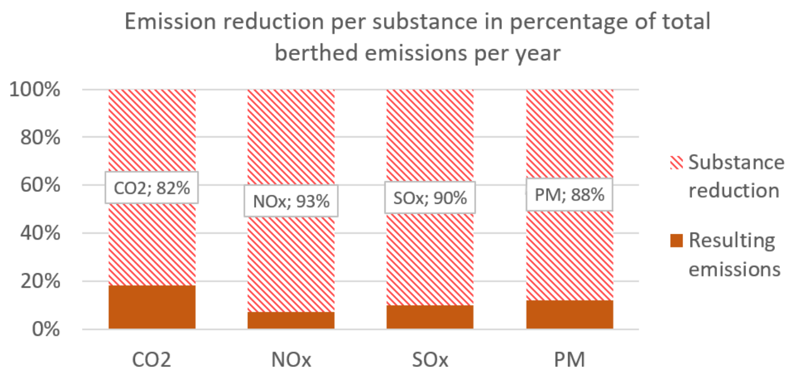

Figure H.3: Yearly at berth emission reduction of chemical parcel tankers

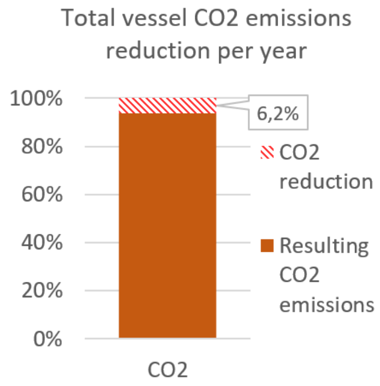

Figure H.4: CO_2 reduction as percentage of yearly CO_2 emissions of a chemical parcel tanker