Utrecht University

Master's Thesis – master Energy Science

Towards the implementation of Bunkering Infrastructure for New Energy Carriers for Inland Navigation in The Netherlands

A Techno-Economic Feasibility Study

By Ruben Damwijk (4087542)

Rijkswaterstaat
Ministry of Infrastructure and Water Management

Griffioenlaan 2 | 3526 LA
UTRECHT

Supervisors:	Prof. dr. Gert Jan Kramer (UU)
	Evelien Korbee (Rijkswaterstaat)
	Sacha Scheffer (Rijkswaterstaat)
Second reader:	Prof. dr. Martin Junginger (UU)

Summary

To reach the goals set in the Climate Agreement (Klimaatakkoord), many industrial sectors must take measures to reduce greenhouse gas emissions. The transition to a more sustainable Netherlands has gained momentum, with logistics and mobility as one of the key components. An important role is reserved for the inland navigation (i.e., inland shipping) sector within the logistics and mobility sector, as it is responsible for 43% of the total transport performance. For the inland navigation sector, the ambitions are to have at least 150 vessels with a zero-emission power train in 2030 and to have a virtually zero-emission and climate-neutral inland fleet by 2050. However, the process of making the inland navigation sector sustainable is still in an early stage and consists mostly of pilot projects. To shape the transition to sustainable mobility, more insights are needed into which bunkering infrastructure is required.

The aim of the research is to generate a techno-economic framework that can be used to determine whether bunkering and charging infrastructure for new energy carriers (i.e., hydrogen, methanol and electricity) is feasible from an economic and technical point of view in the inland navigation sector. The techno-economic framework consists of a supply chain analysis of the different energy carriers and a cost model simulation of different scenarios by 2030. Additionally, interviews with experts and stakeholders provide insights into which bunkering infrastructure components are applicable in the Netherlands by 2030.

The equivalent annual cost, capital investment, demand of an energy carrier, spatial requirements and cost of energy service for different bunkering infrastructure business cases have been calculated by the model. The demand is based on the ambition of having 150 sustainable vessels by 2030. To facilitate a bunkering infrastructure for 150 vessels with a zero-emission power train, the implementation of a bunkering infrastructure for battery electric containers with small charging facilities would be overall the best option. In the short-term, a bunkering infrastructure for methanol could be implemented as the investment is relatively small. Methanol has better use as a transitional energy carrier.

Much depends on external factors such as competition of other sustainable energy carriers. Besides the technological and economic parameters, an equal consensus among vessel owners, investors and energy carrier suppliers to invest and use such bunkering infrastructure.

Preface

This thesis is part of the mandatory courses of the Energy Science Master's program at the Utrecht University. As part of the thesis, an internship at the Sustainable Mobility division of Rijkswaterstaat has been conducted. Rijkswaterstaat manages the national waterways and is therefore an essential partner in the inland navigation. In addition, Rijkswaterstaat is a knowledge partner as part of the Ministry of Infrastructure and Water Management. Rijkswaterstaat serves as the executive organization of the Ministry. This includes performing operational tasks, such as managing the national waterways.

Rijkswaterstaat has an active role in reaching the ambitions set by the national sustainability plans such as the Climate Agreement (Klimaatakkoord). One of the ambitions is to facilitate more sustainable and/or zero emission transportation in the inland navigation sector. To shape the transition to sustainable inland navigation, more insights are needed to improve Rijkswaterstaat's knowledge position in the field of sustainable fuel and bunkering infrastructure for the inland navigation sector. This research contributes to this knowledge position by providing more insights in technologies and costs involved in the sustainable bunkering infrastructure.

Table of Figures

List of Tables

Abbreviations

AFID	Alternative Fuel Infrastructure Directive
BOL	Begin-of-Life
CAPEX	Capital expenditures
CCT	Combined cargo terminals
CGH_2	Compressed gaseous hydrogen
CRF	Capital recovery factor
EAC	Equivalent Annual Cost
EOL	End-of-Life
FPS	Future Proof Shipping
GHG	Greenhouse gas
H_2	Hydrogen molecule
H_2O	Water molecule
HHV	Higher heating value
ICE	Internal combustion engines
LH_2	Liquid hydrogen
LHV	Lower heating value
LNG	Liquid natural gas
LOHC	Liquid organic hydrogen carrier
MCP	Multiple cyclinder packs
MEGC	Multiple-element gas containers
MSW	Municipal solid waste
$NaBH_4$	Sodium borohydride
NH_3	Ammonia
NO_x	Nitrogen oxides
O&M	Operation and maintenance
O_2	Oxygen molecule
OH^-	Hydroxyl ions
OPEX	Operational expenditures
PGS	Publicatiereeks Gevaarlijke Stoffen
PM_{10}	Coarse particulate matter
PSA	Pressure swing adsorption
RH_2INE	Rhine Hydrogen Integration Network of Excellence
SoC	State of Charge
SO_x	Sulfur oxides
STS	Ship-to-Ship
TRL	Technology readiness level
TSO	Transmission System Operators
TTS	Truck-to-Ship
ZES	Zero Emission Services

Table of Contents

1. Introduction

1.1 Problem definition

Global warming and climate change are presently one of the biggest threats to humankind. To reduce the threat of global warming and climate change, the vast majority of the world agreed in the Paris Agreement to aim the temperature rise by global warming to stay below 2ºC by reducing greenhouse gas (GHG) emissions (Rogelj et al., 2016). To act against the world's climate and biodiversity emergencies, the European Union (EU) provides revised laws and tools for the reduction of GHG emissions in the EU. One of the recent contributions by the EU is the presentation of ambitious measures in the 'Fit for 55' package. This package provides legislative instruments needed to achieve a net GHG emissions reduction of at least 55 percent by 2030 compared to 1990 levels (ECER, 2021; European Commission, 2021a). These instruments are necessary to realize the goals set in the European Climate Law. The Netherlands has agreed on a national level by means of the Climate Agreement (Klimaatakkoord) to reduce and limit the Dutch contribution towards global climate change by reducing GHG emissions. One of the goals set in the Climate agreement is to reduce the total GHG emissions by 49% in 2030 compared to 1990 (Klimaatakkoord, 2019). To achieve these reductions in GHG emissions, the Climate Agreement provides measurements for the reduction of GHG emissions in multiple sectors e.g., in the transport sector. The transport sector is responsible for a large part of the nation's GHG emissions. In 2018, the transport sector was responsible for 21% of the nation's CO_2 emissions and is thereby the second largest contributor towards the total GHG emissions after the electricity and heat production sector (IEA, 2020). Therefore, the reduction of GHG emissions in the transport sector can have a considerable effect on the total reduction of the total GHG emissions in the Netherlands. In the Climate Agreement it states that the goal for the Dutch transport sector is to be emission-free by 2050 (klimaatakkoord, 2019).

Inland navigation (i.e., the inland freight transport by inland vessels) plays an important role in the transport sector of the Netherlands. Inland navigation is responsible for 43% of the total transport performance (measured in tonne-kilometres) (Eurostat, 2021). Moreover, the inland navigation sector is responsible for 18% of the total weight of goods transported, which comes to 316 million kilotons (CBS, 2021). It is expected that the inland navigation will grow in the upcoming 30 years (Rijksoverheid, n.d.; Vermij & De Vries, 2019). Both the EU and the Netherlands aim to promote and increase the popularity of inland waterway transport and encourages a strengthening of the competitive position of inland navigation against transportation by road or railway (European Commission, 2020; Rijksoverheid, n.d.). To fulfil the ambitions stated in the Climate Agreement, the Dutch national government, together with other stakeholders and representatives in the shipping industry have constructed the Green Deal on Maritime, Inland navigation and Ports (Green Deal, 2019). This deal provides further specifications of projects, ambitions and goals needed to reduce the GHG emissions and harmful substances emitted by the shipping industry. For inland navigation, the ambitions are to have at least 150 vessels with a zero-emission power train in 2030 and to have a virtually zero-emission and climate-neutral inland fleet by 2050 (Green Deal, 2019). Recently, several pilot projects with the implementation of zero-emission power trains have been initiated. A few examples of these pilot projects are the Zero Emission Services[1] (ZES) and Future Proof Shipping (FPS). ZES started operations with the first vessel that uses interchangeable battery containers for propulsion (Zero Emission Services, 2021). FPS is currently working on retrofitting an inland navigation vessel to run on hydrogen (Future Proof Shipping, 2021).

However, the process of making the inland navigation sector sustainable is still in an early stage and consists mostly out of pilot projects. Useful bunkering infrastructure for alternative fuels is a necessity for vessels with alternative drivetrains to operate, but solely coexists if these vessels are available. A recent study by Prussi et al. (2021) concluded that there is a lack of reliable and existing

[1] a collaboration between ENGIE, ING, Wärtsilä and the Port of Rotterdam Authority

shipping fuel infrastructure for alternative fuels such as electricity, hydrogen and methanol in Europe. Additionally, the European Commission sees that there is a lack of available infrastructure in many countries and seeks to ensure a dense, widespread network for alternative fuels in the EU (European Commission, 2021b). This infrastructure is also missing in the Netherlands. Current insights into the various modalities for the inland navigation industry do not always run parallel to the stated policy objectives. The costs involved and feasibility for the various modalities, such as required bunkering infrastructure in the inland navigation sector, are often not clear. To shape the transition towards sustainable inland navigation in the Netherlands, more insights are required in bunkering infrastructure for the Dutch inland navigation sector.

1.2 Scientific background

Previous studies on new energy carriers involving implementation of infrastructure often provide a broad overview, a comparison and/or the limitations of certain new energy carriers (Lucas et al., 2013; Turconi et al., 2013). There are multiple studies that assess how new energy carriers can be implemented for certain transportation modes in general or in certain countries (e.g., the implementation of hydrogen bus transportation in Argentina or alternative marine fuels in Croatia) (Geyer et al., 2021; Iannuzzi et al., 2021; Lucas et al., 2013; Perčić et al., 2021). However, there is a lack of research on data and analyses regarding costs in combination with technological possibilities on how a bunkering infrastructure for inland navigation can be rolled out, especially in the Netherlands. This study contributes to new perspectives in the integration of infrastructure and distribution for new energy carriers in the Netherlands.

1.3 The new energy carriers

The European Union has issued the Alternative Fuel Infrastructure Directive (AFID) which includes guidelines for the roll out of alternative fuel and infrastructure deployment (European Parliament, 2014). The AFID obliges European member states to setup national policy frameworks for the market development of new energy carriers and the associated infrastructure (Ministerie van Infrastructuur en Waterstaat, 2020). In a proposed revision of the AFID, the alternative energy carriers suggested for inland navigation are (bio-)liquid natural gas (LNG), hydrogen, methanol and battery electric (European Commission, 2021b). LNG is currently a well-integrated energy carrier, but the other energy carriers likely require a bigger challenge to be implemented. Therefore, this study will focus on the hydrogen, methanol and electricity as energy carriers. The focus on these energy carriers is also chosen from a future proof point of view; because these energy carriers are zero emission carriers or can be climate neutral energy carriers in the case of methanol, whereas LNG is considered a transitional fuel.

1.4 Research questions and scope

This study takes as starting point an internal Rijkswaterstaat report by Rieske & Scheffer (2021). Rieske & Scheffer (2021) provided an analysis and overview of existing bunkering infrastructure for inland navigation and the possibilities of new energy carriers such as batteries, hydrogen and biofuels in the Netherlands. Rieske & Scheffer (2021) also included an overview of different vessel types, policy frameworks regarding sustainable inland navigation and bunkering infrastructure for existing and new sustainable inland navigation. However, this study will continue on the bunkering infrastructure aspect of sustainable inland navigation and will in particular focus on a more in-depth study towards techno-economic aspects required. Although the challenge to decarbonize the inland navigation sector is an international one, this study focuses on the required infrastructure in the Netherlands. Europe highlights that a sustainable inland navigation in the whole of Europe is key to obtain a climate-neutral by 2050 and the goals set are pre-eminently international (European Parliament, 2021). However, each country has its own interpretation of how these ambitions are met and each country decides which contributions are made. Moreover, for Rijkswaterstaat the inland navigation sector in the Netherlands is interesting as Rijkswaterstaat is the waterway manager in the Netherlands. Rijkswaterstaat can provide additional financial measures and guide with policy for projects solely in the Netherlands.

The aim of the research is to generate a techno-economic framework that can be used to determine whether bunkering and charging infrastructure for new energy carriers (i.e., hydrogen, methanol and electricity) is feasible from an economic and technical point of view in the inland navigation industry. Therefore, the main question is formulated as follows:

What is the technological and economic feasibility of a nationwide bunkering infrastructure for hydrogen, electricity and methanol for inland navigation in the Netherlands by 2030?

To answer the main question, the following sub-questions need to be answered:

1. *What are the methods and spatial requirements for bunkering and charging new energy carriers in the Netherlands?*

2. *Which technical components are required for the deployment of bunkering infrastructure for the new energy carriers?*

3. *What is the impact of new bunkering infrastructures for alternative fuels on the current underlying energy infrastructure?*

4. *What cost components should operators consider when implementing bunkering infrastructure?*

In this study, a nationwide bunkering infrastructure is defined as the distribution of the new energy carriers to the end user. Hence, the research scope will consist of the distribution in the downstream logistics of new energy carriers for the inland navigation sector. However, this can be rather arbitrary as to what is defined by and what is included in the distributional phase in the supply chain of the new energy carriers to the end user. Therefore, to provide a better understanding of the research scope, a schematic flow-chart has been made to clarify the systems boundaries of this study. Figure 1, Figure 2 and Figure 3 show the system boundaries of the research scope for hydrogen, electricity and methanol respectively.

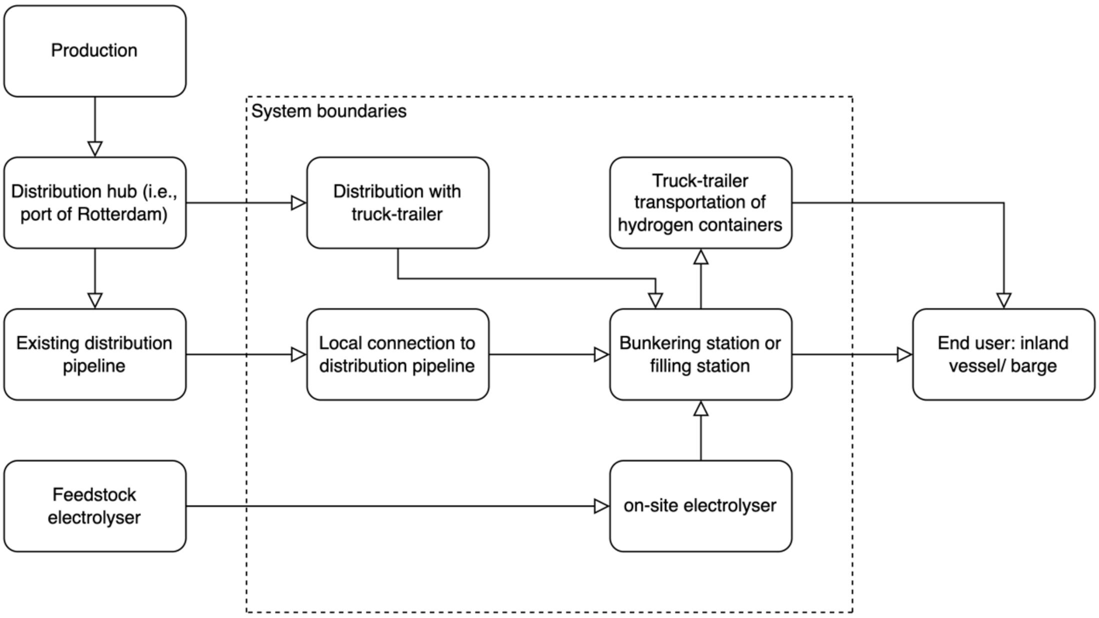

Figure 1: Simplified supply chain of hydrogen for the inland navigation sector. The system boundaries are defined by the dotted lines

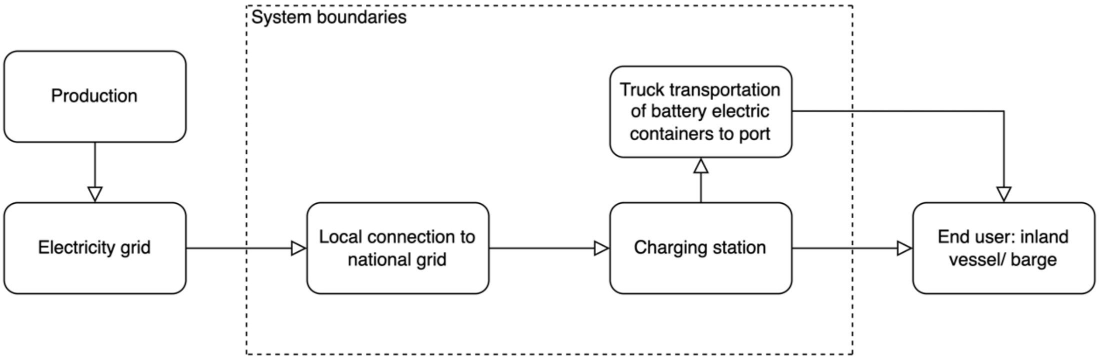

Figure 2: Simplified supply chain of electricity for the inland navigation sector. The system boundaries are defined by the dotted lines.

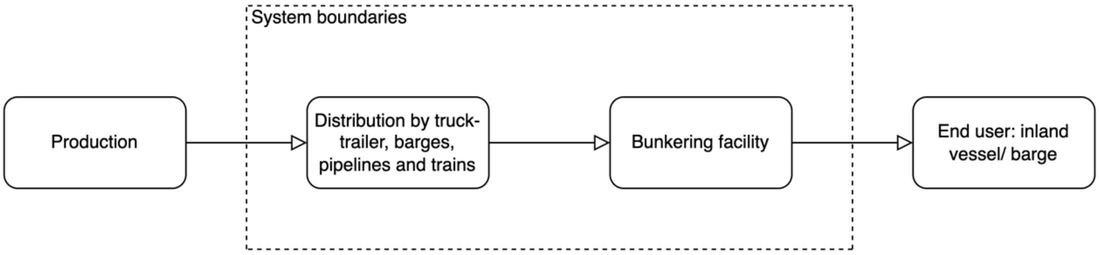

Figure 3: Simplified supply chain of methanol for the inland navigation sector. The system boundaries are defined by the dotted lines.

To understand the delivery and bunkering process within the system boundaries and thereby the additional costs and required technology, the spatial requirements have to be investigated. Rieske & Scheffer (2021) investigated the minimal spatial requirements i.e., the minimum distance between bunkering stations, to have a nationwide bunkering infrastructure.

However, this research will focus more on the spatial application of bunkering and charging infrastructure i.e., the footprint of the bunkering and charging infrastructure. A detailed investigation of how the bunkering and charging infrastructure for energy carriers looks from a technological point of view and a detailed investigation of the delivery methods are necessary to gain a better understanding of the supply chain. This includes distribution methods of hydrogen, electricity and methanol from post-production towards bunkering or charging facilities. The detailed investigation also includes the methods of the bunkering process itself. The aspects involved during building additional bunkering and charging infrastructure are considered if available.

Currently, the energy carriers discussed have the possibility to be distributed partly with existing infrastructure. During this study the distribution of the energy carriers from the underlying energy infrastructure (e.g., electricity grid or pipelines) to the charging or bunkering facility is considered. An example is electricity, which infrastructure can be retrofitted to the existing national electricity grid. This is also applicable for the other energy carriers. Local reinforcement on the grid or existing infrastructure reinforcement is considered in terms of technology. However, a holistic approach will be taken from a national point of view; what part of the future energy demand for each energy carrier will contribute towards inland navigation. Moreover, which parts in the national electric grid or existing infrastructure have been reinforced is a study on its own and beyond the research scope.

The techno-economic framework constructed consists of an overview of infrastructure technologies, in-depth cost of required hardware, spatial requirement and demand of the energy carriers. The framework provides parameters that can answer the sub-questions and thereby the main question. To generate a complete framework besides the technological parameters, the financial aspects need to be taken into account. Some systems may only provide the total costs for a system, whereas some provide more detailed costs per part. This will include, besides the initial investment and O&M, the costs related to temporal requirements during construction e.g., the loss of income generated by the shutdown period of construction or expenses made during construction. During this study, the perspective of the operator of bunker and charging stations is used to generate an overview of the costs involved during the investment and exploitation. This overview can be used to determine if the deployment of a nationwide bunkering infrastructure is feasible by 2030. A detailed method description is provided in Section 2.

2 Methodology

2.1 Supply chain analysis

To find out if the implementation of new bunkering infrastructure is feasible, an extensive techno-economic analysis will be carried out. To gain a better understanding of the current available bunkering technologies, the supply chain will be described for each energy carrier. Desk research describes the methods and processes involved during distribution to bunkering stations and the bunkering and charging of the different fuels and electricity inside the system boundaries described by Figure 1 and Figure 2. The desk research forms the basis of the technological background of the different bunkering infrastructures; the analysis provides an explanation of different technological components involved in the different bunkering infrastructures. The technologies reviewed in this analysis should be feasible delivery methods and bunkering possibilities by 2030. Therefore, only bunkering technologies that are mature enough will be considered in this thesis. Other variables that are discussed are the spatial requirements, speed of delivery or speed of bunkering and processable volume quantities. This study will consider spatial requirements from a bunkering, filling or charging facility point of view and not from a certain terminal point of view. A terminal has, a certain layout, depending on the cargo load (e.g., dry bulk, liquid bulk or container). Currently, it is unclear which bunkering installation will be used at which type of terminal because, this highly depends on what drivetrain technology the ships will implement.

The literature consulted consists of available public and/or scientific literature, internal available documents (e.g., reports and presentations) from Rijkswaterstaat and literature gathered from other companies or organisations.

2.2 Bunkering infrastructure cost model assessment

To test the techno-economic feasibility of the implementation of new bunkering infrastructure for the inland navigation, a cost model of the bunkering infrastructure will be implemented. The cost model calculates the different cost outputs for the different bunkering infrastructures. These will be the Installed Capital Cost (M€), Equivalent Annual Cost (EAC) for the required distribution, the cost of energy service i.e., the cost of bunkering a certain energy carrier (€/km). Moreover, the spatial requirement for the bunkering infrastructure and demand of an energy carrier are calculated.

What is necessary for this model are, besides the technical input parameters and footprint, the capital expenditures (CAPEX), operational expenditures (OPEX) and replacement expenditures. Theoretically, a division of the involved CAPEX and OPEX parameters can be made. These CAPEX and OPEX components are shown in Figure 4. Once the CAPEX of an arbitrary component is known, the replacement expenditures of this component is calculated with the CAPEX and lifetime of a component, the lifetime of the project and interest rate. Unfortunately, cost parameters are often combined in practice. For example, the construction, delivery and installation costs are combined with the cost for equipment in most of the cases. If this is the case, the model incorporates these combined cost parameters. Moreover, some minor cost components do lack, as no information is known about this due to the lack of reference. Initially the cost parameters are found by literature research. Which input parameters are put into the model depends on what is considered feasible and will be used in terms of bunkering and delivery techniques by 2030.

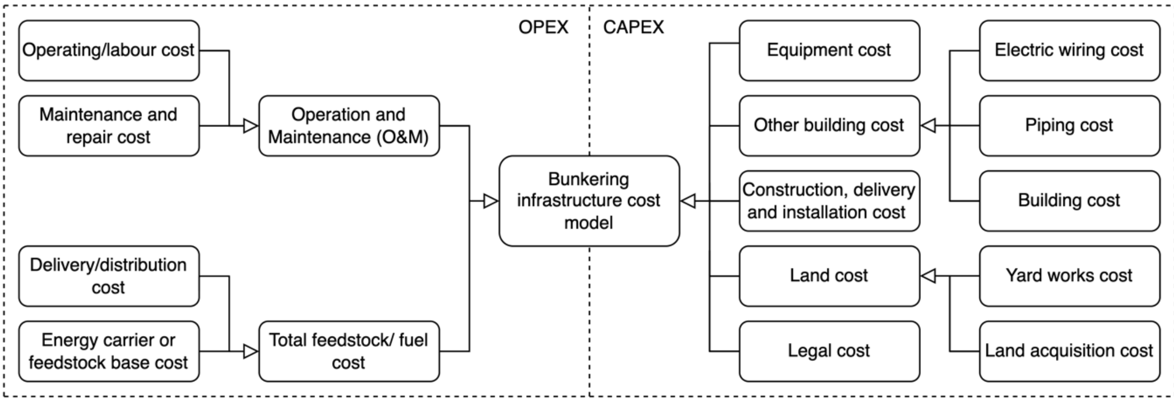

Figure 4: The key OPEX and CAPEX parameters for bunkering infrastructure for an energy carrier

The OPEX can be divided into several cost parameters. The operating/labour cost parameter includes all the costs for operating a station. This includes the loan and recharging/refilling costs. The utilities costs describe the costs for use of electricity used for operation. The equipment and other building maintenance and repair cost parameter describe all the costs involved in maintaining all the facilities and equipment inside a bunkering station and for the required distribution infrastructure. This also includes the costs during a possible shutdown. The operation and maintenance (O&M) are made up by the previous stated parameters. The total feedstock/fuel cost parameter can be divided into the cost for the energy carrier or feedstock (feedstock for e.g., the electrolyser) and the cost of delivery and distribution of this energy carrier to the bunkering station. However, during this research the distribution cost for feedstock/ fuel is counted within the total feedstock price if mentioned. Noted should be that the initial investment for equipment required for distribution is counted towards CAPEX.

The CAPEX is divided into multiple cost components. The equipment cost components describes all equipment cost for the required bunkering station and infrastructure in a supply chain. These include for hydrogen e.g., compressors, temporal storage and refuelling equipment. The equipment required has been found with the supply chain analysis for each energy carrier. The cost for the equipment required for a local connection to the e.g., electricity grid. The other building costs involve all the other building costs required besides the equipment. These involve the costs for additional buildings and costs for auxiliary systems such as piping and electric wiring costs. The construction, delivery and installation cost parameter describe all the costs required for building and installation the equipment and other buildings. Land cost is divided into yard works cost and land acquisition costs if necessary. The yard works cost describes the required adjustment towards land before construction is possible

The Installed Capital Cost is equivalent to the total CAPEX of all the required components in the supply chain. The EAC for the implementation of a bunkering infrastructure allows investors or bunkering operators to compare different business cases on their cost-effectiveness. The business case with the lowest EAC should be the best cost-effective business case over the total project lifetime. The EAC of a supply chain (EAC_{SC}) is the sum of the annual CAPEX, the annual OPEX and the annual replacement cost of all the components involved in the supply chain for a certain energy carrier. The EAC of a supply chain is calculated by the following equation (Viktorsson et al., 2017):

$$EAC_{SC} = \sum Comp_{CAPEX,a} + \sum Comp_{OPEX,a} + \sum Comp_{rep,a}$$

Where $Comp_{CAPEX,a}$ is the annual CAPEX for a component, $Comp_{OPEX,a}$ is the annual OPEX for a component and $Comp_{rep,a}$ is the annual replacement expenditures for a component. The total CAPEX of a certain component can be annual with the capital recovery factor (CRF). The CRF is calculated by an equation derived from Viktorsson et al. (2017):

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1}$$

Where r is the discount rate and n is the economic lifetime of the project/ supply chain. To get the annual CAPEX of a component, $Comp_{CAPEX,a}$, the following equation is applied (Viktorsson et al., 2017):

$$Comp_{CAPEX,a} = CRF \times Comp_{CAPEX}$$

The annual OPEX of a component is divided into multiple expenses. The annual OPEX of a component has annual costs for maintenance of components ($Comp_{om,a}$) and if it uses fuel or feedstock it also includes annual cost for feedstock or fuel cost ($Comp_{f,a}$). Although the latter is used as input for the whole system, fuel or feedstock can be counted towards a certain component (e.g., electrolyser). The following equation calculates the annual OPEX of a component:

$$Comp_{OPEX,a} = Comp_{om,a} + Comp_{f,a}$$

The annual replacement expenditures consist of the replacement expenditures and the depreciation expenditures of components. The annual replacement costs, $Comp_{rep,a}$, can be calculated with the following equation (Viktorsson et al, 2017):

$$Comp_{rep,a} = CRF \times \frac{Comp_{rep}}{(1+r)^t}$$

Where t is the year of replacement and $Comp_{rep}$ are the replacement expenditures for a certain component. The EAC of the supply chain covers all the components and costs involved in the delivery and bunkering process.

The footprint is calculated by a summation of the footprint of individual components with their corresponding safety contours. The yearly demand of each energy carrier is calculated with the fuel economy, the average distance travelled in a year and the number of vessels that sail on that particular energy carrier. When all cost components are known, the cost of energy service can be calculated by dividing an annualized cost component with the yearly distance travelled. The calculations and conditions for the different parameters are provided in Chapter 4.

Different scenarios and business cases have been developed to provide a cost estimate, footprint of bunkering infrastructure and the demand of the different energy carriers in 2030. 2030 has been chosen, because different sustainability goals are available for the inland navigation industry. Moreover, there are large uncertainties in providing a good estimate for e.g., 2050. The scenarios are based on a combination of different bunkering possibilities of an energy carrier with the ambitions stated in the Green Deal on Maritime, Inland Shipping and Ports.

2.3 Interviews

To compliment the analysis made during the literature research, interviews have been conducted with experts and stakeholders involved in the bunkering infrastructure of new energy carriers. A selection of experts and stakeholders who are involved in the bunkering infrastructure of new energy carriers was made in consultancy with Rijkswaterstaat and different stakeholder meetings. These experts and stakeholders have been interviewed to gain more insights in the possibility to integrate new bunkering infrastructure in the Netherlands. Moreover, a more societal view and a better understanding of the practical experiences involved in the implementation and construction of new distribution and bunkering infrastructure is gained from these interviews. Additionally, the interviews provide additional information to support the data found in the context of bunkering infrastructure in the Netherlands.

A list of stakeholders and experts that are interviewed is provided in Table 1. The selected stakeholders and experts cover different aspects in the cost model and supply chain.

Table 1: Stakeholders and experts that have been interviewed

Interviewee	Function	Affiliation	Specific topic knowledge	Stakeholder or expert
1	Business Developer Green Maritime Performance	TNO	Distribution and bunkering of methanol, projections on the implementation of methanol	Expert
2	Senior Advisor Sustainable Mobility	RVO & RH_2INE	Projections of distribution and bunkering infrastructure for hydrogen	Expert/ stakeholder
3	Senior Expert Project Manager	EICB	Overall knowledge of bunkering infrastructure and cost components of methanol, electricity and methanol.	Expert
4	Stakeholder manager	ZES/ Darel	Equipment costs, construction and installation, operation of battery electric bunkering infrastructure	Stakeholder
5	Shipping program manager	Port of Rotterdam	Spatial requirements and rent in ports	Expert

2.4 Evaluation phase

The final step is the evaluation of the techno-economic analysis. The goal is to provide a complete framework that assesses the feasibility of the implementation of bunkering infrastructure for new energy carriers as well as possible. An evaluation is provided on the outcome of the different scenarios.

A comparison and breakdown in costs and techniques of the different bunkering infrastructures has been made. The overall best performing business case is chosen based on cost of energy service, capital investment, EAC and footprint. Evaluation regarding expansion of the existing distribution infrastructure of the different energy carriers is taken with a holistic approach. In general, a holistic approach is necessary for the nationwide distribution of the energy carriers, because other sectors depend on the same infrastructure as well. An evaluation on how much of the inland navigation sector will contribute to the nationwide energy consumption is provided.

The techno-economic analysis incorporates a first cost estimate of implementing bunkering infrastructure. However, as a result of the complexity of the techno-economic analysis, there are large uncertainties that come with formulating a first cost estimate. Therefore, to establish robustness of the results, sensitivity analysis is added to the framework. A sensitivity analysis shows which parameters determine the uncertainty of the study. Moreover, the sensitivity analysis quantifies how much these key parameters will create the uncertainty of the study (Taylor, 2009). A local sensitivity analysis is applied to show with a one-factor-at-a-time method how parameters individually show the impact on the uncertainty of the feasibility (Tian, 2013).

All the steps together considered in the methodology form the techno-economic framework. Figure 5 shows a schematic overview of the techno-economic framework.

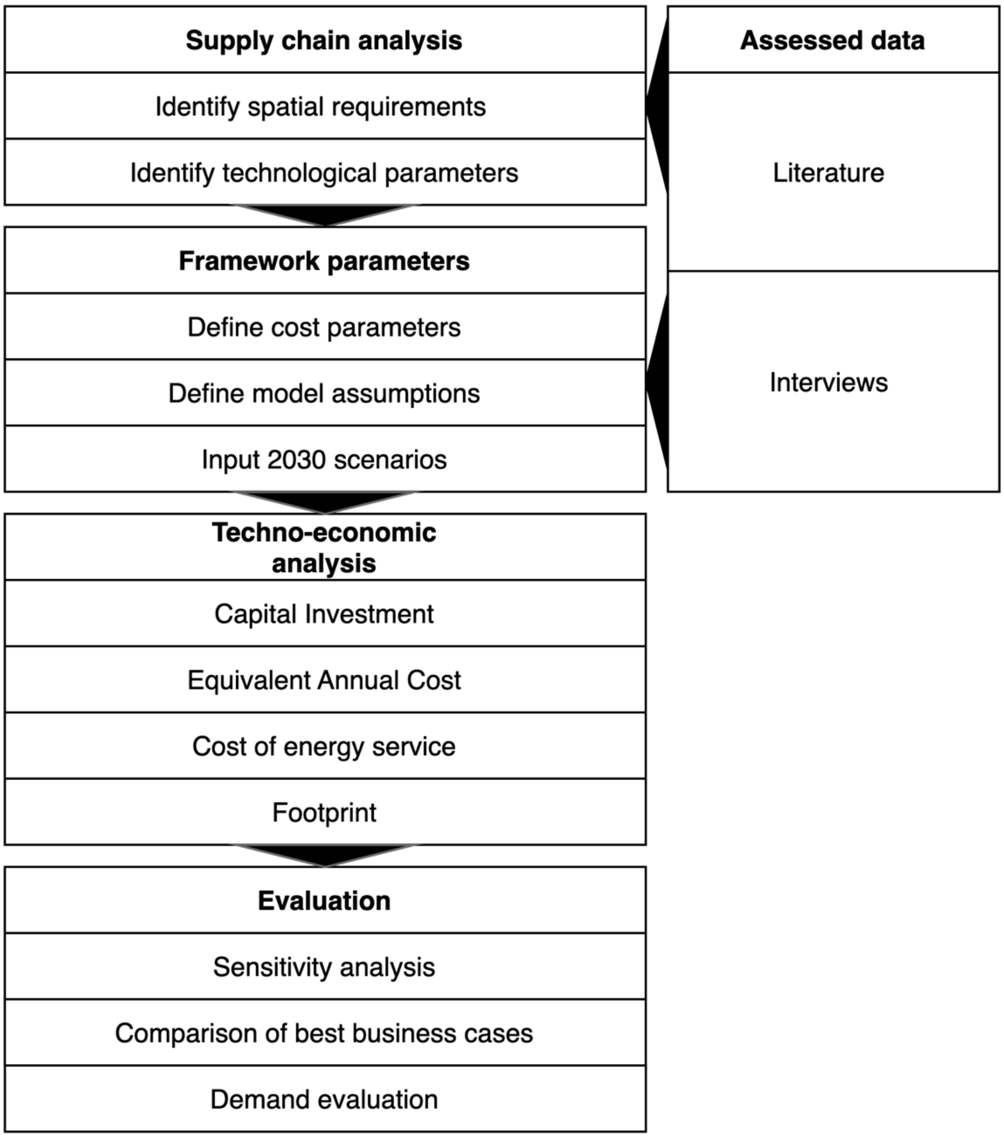

Figure 5: Schematic overview of the design of the techno-economic framework

3 Supply chain analysis

One of the fundamental steps of this study is the accumulation of technology data regarding bunkering infrastructure for hydrogen, methanol and electricity for the inland navigation sector in the Netherlands. This is provided by a partial supply chain analysis. In general, a supply chain analysis is the process of evaluating every stage of a supply chain. The supply chain for energy carriers in the inland navigation sector is described simplified by Figure 6.

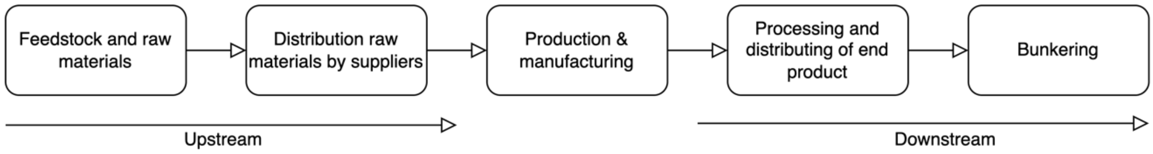

Figure 6: simplified schematic overview of the supply chain for energy carriers in the inland navigation sector

However, in line with the scope of the study, the supply chain of the downstream logistics is analysed. The downstream logistics refers to all the logistic activities in providing the end consumers (i.e., the inland vessels) with a product as shown in Figure 6 (GEFCO, n.d.). Therefore, only partial supply chains of the energy carriers are analysed. The downstream logistics of hydrogen, electricity and methanol in the context of inland navigation consists of the following:

- bunkering of the specific energy carrier;
- the processing and distributing of the specific energy carrier towards the location of bunkering

Bunkering refers to the process of fuelling the ship. There are different methods of bunkering an energy carrier into a ship. This can be by hose (e.g., hydrogen or methanol), by swapping container filled with a specific energy carrier (e.g., hydrogen storage in containers or battery electric containers) or by cable (e.g., electricity). The necessary processes that are required for bunkering an energy carrier into a ship are described. An example would be the filling process of containers with compressed hydrogen. This filling process can be done centralized, but also decentralized near a e.g., a container terminal. A decentralized solution is therefore part of the distribution and bunkering process.

There are on-site production methods included for the energy carriers. An example would be an on-site electrolyser for hydrogen production. Although this is not part of the downstream logistics, these on-site production methods can be a necessity for implementation of new energy carriers for the inland navigation sector. On-site production can be a necessity when the distribution is not feasible for a certain energy carrier. Therefore, these production methods are included into the supply chain analysis for the new energy carriers.

The technologies reviewed in this analysis should be feasible delivery methods and bunkering possibilities by 2030. As described in the methodology (Chapter 2), the feasibility of delivery methods and bunkering methods is described with an analysis that includes variables such as the speed of delivery or the speed of bunkering (capacity), technology readiness level (TRL), footprint (i.e., spatial requirements) and processable volume quantities. Investment costs are included and discussed more qualitatively but are quantified in chapter 4. The delivery methods and bunkering possibilities should have a high enough TRL to be applicable now and in the near future. An explanation of each TRL is explained in Appendix I. Technologies must be of a certain maturity to be adopted in the upcoming 8 years. As a starting point, the technologies involved in the current pilot projects and small-scale demonstrations are considered to be commercially adopted in the upcoming 8 years. As a threshold, the technology should be demonstrated in relevant environment. Therefore, during this study it is assumed that a TRL of 6 is sufficient to be feasible before 2030. After each partial supply chain, the competitive analysis is presented. Section 3.1, 3.2 and 3.3 discusses the partial supply chain of hydrogen, electricity and methanol. A conclusion and prediction of bunkering and charging infrastructure adopted in 2030 is provided in Section 3.4.

3.1 Partial supply chain analysis of hydrogen

Hydrogen as an energy carrier for inland navigation is currently in development in the Netherlands. Currently, the Rhine Hydrogen Integration Network of Excellence (RH_2INE) wants to realise market-ready hydrogen applications along one of the major waterways in the Netherlands. Hydrogen has applications in a gaseous form, as compressed gaseous hydrogen (CGH_2) and also in a liquid state as liquid hydrogen (LH_2). Besides hydrogen in a pure form, hydrogen can be stored and transported in a chemical bounded from. Examples are liquid organic hydrogen carrier (LOHC), ammonia (NH_3) or sodium borohydride ($NaBH_4$). However, the application of these chemically bounded hydrogen energy carriers in the inland navigation are beyond the scope of the study.

Section 3.1.1 discusses the bunkering methods for CGH_2. The hydrogen adopted by inland navigation vessels will initially be high-pressure CGH_2 in the first stages. Expected is that the first retrofitted vessels will sail in Q3 2022 on CGH_2 (FPS, 2021). The first newly build vessel will sail in 2023 on CGH_2 (NPRC, 2021). Bunkering of LH_2 might be possible in the near future according to RH_2INE (2021). Therefore, the bunkering methods for LH_2 are discussed in 3.1.2. The distribution methods for hydrogen are discussed in 3.1.3.

3.1.1 Bunkering of CGH_2

Currently, there are three known bunkering options proposed to be feasible for CGH_2 (Abma et al., 2019b). The first option is bunkering by a hose which is suitable for bunkering high-pressure CGH_2 (350 to 500 bar). This bunkering technique is suitable for vessels that have fuel cells and a hydrogen storage permanently installed. The second bunkering option is exchangeable hydrogen storage containers. CGH_2 storage containers are containers with hydrogen tanks filled at a filling station and bunkered with a container crane. The third option uses power packs: hydrogen storage containers with integrated fuel cells (Abma et al., 2019b). However, the last option is not considered as this requires extensive research towards power packs with integrated fuel cells. Additionally, there are significant extra investment costs as it requires the addition of a fuel cell.

3.1.1.1 CGH_2 Bunkering and filling facility layout

A bunkering facility with a high-pressure dispensing and a filling facility for exchangeable hydrogen storage containers show similar components. Two studies by Abma et al. (2019b) and Jungsbluth et al. (2021) proposed respectively a schematic layout for a bunkering facility with dispensing by high-pressure hose and a filling facility that incorporates the filling of exchangeable hydrogen storage containers. Both systems rely on a supply of gaseous hydrogen. Figure 7 shows a schematic layout of the bunkering facility by Abma et al. (2019b) that incorporates dispensing by hose and temporal storage with constant pressure tubes (CPT) as a bunkering option.

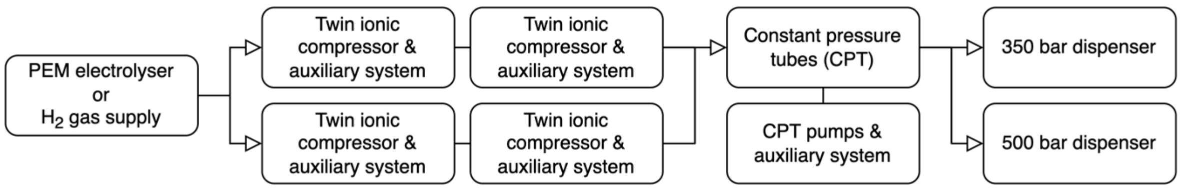

Figure 7: A schematic overview of a bunkering facility with dispensing by high-pressure hose (Abma et al., 2019b).

Figure 8 shows a schematic overview of filling facility by Jungsbluth et al. (2021) that fills exchangeable hydrogen storage containers. Although the filling station is not a complete bunkering facility; the facility can be placed at a docking station or container terminal making it part of the bunkering facility.

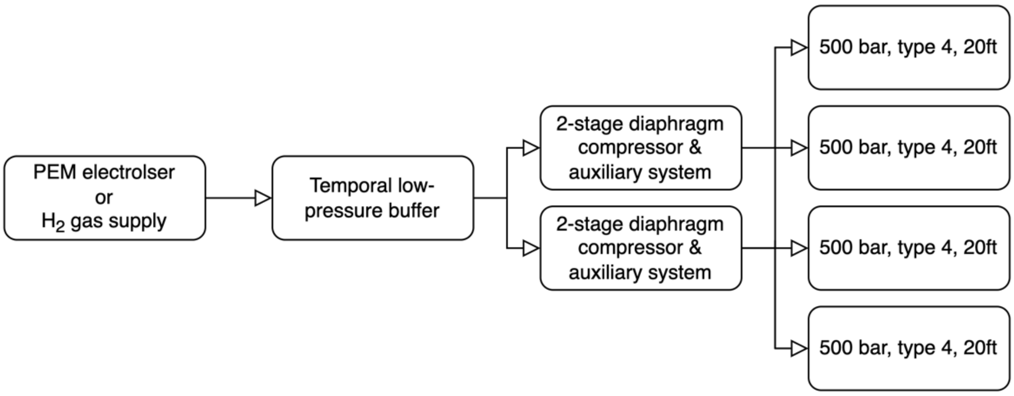

Figure 8: A schematic overview of a filling facility with hydrogen storage containers (Jungsbluth et al., 2021).

An onshore bunkering facility can have several preferable layouts depending on the bunkering option. However, by analysing Figure 7 and Figure 8, each type of bunkering or filling facility has the following key components: high-pressure hydrogen compressors, CPTs and/or temporal storage in the form of low-pressure buffers. Both facilities can incorporate an on-site electrolyser instead of a supply of hydrogen gas. The main difference of these types of facilities is the dispensing/refilling method: by high-pressure hose or by exchangeable hydrogen containers.

The following sections explain the different components for a hydrogen filling or bunkering installation. Section 3.1.1.2 provides an analysis of on-site hydrogen production by electrolysis. The key components are discussed in sections 3.1.1.3 and 3.1.1.4, which give an analysis of the compressors and temporal storage systems, respectively. Section 3.1.1.5 provides an analysis of the dispensing systems required for high-pressure dispensing. Section 3.1.1.6 provides an analysis of the hydrogen storage containers.

3.1.1.2 On-site hydrogen production by electrolysis

An electrolyser can be used to generate hydrogen on site. The advantage of an on-site electrolyser is that there are no distribution costs for hydrogen and a complicated distribution infrastructure is not required with an on-site electrolyser. However, the investment costs for an electrolyser are significant. Currently, there are several types of electrolysis technologies commercially available. These technologies are alkaline water electrolysis (AWE), solid oxide electrolysis (SOE) and polymer electrolyte membrane (PEM) electrolysis. A technical analysis of the different techniques is provided in Appendix II.

By comparing the different electrolysis techniques, the PEM electrolysis is overall superior to the other techniques as concluded by Van der Burg (2020). In the analysis provided in Appendix II, the compactness, low power consumption, high efficiency and quick ramp up time of a PEM electrolyser are highly applicable and suitable for a bunkering facility or filling station. Therefore, during this study, PEM electrolysis is considered as an on-site production method for hydrogen at bunkering facilities or filling stations. Table 3 shows the specific technological variables for a PEM electrolyser.

3.1.1.3 Compressors

To dispense high-pressure CGH_2 from a bunkering facility, compression is required for direct dispensing onto a boat. Abma et al. (2019b) mentioned that for high-pressure hydrogen compression, mechanical ionic compressors can be used. State-of-the-art ionic compressors have fewer moving parts (only 8) and a limit number of seals and bearings (Zou et al., 2020). The ionic fluid used prevents hydrogen leakage in these types of compressors. Ionic compressors are capable of compressing hydrogen to 500 bar or higher, which are suitable pressures to be used in the inland navigation sector.

Jungsbluth et al. (2021) mentioned that two other mechanical compressors can be used: a non-lubricated piston compressor or a membrane compressor (also known as a diaphragm compressor). The non-lubricated compressor is preferable in situations where there is non-continuous operation because membranes in a membrane compressor can crack when it frequently starts and stops. If continuous operation is ensured, the membrane compressor is favourable as it has lower maintenance costs. Additionally, the membrane compressor has a high throughput, a lower power consumption and high levels of volumetric efficiency (Zou et al., 2020).

High-pressure hydrogen compression is also possible with non-mechanical compressors (TRL 9), such as cryogenic compressors, adsorption compressor and the electrochemical hydrogen compressor. However, non-mechanical compressors require large-scale sites, large-volume requirements, slow reaction kinetics and special thermal control systems (Zou et al., 2020). For continuous sailing is a relatively quick filling of hydrogen a necessity. Therefore, non-mechanical compressors with a low throughput during start up are not suitable for the applications of bunkering.

Although non-mechanical compressors are unfavourable for the applications in bunkering and handling CGH_2, the cryogenic compressors do have an application for processing the supply of LH_2 to CGH_2. A cryogenic compressor system consists of multiple components, such as a low-pressure hydrogen storage container for the storage of a LH_2 container and cryogenic pump. The cryogenic pump pressurizes the LH_2 to the desired pressure. The pressurized hydrogen passes subsequently through a high-pressure evaporator where the hydrogen is evaporated into a gaseous state (PGS 35, 2020).

3.1.1.4 Temporal storage systems

Different types of storage cylinders can be considered for a hydrogen storage. The different types of storage cylinders are shown in Table 2. Type I cylinders are often used as for other gases instead of CGH_2 as single bottles. Type II cylinders are typically used for stationary applications. Both type I and II cylinders are low cost. Type IV has comparatively high costs but has a relatively low weight. Therefore, often type IV cylinders are used for mobile applications (Jungsbluth et al., 2021; Rivard et al., 2019). Figure 9 shows a model of a type IV pressurized cylinder.

Table 2: Overview of the different types of storage cylinders (Abma et al., 2019b; Jungsbluth et al., 2021; Rivard et al., 2019; Wulf et al., 2018).

Type	Construction
I	Steel cylinder
II	Cylinders with a metal liner with partial carbon fiber overwrap
III	Cylinder with a metal liner with a full carbon fiber composite overwrap
IV	Carbon fiber composite cylinder with a high-density polymer liner

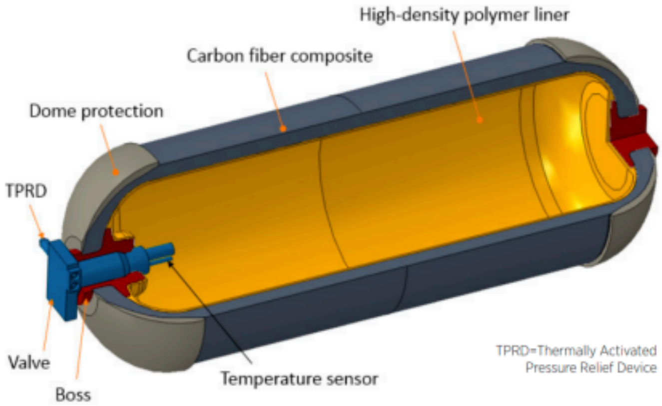

Figure 9: Type IV carbon fiber composite cylinder with a high-density polymer liner used for CGH2. Retrieved from Fuel Cell Technologies Office (2017).

Temporal storage is required in both bunkering options. A distinction is made between the usage of low-pressure and high-pressure tanks. Low pressure tanks (TRL 9) can be used as a buffer before compression (Jungsbluth et al., 2021). These are necessary when on-site hydrogen production by electrolysis or the delivery are mismatched and cannot adjust to the consumption of filling hydrogen comtainers or by dispensing with a high-pressure hose (Jungsbluth et al., 2021). Moreover, these buffers are a necessity when the electrolysers and compressors used have a different start-up time (Hyde et al., 2019). Typical low-pressure buffers have the capacity of approx. 200 kg and can be pressurized around 20-40 bar and made from a type I or II (Hyde et al., 2019; Jungsbluth et al., 2021).

Direct dispensing after compression is possible in the hydrogen storage of a ship or in a power pack. However, high pressure storage is advised. Although high pressure storage is optional, it allows for faster refuelling in comparison without high-pressure storage: a compressor may have a lower capacity as the r whereas dispensing with high pressure storage is capable of ~400 kg per hour (Abma et al., 2019b; Hyde et al., 2019). Hyde et al. (2019) describes two distinct traditional formats to be used: multiple cylinder packs (MCPs) (TRL 9) and large tubes (TRL 9). MCPs are racks of e.g., 50 L type I cylinders bundled in a protective frame. These are a low-cost solution as the type I steel cylinders are mass produced. The large tubes often have a radius of 10 m and a diameter of up to 0.5 m. Abma et al. (2019b) mentions that CPT systems are also a feasible solution for high-pressure tanks. CPT systems are capable of maintaining a constant pressure at refilling. The refill speed of CGH_2 with the usage of CPTs is 900kg in 75 minutes (Abma et al., 2019b).

High-pressure storage can be used as dispensing by differential pressure (i.e., the pressure difference between the high-pressure land-based storage and the lower pressure ship storage causes hydrogen to move between them). By implementing the high-pressure storage systems suggested by Hyde et al. (2019), a significant amount of high-pressure ground storage is required. Hyde et al. (2019) calculated that to fill a ship with 500 kg of hydrogen at 350 bar, 2,070 kg of 500 bar storage is required on land. Abma et al. (2019b) concluded that three 40 ft containers with type IV cylinders (TRL 9) are required to fill one exchange container. Abma et al. (2019b) concluded that this is not feasible, as it requires a large amount of land-based storage (minimum of 84.6 m^2, excluding auxiliary systems) which adds to the complexity and costs of the bunkering system.

3.1.1.5 Bunkering by high-pressure hose

When a vessel has an internal storage for hydrogen, dispensing CGH_2 is possible by high-pressure hose and nozzle. During the refuelling of any vehicle, one of the key requirements is often that the vehicle is stationary. However, refuelling a ship is more challenging: tides and swells might act as vertical movement on the ship (Hyde et al., 2019). To overcome dangerous problems, a breakaway coupling could be installed. Furthermore, there are two nozzles proposed by Hyde et al. (2019) that are similarly used for road vehicles: a one-handed operation nozzle (TRL 9) and a two-handed operation nozzle (TRL 9). The two-handed nozzle is familiar to the ships' crew. An example of the two nozzles is shown in Figure 10. High-pressure hose filling is only possible when a storage tank for CGH_2 is available onboard of a vessel. Dispensing rate depends on the availability of high-pressure storage and compression rate. A dispensing rate of 0.12 kg/s is possible with high-pressure storage systems (Hyde et al., 2019).

Figure 10: A one-handed nozzle (left) and a two-handed nozzle (right) (Hyde et al., 2019).

3.1.1.6 Bunkering of hydrogen containers

As mentioned before, bunkering with hydrogen containers is also considered an option. CGH_2 is stored in multiple cylinders inside a container. Different types of storage cylinders can be considered for a hydrogen container. The different types of storage cylinders are shown in Table 2 in section 3.1.1.4.

Jungsbluth et al. (2021) proposes three different types of 20 ft containers that can be used in bunkering hydrogen containers. Although other sizes for the containers exist as well, Jungsbluth et al. (2021) stated that 20 ft containers have the preference with shipowners. All containers use the multiple-element gas containers (MEGC) as storage system and have a TRL of 9 (Jungsbluth et al., 2021). An example of the MEGC storage container is shown in Figure 11. The specific technical parameters are shown in Table 3. The higher the storage capacity, the higher the costs.

Figure 11: A 20 ft 500 bar container with type IV cylinders (Jungsbluth et al., 2021).

Table 3: Technical parameters for the different containers (Jungsbluth et al., 2021)

20ft container	Unit	300 bar, type II	300 bar, type IV	500 bar, type IV
Pressure	Bar	300	300	500
Cylinder type	Type	II	IV	IV
Storage capacity	kg CGH_2	312	371	518
Volumetric content	L	15,912	18,900	16,800
Weight (empty)	Kg	21,000	9,250	14,000
Cost	€	150,000	250,000	380,000

According to Jungsbluth et al. (2021), filling plants are designed to fill type I 200 and 300 bar cylinder bundles and bottles. The flow rate for filling a type IV 500 bar container is larger compared to a type II 300 bar container, as there are higher pressures and larger amounts of gas to be filled. There currently are restrictions on the filling rate for type IV 500 cylinders. However, rapid filling is desirable, especially when demand is high.
Storage of hydrogen containers requires safety distances, as hydrogen is a flammable substance. For storage, a safety contour of 230 m is proposed for three stacked hydrogen containers (DNV, 2021). However, concrete regulations regarding distances for the storage of hydrogen containers are currently not set.

To swap the hydrogen storage containers, a container crane is necessary to lift it from the shore onto the ship and vice versa. The facility is ideally situated near or at container terminals as the system comprises container exchanges. Container terminals have cranes that can replace the container-based hydrogen storage units. A container crane (TRL 9) is sufficient for the loading and unloading of containers (Abma et al., 2019a). Typical container cranes are overhead portal or ship-to-shore gantry cranes (Figure 12). Ports may also use reach stackers (TRL 9) for loading and unloading (Figure 13). These are container handler vehicles that are often used at smaller or medium-sized ports. The advantage of a reach stacker is that it has the ability to move containers fast over a short distance, whereas the container cranes are limited to a certain designated area. A reach stacker is often available on-site. A reach stacker is necessary when the filling station is situated on the terminal and the container crane is not able to reach the container. The investment costs for a reach stacker are relatively small: between €130,000 and €250,000 (Aroundoffice, n.d.).

Figure 12: Overhead portal crane (left) and a ship-to-shore gantry crane (right) (Dijkhuizen, 2014; Weihua, n.d.)

Figure 13: Reach stacker (Hyster, n.d.)

3.1.2 Bunkering of LH_2

According to Jungsbluth et al. (2021), LH_2 currently cannot be used as fuel for the inland navigation. The current projections state that LH_2 as a fuel might be feasible by 2025 (RH_2INE, 2021). However, it is unclear when the first vessels will be implemented in the inland navigation industry. Currently, the only plant in the Netherlands that produces LH_2 is situated in Rotterdam and has a capacity of 6 tonne/day (Weeda & Segers, 2020). This supply of LH_2 is capable to feed a small fleet in theory as the hydrogen demand for a round trip Rotterdam-Duisburg is already calculated to be a maximum of 2.7 tonne. As a solution, LH_2 can be imported. This would however require a suitable and specially designated distribution system with LH_2 trailers.

Hydrogen liquefaction is not possible at a bunkering point; the production of LH_2 is solely possible at central points (Jungsbluth et al., 2021). The process of bunkering happens via a hose. Swappable liquid hydrogen tank-containers are most likely not to be applied, as there are large safety risks associated with them (Hübner & Douma, 2021). The bunkering of LH_2 has not been tested yet. Therefore, LH_2 is not considered in the cost model as there are no values available. The bunkering of cryogenic fuels by hose has been proven through LNG bunkering (Jungsbluth et al., 2021). If LH_2 will be implemented as a fuel in the inland navigation sector, bunkering of LH_2 would probably happen via truck during the begin stages. Bunkering stations or bunkering ships would have similar concepts with regard to LNG bunker stations or barges.

LH_2 will be used by multiple heavy-duty sectors and is thereby not only limited to be used in the inland navigation sector.

3.1.3 Distribution of hydrogen

Currently, the distribution of hydrogen happens predominantly by two modes of transportation: with tube trailers (either by truck or by water) and by pipeline. Demir and Dincer (2018), described that the methods of hydrogen transportation are by tube trailers which are filled with CGH_2 (TRL 9), by liquid tanker trailer in which LH_2 is transported under cryogenic conditions (TRL 9), and through pipelines in a relative low pressure gaseous condition (<100 bar) (TRL 9). Adolf et al. (2017) does also mention that hydrogen can be transported by a container trailer filled with CGH_2. These consist of smaller tanks compared to the tube trailer variant and can withstand a higher pressure. Figure 14 shows a schematic overview of the different trailer options for hydrogen storage and distribution.

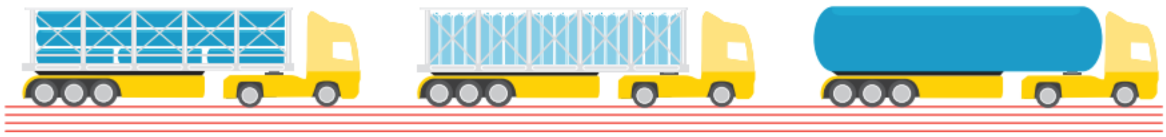

Figure 14: The different trailer options for hydrogen distribution. Retrieved from Adolf et al. (2017).

3.1.3.1 CGH_2 Distribution by tube trailer

CGH_2 can be transported by tube trailer. Tube trailers consist of several pressurized gas cylinders or tubes which are bundled together in a protective frame arranged in stacks (Adolf et al., 2017). A tube trailer can have different storage capacities of hydrogen, depending on the pressure and temperature of hydrogen (Adolf et al., 2017; Moreno-Blanco et al., 2020; Wulf et al., 2018). Comparable to hydrogen container trucks, road transport of hydrogen takes place at a pressure of 300 or 500 bar (Jungsbluth et al., 2021; Wulf et al, 2018). The tubes in tube trailer with a pressure of 500 bar are constructed from type IV (Jungsbluth et al., 2019; Rivard et al., 2019; Wulf et al., 2018). However, tubes in a tube trailer with a pressure of 300 bar are made from either type I, II or IV cylinders (Jungsbluth et al., 2021). The transportation of swappable hydrogen containers by truck-trailer is based on the concept of tube-trailers.

A tube trailer with CGH_2 cannot transport as compactly as a liquid fuel. At a temperature of 15°C (288 K), the volumetric storage density of CGH_2 is at a 300 and 500 bar approximately 19.6 kg/m^3 and 30.8 kg/m^3 respectively (Jungsbluth et al., 2019; Kunze & Kirchner, 2012). Put in perspective, LNG has a far higher density that ranges typically between 430 kg/m^3 and 470 kg/m^3 (GIIGNL, 2009). Moreover, the energy density of CGH_2 is lower compared to most fuels. CGH_2 at 300 or 500 bars has a volumetric energy density of 2.4 MJ/l and 3.7 MJ/l respectively. LNG has a volumetric energy density of 21 MJ/l (Adolf et al., 2017). The advantage of hydrogen transport by tube trailer is that it can use the public road and the existing road infrastructure. In general, the initial investment is far lower in comparison with the construction costs required for a pipeline (Demir & Dincer, 2018).

An increase of hydrogen transportation by road will generate a great impact and increase the risks on the transportation of Hazardous Substances in the Netherlands via the Basic Network[2] (Van Weyenberg, 2021).

3.1.3.3 LH_2 distribution by liquid trailer

A liquid trailer can also be used to transport hydrogen in a liquid state. Hydrogen changes from a gas to a liquid at approximately -253 °C (20 K) at ambient pressure (Demir & Dincer, 2018; Rivard et al. 2019) The density of LH_2 is approximately 78 kg/m^3 and is thereby still far less dense than many other liquid fuels, such as LNG (Adolf et al., 2017; Rivard et al., 2019). One liquid trailer is capable to transport approximately 3500 to 4300 kg of LH_2 (Adolf et al., 2017; Lee et al., 2020; Petitpas et al., 2017). The transportation of LH_2 by trailer is economically more attractive over longer distances compared to transportation of CGH_2 by tube trailer, because a liquid trailer truck is capable of holding a much larger quantity of hydrogen. However, the downside of LH_2 distribution by trailer is that the hydrogen has to be liquified, which is expensive and requires a relatively large amount of energy. The current liquefaction technology of hydrogen tends to increase the price of hydrogen by more than approximately €0.85/kg to €1.32/kg (Incer-Valverde et al., 2021; U.S. Drive, 2017). However, this highly depends on the price of electricity (Incer-Valverde et al., 2021). The required energy used in the liquefaction process of hydrogen is equivalent to 35% of the energy content in liquified hydrogen. (U.S. Drive, 2017).

[2] Basic Network is the network for the transport of hazardous substances in the Netherlands

Furthermore, LH_2 storage and trailer transportation must cope with 'boil-off' losses. During transportation, the pressure rises as heat transfers from the environment to the LH_2 tank. The tank is incapable to withstand high pressure. Therefore, hydrogen has to escape through a relief valve (Rivard et al. 2019). Modern systems are optimised so that boil-off does not lead to substantial losses during transport (Adolf et al., 2017). These boil-off loses are almost reduntant; typical boil-off ratios are between 0.03% to 0.25%/day (Demir, & Dincer, 2018; Reuß et al., 2017).

According to PGS35 (2020), a CGH_2 filling or bunkering installation requires extra components for the delivery of LH_2. These are the cryogenic compressor systems and high-pressure evaporators described in 3.1.1.3. Low-pressure evaporators can be used as well.

3.1.3.4 Hydrogen distribution by pipeline

Hydrogen transportation is also possible by pipeline. The advantage of distribution by pipeline is the high throughput (up to 100,000kg/ day) at a relatively low pressure (75 to 100 bar) (Adam et al., 2020; Brey, et al., 2018; U.S. Drive, 2017). Furthermore, distribution by pipeline is considered to be the safest compared to the other distributional options. However, the downside is that the capital costs are currently still significantly larger in comparison to the other distribution options. There are some concerns regarding the pipeline material and compression technology. Pipelines need to be of high strength steel to overcome major hydrogen embrittlement. Compression is also necessary over a large distance. Due to the low molecular weight of hydrogen, a centrifugal compressor requires a high rotational velocity and compression at multiple stages (Gondal & Sahir, 2012; U.S. Drive, 2017). Therefore, these compressors are costly as these require materials that withstand hydrogen embrittlement and high rotational speeds (U.S. Drive, 2017). Furthermore, special seals have to be applied as hydrogen is highly diffusive and can leak very quickly through tiny gaps (Demir & Dincer, 2018).

The above mentioned concerns can be tackled. There are hydrogen pipelines in the Netherlands for industrial use. However, transport via pipeline can cause the hydrogen to be contaminated. For hydrogen to be used in PEM fuel cells, purity levels need to be very high (above 99%). This level of purity can only be reached by hydrogen production via electrolysers after which the hydrogen needs to be transported by sealed cylinders to prevent contamination. If hydrogen is being transported via pipelines for the purpose of use in a PEM fuel cell, purification is necessary at a bunkering location or filling plant. This purification process can be possible with a pressure swing adsorption (PSA) unit. The application of hydrogen in internal combustion engines (ICE) does not require such high levels of purity.

Currently, there are pilots with existing pipelines for natural gas. With rededication of natural gas pipelines, hydrogen transport is possible. Therefore, CGH_2 transport by existing natural gas pipelines has a TRL of 6-7 (Jungsbluth et al., 2021). It is expected that the transportation of hydrogen from former natural gas pipelines is possible on a nationwide scale from mid-2027 (Van Weyenberg, 2021).

3.2 Partial supply chain analysis of electricity

3.2.1 Battery electric sailing

Battery electric vehicles are currently applied on a large-scale in rail and road transport (e.g., battery electric passenger cars and utility vehicles such as garbage trucks and buses). However, battery electric applications in the shipping industry are currently limited. The amount of power required by inland navigation vessels combined with limited time to charge makes the use of battery electric applications highly unsuitable. For example, there are currently a few battery-powered ferries sailing in Scandinavian waters (i.e., in Oslo, Norway) (Randall, 2021).

There are two distinct options considered as feasible for sailing on electric batteries. The first option is vessels with pre-installed electric batteries that are charged by cable or by induction. Current battery electric ferries use this option. These ferries usually sail fixed and relatively short routes. Therefore, the same charging points can always be used to recharge. The second option is vessels that use exchangeable power packs. These power packs are standardized containers with integrated battery systems. These power packs are charged at a charging facility on shore. Loading or unloading a container can be done in 2-3 minutes (Abma et al., 2019a). However, if a battery of the powerpack would be integrated into the container barge, it would take 2 to 2.5 hours to recharge (Abma et al., 2019a; Engie, 2020). By installing power packs instead of direct charging by cable, the recharging of the batteries has been shifted outside the vessels operating time. As this option saves time, this option could reduce the potential loss of revenue for the shipper. Moreover, the initial investment made by the shipper for retrofitting or constructing a vessel would be reduced as a large investment into an expensive battery is not required. At least batteries the size of 3 containers are required to sail distances over 150 km. This would roughly increase the investment costs to approx. €3 to €4 million. Currently, the inland navigation sector in the Netherlands has adopted the first pilot project consisting of an inland navigation container barge that sails on swappable electric battery containers; ZES

The following section discusses the technical features of a bunkering point for battery electric power pack charging, the technical features of battery packs and the technical aspects of electricity delivery.

3.2.2 Bunkering point for battery electric charging

A bunkering point for the exchange of battery electric power packs, or mobile energy container (MEC) consists of two parts. The first part is the mooring place which is needed where a container can be loaded or unloaded; the docking facility or terminal. The second part is a charging facility where battery electric containers are being charged. Recently, the first charging facility in the Netherlands has been developed by ZES at the combined cargo terminals (CCT) Alpherium in Alphen aan de Rijn, the Netherlands. ZES facilitates the charging of power packs for the Alphenaar, the first Dutch inland navigation vessel to use interchangeable energy containers for propulsion (Port of Rotterdam, 2021b). The current TRL of a docking and charging station is around 7 (Rieske & Scheffer, 2021). The bunkering facility works as followed:

1. A vessel arrives at a docking point where the (near) empty battery electric containers are lifted out of the vessel and are stationed at the charging platforms of the charging facility. The docking point is a place where a container can be loaded or unloaded from the vessel.
2. The charging platforms charge the battery electric containers to the desired State of Charge (SoC). When charged to the desired SoC, the fully charged battery electric containers are placed with a crane or reach stacker near the charging platform to make room for empty battery electric containers. For continuous sailing, fully charged battery electric containers should be readily available at the charging facility when a vessel exchanges empty battery electric containers for charged battery electric containers to prevent the loss of income.
3. The charged battery electric containers are loaded into the vessel at the docking point.

In addition, as the system comprises container exchanges, the charging facility is ideally situated near or at container terminals. Container terminals have cranes that can replace empty battery packs with full battery containers. For the power packs to be used, a container crane is necessary to lift it from shore onto the ship and vice versa. Therefore, to reduce costs, a bunkering installation with the power pack bunkering option is appealing near or in container terminals. A container crane is sufficient for the loading and unloading of containers (Abma et al., 2019a). Moreover, a reach stacker can also be used. Both crane variants have been discussed in 3.1.1.5. The following sections discuss the specific layout of the charging and docking facility and the battery electric power pack. The costs for handling containers are described in chapter 4.

The advantage of the ZES charging facility is that it can be placed at locations where there is no grid congestion. Thereby the facility is not bound to a specific location near e.g., a terminal or docking facility. However, the placement of the charging facility is preferable next to a terminal, as no extra distributional costs are involved.

3.2.2.1 Charging facility lay-out

Figure 15 shows a schematic rendering of a power pack charging facility that has been facilitated at the combined cargo terminals (CCT) in Alphen aan de Rijn, the Netherlands. The charging facility of ZES for electrical power packs can be constructed as followed (each number shows the specific key component) (Engie, 2020):

1. Grid connection point (2MVA connection)
2. Power distribution container (10kV to 690 V)
3. Power interface container (conversion of switchable AC/DC: 0-2000kW can be supplied)
4. Docking platform for 20 ft containers
5. The connector (fully automated plug for energy and data communication between the power packs and the docking station)

Figure 15: A schematic rendering of a power pack docking station (Engie, 2020)

A DC charging column could be installed for E-trucks, E-buses or other vehicle types with a standard CCS (Combined Charging System) connection (Engie, 2020). By installing a CCS for road vehicles, additional revenue could be generated by selling electricity to these vehicles. However, this is optional and does not have a direct application for the inland navigation sector. The charging facility for battery electric is as standard and modular as possible to allow room for scale-up and to be replicable in other locations when there is an increase in demand. This particular setup covers an area of 224 m^2 (Engie, 2020). This is comparable to the fuelling station for hydrogen containers.

3.2.2.2 Battery electric power pack

The battery electric containers consist of Lithium-ion batteries (Engie, 2020). Lithium-ion batteries are the most suitable for ship propulsion, as these have a relatively high energy mass, volume density and a low energy loss for the charging and discharging (Abma et al., 2019a). Currently, there are several suppliers for battery electric containers such as Siemens, Wartsila and Samsung.

The battery electric containers itself are configurated into the standard container sizes of either 20 ft or 40 ft. The energy capacity of containerized batteries depends on multiple factors such as the kind of batteries used and the number of battery units in a single container (Abma et al., 2019a). According to Zero Emission Services (n.d.), a 40 ft battery electric container is able to deliver 2000kWh capacity. However, according to Abma et al. (2019a), Corvus Energy can currently produce a 20 ft container configuration and a 40 ft container containing a capacity of 546 kWh and 1365 kWh respectively. These versions do not contain any power electronics and thereby require power electronics on board of ships. A lower capacity will result in a lower range overall. Although the range depends on multiple factors such as sailing upstream or downstream, the current batteries do not have a sufficient energy density to be considered for long to medium routes; one container with a capacity of 2000kWh is capable of propelling a vessel 60 to 120 km depending on sailing conditions (Zero Emission Services, n.d.).

The technique evolved in the battery's cells in electric cars and battery packs used for ship propulsion is similar. Hence, the battery evolution is likely to be the same. Although measured for batteries in cars, expected is that by 2030 the gravimetric energy density (325 Wh/kg or 1.17 MJ/kg) of lithium-ion batteries for vehicle applications increases by 20% (König et al., 2021). An increase in gravimetric energy density would result in a larger battery capacity if the same size of batty is used. This would lead to larger sailing ranges overall. However, such an increase is not sufficient to compete with the energy density of diesel (43.4 MJ/kg), LNG (53.6 MJ/kg at -162 ^{o}C) or hydrogen (120 MJ/kg) (Blok, & Nieuwlaar, 2016; Gangoli Rao et al., 2020)

One of the major downsides of using lithium-ion electric batteries as a fuel is that aging occurs over time in the form of capacity loss in the batteries. This is a great disadvantage compared to the other energy carriers that do not have this problem. Abma et al. (2019a) stated that for a battery electric container the End-of-Life (EOL) capacity is around 80% of the Begin-of-Life (BOL) capacity. However, temperature plays an important role in the degradation of the capacity. Moreover, the temperature plays a role in the charging performance. In general, lithium-ion batteries have an optimal service life at 20^{o}C (293K) (Chang, 2019). However, at 0^{o}C (273K), the temperature loss is approximately 10 to 20% of the rated capacity at the temperature of 20^{o}C (Chang, 2019). At higher temperatures the cycle life (i.e., the number of charge and discharge cycles a battery can have before it is losing performance) is greatly negatively affected; at a temperature of 45^{o}C (318K) the cycle life is only 1/4th of what it is at 25^{o}C (293K) (Xiong et al., 2020). To withstand extreme temperatures, cooling systems are installed in the battery electric containers (Abma et al., 2019a).

The SoC is of great effect on the battery condition. For example, when the SoC is kept between 20-80%, the batteries degrade slower compared to a 0%-100% SoC (Xiong et al., 2020). If the SoC is kept within a smaller range, it would be beneficial for the degradation period of the battery electric container. However, there would be an increase in the amount of charging and docking facilities along a corridor, as less capacity can be used by a single battery electric container to propel a vessel. This would lead to the increase in stops and thereby lead to extra initial investment costs, as more containers and charging and docking facilities are required. When considering aging, a 10% - 90% SoC strategy and a minimal usable electric energy of 1.3 MWh during the lifetime of a battery electric container, a battery electric container can be charged within 2 hours if the charger and the grid connection can deliver approximately 700 kW (Abma et al., 2019a).

There are some safety concerns regarding battery electric containers, especially in the usage for the maritime and inland navigation sector. A battery pack that is damaged or subjected to an intense amount of heat, can suffer from an exothermic reaction, which causes more heat to be generated. This can cause a chain reaction in battery electric containers (Gardner, 2018). Moreover, water can have a reaction with lithium to produce hydrogen gas, which can cause fire or an explosion (Abma et al., 2019a; Gardner, 2018). When battery electric containers are stored on land, a safety distance between containers must be ensured. PGS 37 (2022) states that at least 2.5 m should be between containers placed sideways to each other and 4 m placed in line with each other.

3.2.3 Electric power distribution

3.2.3.1 Electric grid connection.

In the Netherlands, electricity is sourced from the nationwide grid (TRL 9). For a continuous and secure supply of electricity, the national grid is connected to other European countries (e.g., Germany). The exchange of electricity happens on high-voltage grids (i.e., 220 and 380 kV) and is operated by Transmission System Operators (TSO), such as TenneT in Germany and the Netherlands (TenneT, n.d.). However, for a 2MVA battery electric charging facility as described in section 3.2.2.1, electricity is sourced from a lower voltage distributional grid. A lower voltage is acquired by step down transformer substations. The battery electric charging facility with a capacity ranging from 2MVA to 10MVA would require a grid connection within the >173kVA and 10MVA range: the medium voltage grid. A connection with the medium voltage grid has a process and development period of 0.5-3 years (Netbeheer Nederland, 2019). However, this process and development period is solely an indication and can be longer in certain areas. In general, urban areas require a longer process period compared to a rural area.

3.2.3.2 Grid congestion

Net congestion is a potential concern in the development of a future proof nationwide charging and bunkering infrastructure in the Netherlands. Figure 16 shows the current congestion from a demand-side perspective on the partial Dutch electricity grid (Netbeheer Nederland, 2021). The installing of relatively small projects, such as a 2MVA battery electric charging facility that requires a medium voltage connection, could lead to adjustment of the electric grid in other levels (e.g., high voltage) (Netbeheer Nederland, 2019). However, determining an average impact is location dependent and beyond the scope of the study. Moreover, bigger congestion threads may occur as a result of implementing sustainable solutions for electricity production (i.e., wind and solar energy) onto the national grid. As other sectors will use more sustainable solutions as well, expected would be an increase in the demand of electricity overall. Such an increase in the demand for electricity in other sectors (e.g., transport sector in general, and industry sector) would lead to more congestion as well.

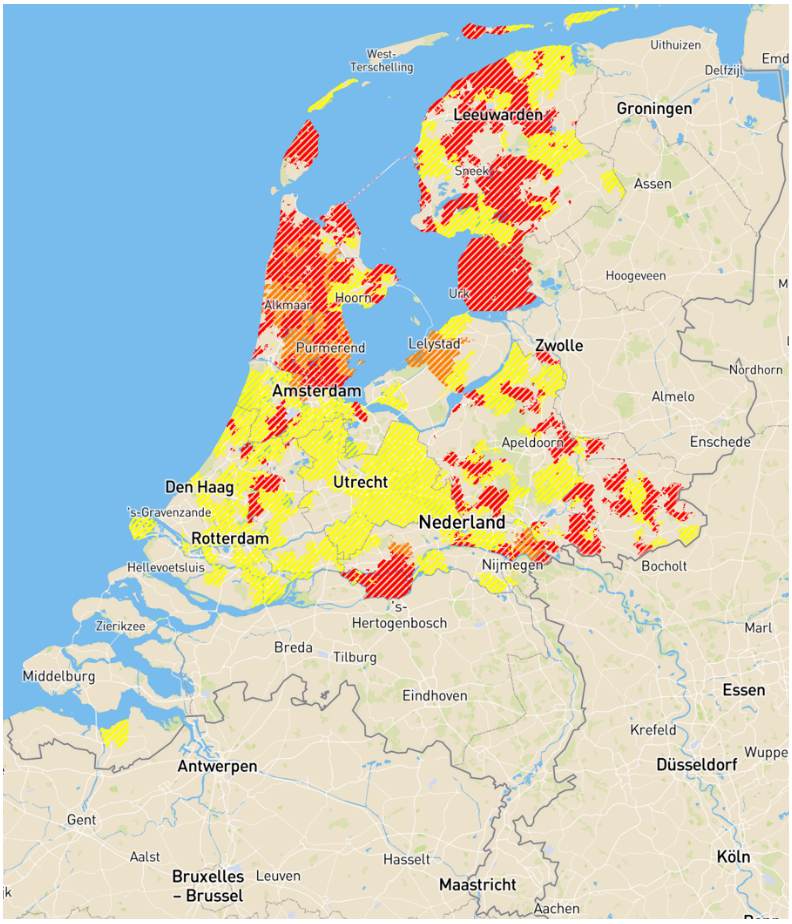

Figure 16: The current electrical grid congestion in the areas of Liander and Stedin from the demand-side. Yellow is a threat of transport scarcity, orange is a pre-announcement of structural congestion and red is current structural congestion (Netbeheer Nederland, 2021).

Net congestion can be tackled by different solutions. One of these solutions is the implementation of a different grid structure. The medium voltage grid consists of radial, annular or meshed grid structures. The simplified constructions are shown in Figure 17. In a radial grid (also called star-shaped grid) the supply point reaches the network station via one connection. By a malfunction, the whole grid is down. In an annular grid, the supply point can reach several stations through two connections. A failure in a connection then leads to a failure of the supply and relocation of the grid opening restores the energy interruption. In a meshed grid, the supply point is reaching several stations by more than two connections (Van Oirsouw & Van Cobben, 2011). By creating additional support points in the medium voltage grid, which are fed from a meshed operated medium voltage transport grid. This would lead to shorter radially operated medium voltage grid structures and increases flexibility and capacity (Van Oirsouw & Van Cobben, 2011). The other solution would be a shorter and fewer complex grid. An example would be that a renewable production source (e.g., wind turbine or solar field) would directly be connected to charging facility. However, renewable energy sources are intermittent and installing such an installation would lead to additional investment costs.

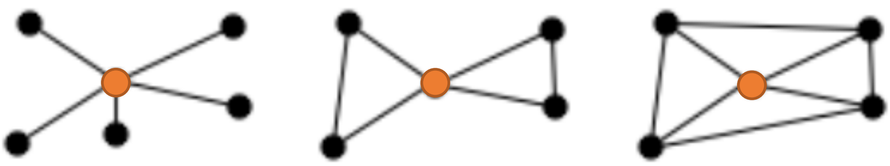

Figure 17: The grid structures in the medium voltage grid. From left to right are shown the radial grid, the annular grid and the meshed grid (Van Oirsouw & Van Cobben, 2011).

3.3 Partial supply chain analysis of methanol

Currently, methanol is widely available on a global and European scale as it has large applications in the chemical industry (Ellis & Tanneberger, 2015). The physical state of methanol under normal conditions is liquid. The gaseous form is not used as a fuel, as this has less energy content. Moreover, to form gaseous methanol, heat is required. Compared to the battery electric and hydrogen energy carriers is methanol readily available and can be retrofitted into the inland navigation sector relatively easy. The costs involved in retrofitting the engine of a vessel for methanol are less in comparison with retrofitting the engine of a vessel to an LNG engine (DNV GL, 2015; Moirangthem, & Baxter, 2016). Besides the positive effects involved in vessel adjustments, the distribution and bunkering process is also similar to conventional fuels in the inland navigation industry, such as for diesel.

Methanol is not a zero-emissive energy carrier; combustion of methanol produces CO_2 and other greenhouse gases such as nitrogen oxides (NO_x), sulphur oxides (SO_x) and coarse particulate matter (PM_{10}). However, bio-methanol or e-methanol can be a sustainable and renewable solution to the conventional energy carriers. The production of bio-methanol, e-methanol and carbon-recycled methanol is currently in development. Bio-methanol is made by anaerobic digestion of wet biomass, whereas e-methanol is produced from feedstock water and air with electrical power (Zomer et al., 2020). Carbon-recycled methanol is produced from fossil-based municipal solid waste (MSW) by use of gasification (Zomer et al., 2020). The development of e-methanol is inherently connected to the development of green hydrogen production, as e-methanol is produced from green hydrogen. The large-scale deployment of biomethanol, e-methanol and carbon-recycled methanol is depended on a stable policy framework over a large period of time (Zomer et al., 2020).

The following section discusses the bunkering process and distribution of methanol by 2030.

3.3.1 Methanol bunkering

With the current technologies, three different distinctive bunkering options are considered for methanol: Ship-to-Ship (STS) bunkering, Truck-to-Ship (TTS) and Shore-Ship bunkering. In the context of methanol as an energy carrier in the inland navigation sector, all the current bunkering options have a TRL of 7 for the bunkering equipment of methanol and have a TRL of 6 for the procedures involved with bunker methanol (Lloyd's Register, 2020) as bunkering systems are not commercially available on an industrial level. Many pilot projects show that the bunkering of methanol is feasible in the upcoming few years.

3.3.1.1 Ship-to-Ship methanol bunkering

STS bunkering is referred to as bunkering a ship by another ship or barge. With conventional fuels, a ship with a length of approx. 110 to 130 m is used to bunker the required fuel. The bunker barge will go alongside the ship that has to be bunkered and will connect a hose to transfer the fuel. A pump, installed on the bunker barge, will first pump the fuel slowly into the ship that has to be bunkered to ensure that the right tanks are getting filled. Operation will continue at full speed when it is ensured that the designated tanks are filled (Zomer et al., 2020). The bunker barges that are currently active in the Netherlands are capable to carry between 2,800 and 6,000 tons and have a bunkering speed of 500 to 1,500 m^3 per hour (Zomer et al., 2020). For bunkering methanol, extra measures have to be taken in place. Methanol has a lower energy content compared to traditional fuels. To store methanol with the same energy content as diesel, it requires roughly twice the amount of space. However, LNG and methanol do have the same energy density (Andersson & Marquez Salazar, 2015). Additional safety measures are required as methanol is categorized as a highly flammable toxic substance. A bunkering vessel must maintain 50 meters from other vessels, 100 meters from installations such as bunker stations and 300 meters from residential areas (Zomer et al., 2020). STS bunkering has been demonstrated in 2020. Waterfront Shipping[3] demonstrated the first STS methanol bunkering operation in the port of Rotterdam (Waterfront Shipping, 2020).

3.3.1.2 Truck-to-Ship methanol bunkering

Currently, due to low investment costs, limited demand and the lack of infrastructure, TTS bunkering is a commonly used option of bunkering methanol for e.g., ferries. However, the bunkering costs are relatively high compared to the other bunkering option due to a low payload per tank trailer (Zomer et al., 2020). TTS bunkering of methanol has been performed by Stena line. The Stena Germanica (ferry) is bunkered by trucks on the quay. It requires pumps installed on the quay that is situated next to the ferry (Andersson & Marquez Salazar, 2015; Stefenson, 2014). TTS shall have minor to no implications in the inland navigation sector as multiple tank trailers are required to fill one vessel and this is not favourable. Moreover, the high price is considered to not be competitive to the other bunkering methods (Harmsen, personal communication, 2022).

3.3.1.3 Shore-ship methanol bunkering

The Shore-ship bunkering option covers the bunkering of a fuel that is directly bunkered from a storage tank or station (Zomer et al., 2020). Compared to the other bunkering option, the fastest bunkering speed can be obtained with Shore-Ship bunkering. As a result of fixed installation, a larger hose can be installed resulting in a bunkering rate of up to 3,000l/min (Zomer et al., 2020). Methanol Institute (2017) mentioned that due to the low flashpoint of methanol, existing storage and bunkering infrastructure requires minor adjustments to handle methanol. Moreover, the investment of a small installation is estimated to be significantly lower compared to LNG terminal (Methanol Institute, 2017).

3.3.2 Distribution of methanol

The distribution methods for methanol are more versatile compared to the distribution of electricity and hydrogen. According to Zomer et al. (2020), there are currently four distribution options that can be used currently for methanol used as inland navigation fuel: inland methanol vessels, by rail, by tank trailers or by pipeline.

3.3.2.1. Distribution by inland methanol vessels

Inland methanol vessels are favourable as these can transport large quantities of methanol over a medium to long distance (Zomer et al., 2020). Typical transportation quantities are between 500 to 650 tons per vessel (Harmsen et al., 2014; Zomer et al., 2020). Compared to the other three distributional modes, this distributional mode has the highest GHG emissions. However, this is likely to decrease in the near future as these vessels will use alternative fuels e.g., methanol, to propel itself (Zomer et al., 2020).

3.3.2.2. Distribution by rail

Transport by rail can be a cost-effective and relatively sustainable way to distribute methanol if a production location does not have any excess to seaports or inland water terminals. In the Netherlands, a good and well-developed rail infrastructure is available. However, methanol is categorized as a highly flammable toxic substance. Transportation by rail is safe when specific safety measures are considered. As methanol is a liquid under normal conditions and does not spontaneously combust or explode, non-pressurized and non-insulated upright chemical tank wagons are used for transportation (Methanol Institute, 2017; SafeRack, n.d.; Shusheng et al.,

[3] Waterfront Shipping (A wholly owned subsidiary of Methanex Corporation) demonstrated STS methanol bunkering in collaboration with the Port of Rotterdam, Vopak, NYK and Tankmatch.

2020). The chemical tankers are equipped with pressure relief systems that can be used to accommodate thermal expansion during transport (Methanol Institute, 2017). Moreover, a closed loop loading operation is required (SafeRack, n.d.). Filling and discharge are carried out through a boiler manhole on top of the tank wagon by a special loading arm that can be hermetically attached to the boiler to prevent leakage (Vorobyov et al., 2021). Chemical tank wagons have significant less payload compared to inland methanol carriers: approximately a payload of 80 m^3 methanol or approx. 50 tons (Harmsen et al., 2014; Zomer et al., 2020). The precautions for rail transport are comparable to ethanol, gasoline, kerosine (jet fuel) and distillate (Methanol Institute, 2017)

3.3.2.3. Distribution by tank trailers

Methanol can also be transported by road when there is a lack of waterways or rail infrastructure. For the use of tank trailers towed by tractor haul trucks for methanol production, the same hazards and safeguards apply as for transportation by rail (Methanol Institute, 2017). Due to a low payload per tank trailer, distribution by tank trailer is considered to be the least sustainable and most cost-expensive distributional option available (Zomer et al., 2020). Therefore, distribution of methanol by tank trailer is only considered to be feasible for low volumes or short distances.

3.3.2.4. Distribution by pipeline

The distribution of methanol by pipelines is not considered to be a feasible option in the Netherlands in the near future. Currently, there is a lack of existing long-range pipeline infrastructure for methanol in the Netherlands. Current pipeline network in the Netherlands is limited to crude oil, oil products, chemicals and some industrial gases (Port of Rotterdam, n.d.). The pipelines are energy- and cost-effective during operation, but the initial investment is exponentially large to be a feasible option as a distribution option solely for the application of methanol for inland navigation. The development of new pipeline infrastructure for methanol is only suitable for very large volumes (Harmsen et al., 2014; Zomer et al., 2020). The major transportations of methanol in the Netherlands take place by road transport, by rail or by inland methanol carriers.

As methanol is widely used in the chemical industry, there is already a suitable distribution and storage infrastructure for methanol in major ports worldwide such as in Rotterdam and Antwerp (Ellis & Tanneberger, 2015). Only minor modifications would be necessary to provide methanol as a marine fuel or fuel applicable in the inland navigation sector.

3.4 Projections for 2030

Different bunkering and delivery options for each energy carrier have been analysed. In the context of inland navigation by 2030, hydrogen has two distinctive bunkering options to be used in the inland navigation sector. Bunkering of hydrogen is possible by a high-pressure hose and by swapping containers filled with CGH_2. The hydrogen storage containers are filled at a filling station. These filling stations can be placed at a docking station but may also be placed closer to the production location. A centralized filling facility is expected to develop in the first place (Interviewee 2, personal communication, January 21, 2022). However, filling facilities might also be placed near hydrogen production facilities situated in ports as these production facilities already have special permits and safety measurements implemented for handling hydrogen (Interviewee 5, personal communication, February 2, 2022). Moreover, the placement near a hydrogen production facility lowers the delivery distance and thereby the delivery expenses. As an alternative, an on-site electrolyser can be placed to tackle distributional costs and additional distributional risks. However, placement of an on-site electrolyser would increase the initial investment significantly. The distribution methods possible for hydrogen are by tube-trailer and container trailers in a compressed gaseous state, in a liquid trailer as a cryogenic liquid and by pipeline in a gaseous state. Transportation by tube-trailer and container trailer are considered feasible to be used to transport hydrogen in the inland navigation sector in the upcoming years (Interviewee 2, personal communication, January 21, 2022). Although, a larger transportation capacity can be generated by transportation of liquid hydrogen, the liquification costs and lack of application as a fuel in the inland navigation sector make the distribution option of liquid hydrogen not appealing. With the current hydrogen pipelines, supply of hydrogen is limited to important industrial clusters. It is however expected that the development of hydrogen delivery by existing natural gas pipelines is mature enough to supply bunkering or filling facilities by 2030. However, if the delivery through dedicated pipelines will happen depends largely on the fixed purchase of hydrogen according to Interviewee 2 (personal communication, January 21, 2022). Contracts or agreements could aid towards the investment to facilitate such pipeline infrastructure (Interviewee 2, personal communication, January 21, 2022).

The applications for electricity in the inland navigation sector is limited to battery electric containers. Direct charging of electricity by cable to an integrated battery on board of a vessel is in theory feasible. However, this is inconvenient for the continuation of sailing as charging takes a relatively long period of time. Therefore, this is not seen as an option for vessels used in the inland navigation sector. The bunkering point consists of a docking station and a charging station. However, charging stations can be placed elsewhere when there is no capacity on the electric grid at the port (Interviewee 4, personal communication, January 25, 2022). The docking station should have a container crane to provide the bunkering of battery electric containers. The charging station consists of modular components and initially requires a grid connection of 2MVA. However, this can be expanded to a 10 MVA capacity. Electricity is sourced and distributed by the national grid. The charging station requires a grid connection within the >173kVA and 10MVA range: the medium voltage grid.

Methanol is widely available on a global and European scale as it has large applications in the chemical industry. Methanol has similar distribution and bunkering methods as conventional energy carriers. The methods for bunkering methanol are Ship-to-Ship (STS) bunkering, Shore-Ship bunkering and Truck-to-Ship (TTS) bunkering. It is expected that bunkering is either performed by (retrofitted) bunkering ships or by bunkering installations situated on docks (Interviewee 1, personal communication, January 13, 2022; Interviewee 3, personal communication, January 31, 2022). The development of TTS bunkering in the inland navigation sector is considered not to develop, as the other methods are more cost efficient and have a larger volume to bunker (Interviewee 1, personal communication, January 13, 2022). Distribution of methanol is possible by inland methanol vessels, by rail, by tank trailers and by pipeline. The pipelines, compared to the other delivery method, are energy- and cost-effective during operation, but the initial investment is exponentially larger to be a feasible option as a distribution option solely for the application of methanol for inland navigation. The major transportations of methanol in the Netherlands take place by road transport, by rail or by inland methanol carriers. For large quantities transportation by inland methanol carriers or by rail are the best cost-efficient options.

4 Input parameters

The following section discusses the input parameters for the cost model. These are categorized by miscellaneous input data and by the input data for the different energy carriers i.e., hydrogen, battery electric and methanol. The miscellaneous consists of sailing profile, fuel economy and input data that is relevant for multiple energy carriers such as cost of rent, utility cost and storage and handling of containers. The input of the different constructed scenarios is provided in 4.5

4.1 Miscellaneous input data

4.1.1 Determining yearly demand by sailing profiles and fuel economy

To determine the required charging and bunkering infrastructure for 2030, the yearly demand must be known. A large demand may require additional bunkering components such as additional bunkering or filling stations. The yearly demand determines how much of a certain energy carrier is required yearly to have a pre-determined number of boats to sail for the different scenarios. The required yearly demand of an energy carrier can be calculated by the following equation:

$$Yearly\ demand_{EC} = Vessel_{EC} \times FE_{EC} \times SP$$

Where $Vessel_{EC}$ is the number of vessels that sail with a certain energy carrier, FE_{EC} is the fuel economy of a certain energy carrier (kg/km for hydrogen, kWh/km for battery electric and l/yr for methanol) and SP is the average sailing profile of inland navigation vessels (km/yr). During this study the sailing profiles do represent the distance a vessel travels each year. With the yearly demand for each energy carrier, the requirements of components can be determined and calculated for the output of the different supply chains charging and bunkering infrastructure.

4.1.1.1 Fuel economy

Unfortunately, due to the novelty and thereby the current lack in adoption of the energy carriers in the inland navigation sector, the fuel economy cannot be determined from real time data from commissioned vessels as these simply do not exist. The fuel economy of each energy carrier has been determined by the data provided in the studies of several pilot projects and other scientific studies. Therefore, different ways of obtaining the fuel economy for each energy carrier had to be approached.

For both the average hydrogen fuel economy and the battery electric fuel economy the average electrical consumption has to be known. The average electrical consumption is derived from different vessels in the inland navigation sector and shown in Table 4 (Piña Rodriguez, 2021). The average fuel consumption for battery electric vessels, and thereby the fuel economy, is 32.84 kWh/km

Table 4: The average electrical consumption derived from different vessels

	Unit	Den bosch Max groen & Blauw	Alphenaar & gouwenaar	Nijmegen Max	Sendo Mare	Sendo Nave	Average
TEU	#	140	104	220	315	315	219
Length trip	km	240	122	382	296	296	267
Avg. Energy consumption	kWh	7,200	4,100	13,000	8,969	10,736	8,801
Time	hr	25	24	62	19	25	31
Avg. electrical energy fuel consumption	kWh/ km	30.00	33.61	34.03	30.30	36.27	32.84

It will be assumed that fuel cells will be used for sailing with hydrogen. Therefore, the average hydrogen fuel economy for inland navigation vessels is derived by multiplying the consumption of H_2 by a fuel cell to generate a MWh of electrical energy (kg/MWh) by the average electrical energy fuel consumption (MWh/km). Abma et al. (2019b) determined that with an average fuel cell efficiency of 40% and with a higher heating value (HHV) for hydrogen of 141.7 MJ/kg, 63.5 kg of H_2 is required to generate a MWh of electrical energy. Therefore, the average hydrogen fuel economy for inland navigation vessels is:

$$FE_{H2} = 63.5\frac{kg}{MWh} \times\ 32.84\frac{kWh}{km} \times 1000\frac{kWh}{MWh} = 2.09\frac{kg}{km}$$

Where FE_{H2} is the average hydrogen fuel economy.

No data is available on the average fuel economy of methanol vessels. However, tests with the performance of engines that use methanol as a fuel have been carried out. Together with the average fuel economy for diesel vessels, the average fuel economy of methanol sailing vessels can be derived. The fuel economy of vessels sailing on methanol is derived by the following equation:

$$FE_{MeOH} = \frac{FC_{diesel} \times \eta_{diesel}}{LHV_{MeOH} \times \eta_{MeOH} \times \rho_{MeOH} \times SP_{MeOH}}$$

Where FE_{MeOH} is the fuel economy for methanol vessels (l/km), FC_{diesel} is the fuel consumption for diesel vessels, η_{diesel} is the efficiency of a diesel engine, LHV_{MeOH} is the Lower Heating Value (LHV) of methanol, η_{MeOH} is the efficiency of a methanol engine, ρ_{MeOH} is the density of methanol and SP_{MeOH} is the sailing profile for methanol vessels. Table 5 shows the input values to get the fuel economy for methanol vessels. The fuel economy for methanol vessels is 20.73 l/km.

Table 5: Input values for the equation to obtain the fuel economy

	Unit	Values	Source
Average diesel consumption	MJ/yr	9,000,000	Panteia (2019)
Density Methanol	kg/l	0.791	Keera et al. (2011)
LHV Methanol	MJ/kg	19.90	Harmsen (2021)
Engine efficiency diesel	%	50.0	Wartsila (2022)
Engine efficiency methanol	%	37.7	Harmsen (2021)
Sailing profile methanol	km/yr	36,574	See 4.1.1.2 for sailing profiles

With the outcome of the model, a comparison can be made with the bunkering infrastructure for the current energy carrier i.e., diesel. For this comparison the average fuel economy has to be known. This is calculated by the following equation:

$$FE_{diesel} = \frac{FC_{diesel}}{LHV_{diesel} \times \rho_{diesel}}$$

Where FE_{diesel} is the fuel economy of diesel, LHV_{diesel} is the LHV of diesel (43.60 MJ/kg), ρ_{diesel} is the densitiy of diesel (0.83 kg/l) and SP_{Diesel} is the sailing profile of diesel vessels (equal to the sailing profile of methanol) (Harmsen, 2020). The fuel economy of diesel vessels is 6.96 l/km.

It should be mentioned that the fuel economy is affected by multiple external factors. These include factors such as the speed of sailing, weight of the vessel, the amount of water between hull and river floor, sailing upstream or downstream and the wind direction (Connekt, 2021). These factors are not included during this study, as these would require a modelling study on its own.

4.1.1.2 Sailing profiles

According to multiple interviewees, methanol could be a favourable energy carrier to be used for large vessels with dry bulk, wet bulk or container cargo and (containerized) hydrogen or containerized battery electric will be used by vessels with containerized cargo that shuttle between two ports (Interviewee 1, personal communication, January 13, 2022; Interviewee 2, personal communication, January 21, 2022; Interviewee 4. Personal communication, January 25, 2022). However, this cannot be concluded with certainty as these are assumptions. Moreover, to show how the different energy carriers compare to each other, the same sailing profiles have to be used for all energy carriers. Hence, the same sailing profiles are implemented in the model for hydrogen vessels, battery electric vessels and methanol vessels The average sailing profile for all vessels will include all types of cargo vessels i.e., dry, wet, break bulk and container cargo vessels. The average sailing profile for the different fuelled vessels is 36,574 km/yr. The input data and calculations used to obtain the average sailing profile is shown in Appendix III.

4.1.2 Ground rental prices and cost of berth

The ground rental prices in ports are considered commercially confidential information that is not allowed to be shared. However, Interviewee 5 (personal communication, March 3, 2022) and Port of Rotterdam (2021a) stated that the revenue from ground rental in the port of Rotterdam was €418,065,000. - in 2020. The yearly allocable land was approximately 6,000 ha (Interviewee 5, March 3, Date, 2022). When these factors are known, the average rental price can be calculated by dividing the revenue with the total allocable land:

$$Average\ rental\ price\ of\ land\ (€/m^2) = \frac{Revenue\ from\ ground\ rental}{allocable\ land} = \frac{€418{,}065{,}000}{6{,}000\ ha} = \sim €7/m^2$$

Static bunkering installations in ports have to pay the cost of berth to dock ships and vessels. The average cost of berth is €1,050/day (Zomer et al., 2020). This is equivalent to ~€383,513/year.

4.1.3 Safety contours and guidelines

The processes involved in bunkering of methanol, hydrogen or battery electric containers have risks that have to be taken into account as mentioned in Chapter 3. The energy carriers can cause severe damage if a leakage appears in e.g., a hydrogen container or methanol tank. Guidelines in the form of safety contours and safety measures have been proposed or set to control and mitigate the risks during bunkering and storage of the energy carriers.

Many of these guidelines are constructed by the Publicatiereeks Gevaarlijke Stoffen (PGS) (publication series of hazardous substances). The PGS is a guideline for companies that produce, transport, store or use hazardous substances and for governments who provide the supervision and licensing of these companies. As bunkering of hydrogen, battery electric or methanol powered vessels is still in the pilot phase, safety guidelines for bunkering or storage of hydrogen, battery electric containers and methanol sometimes lack as research towards these guidelines is still conducted. However, many safety guidelines can be adapted from road traffic. A list of safety guidelines for the different energy carriers is provided below:

Hydrogen:

- According to PGS 35 (2020), a 4 m safety contour for hydrogen installations is required. Therefore, during this thesis, a bunkering facility via direct dispensing or filling facility for hydrogen containers will have a safety contour of 4 added to the footprint of the facility.
- Hydrogen containers can be stacked in towers of three. The safety contour required for this stack is calculated to be 230 m (DNV, 2021). There is currently no data on the distances required between stacked hydrogen containers. No distance is set as a default for the distance between stacked hydrogen containers.
- Bunkering of hydrogen containers does not require extra safety contours (Heitink & Mentink, 2022).

Battery electric:

- No safety contours are known for battery electric charging facilities.
- Battery electric containers are considered battery electric storage systems (BESS). According to PGS 37 (2022), the shortest distance between BESS installed is at least 2.5 m sideways to each other and the shortest distance between BESS that are installed in line with each other is at least 4 m. Therefore, in this study the battery electric containers are stored sideways to each other to provide the least amount of area required for safety contours. No information regarding safety contours on stacked battery electric containers is available. As a default, stacks of 3 battery electric containers are allowed in this model.
- Bunkering of battery electric containers does not require extra safety contours (Heitink & Mentink, 2022).

Methanol:

- Methanol bunkering stations do require a safety contour of 25 m (Heitink & Mentink 2022).

Theoretically, the minimum can be obtained by storing the stacked hydrogen and battery electric containers sideways to each other. Therefore, the minimum land required to store the hydrogen and containers at a location is derived with the following equation:

$$Land\ for\ hydrogen\ container\ storage_i = (Stacked\ containers_i \times W + 2 \times SC_{H2}) \times (L + \times\ SC_{H2})$$

Where $Land\ for\ hydrogen\ container\ storage_i$is the land required for container storage at location i, $Stacked\ containers_i$ is the number of container stacks at location i, W is the width of a 20 ft container (2.44 m) , L is the length of a 20 ft container (6.1 m), and SC_{H2} is the safety contour for hydrogen containers (230m). The land required for battery electric containers can be derived with the following equation:

$$Land\ for\ battery\ electric\ container\ storage_i = \left(Stacked\ containers_i \times \left(W + SC_{BE,SW}\right) + SC_{BE,SW}\right) \times \left(L + SC_{BE,IL}\right)$$

Where $Land\ for\ battery\ electric\ container\ storage_i$ is the land required for battery electric container storage, $SC_{BE,SW}$ is the safety contour sideways to a battery electric container (2.5 m) and $SC_{BE,IL}$ is the safety contour in line of the battery electric container (4 m).

The additional land required for the safety contours is combined with the spatial requirements i.e., footprint for the bunkering and charging infrastructure of hydrogen, electricity and methanol to generate a complete image of the spatial requirements. The total footprint is multiplied with the rental price of land to obtain the total cost of rent.

4.1.3 Grid connection

The different facilities require electricity to operate. An example is hydrogen container filling or bunkering facilities that require a grid connection to provide electricity required for the operation of e.g., compressors and/or electrolysers. Another example is that charging stations must be connected to the electric grid for the supply of electricity to charge the battery electric containers. The cost of investment for a grid connection are the same for a range of grid connection capacities: a grid connection between 2 MVA and 5 MVA has the same investment cost. The range for which the capacity of a grid connection has the same investment cost are different between grid operators and provinces. In areas where Liander is the grid operator, the cost for grid connections is the same for grid connections ≤2 MVA (Liander 2021). The same goes for grid connections ranging between 2-5 MVA and grid connections ranging between 5-10 MVA. However, in areas where Stedin is the grid operator, the same applies to cost of investment for grid connections ranging between 1-1.75 MVA (Stedin, 2021). The same applies to grid connections ranging between 1.75-3 MVA and 3-10 MVA. For simplification reasons, the ranges for the grid connections with the same investment cost in this study are set to those of Liander (2021): ≤2 MVA (Cat. 1), 2-5 MVA (Cat 2.) and 5-10 MVA (Cat. 3). The cost and performance parameters for the different grid connections are shown in Table 6.

Table 6: Cost and performance parameters for the different grid connections

Info	Unit	≤2 MVA (Cat. 1)	2-5 MVA (Cat. 2)	5-10 MVA (Cat. 3)	Sources and notes
Investment grid connection (incl. 25m)	€	43,478	228,887	288,288	Stedin (2021), Liander (2022)
Investment cable (until 100m, excluding the 25m)	€	20,253	25,491	28,700	Stedin (2021)
O&M grid connection	€/yr	729	1,728	8,745	Stedin (2021)
Max grid connection	MVA	2	5	10	Stedin (2021)
lifetime	yr	20	20	20	Default to the project lifetime

4.1.4 Utility costs

Bunkering, charging and filling facilities may require electricity, hydrogen, methanol and/or water depending on the energy carrier. It is assumed that all energy carriers are produced on a sustainable and/or renewable. Therefore, the model incorporates the cost price for green hydrogen, biomethanol/e-methanol instead of conventional methanol and grey hydrogen. Although the electricity is sourced from the electric grid, it is assumed that in theory all the electricity is sourced from a sustainable and renewable source.

Assumed is that half of the sustainable methanol is biomethanol and half is e-methanol. The average of the projected cost price of biomethanol and e-methanol combined is ~35 €/GJ (Zomer et al., 2020). This is equal to the ~0.55 €/l, with a density of 0.791 kg/l and and a LHV of 19.90 MJ/kg (Harmsen, 2021; keera et al., 2011).

The utility costs for hydrogen delivery by pipeline, water and electricity is shown in Table 7. The values represent projected prices in 2030.

Table 7: Utility costs

Different cost factors	Unit	Values	Source
Electricity cost	€/MWh	60.00	Jungsbluth et al. (2021)
Water cost	€/l	0.01	Jungsbluth et al. (2021)
Cost of hydrogen by pipeline	€/kg	3.00	EICB (2020)
Methanol price	€/l	0.55	Zomer et al. (2020)

4.1.5 Cost of container handling and storage

With the bunkering and storage of hydrogen and battery electric containers costs are involved. Bunkering of a container happens by crane in a port and thereby requires handling and crane costs. Handling involves the displacement of the containers with e.g., a reach stacker. Storage costs have to be considered as well. These may incorporate e.g., permit costs for storage of hazardous materials and security costs. However, the exact cost factors are not mentioned by Jungsbluth et al. (2021). The cost for handling and storage are shown in Table 8.

Table 8: The cost for container handling and storage (Jungsbluth et al., 2021)

	Unit	Value
Crane lifting	€/lift	30.00
Material handling	€/container	25.00
Port storage for a single container	€/day	2.00
Filling facility or charging facility storage for a single container	€/day	5.00

To get the total cost for crane and material handling, the absolute number of containers e.g., the demand for hydrogen or electricity divided by the capacity of a hydrogen or battery electric container, is multiplied by the cost of crane lift and by the cost of material handling.

The total cost for storage is obtained by multiplying the number of containers in either ports or at filling or charging facilities with the number of containers stored at the particular locations. A division of how many containers are in a port or at a filling or charging facility at any given moment is discussed in 4.2 and 4.3

4.1.6 Truck delivery of hydrogen and battery electric containers

Truck delivery must be incorporated in scenarios where the container filling facility and battery electric charging facilities are not situated near or at a port. For truck delivery a truck with a semi-trailer is required. Table 9 and Table 10 show the relevant input parameters for the truck and flatbed respectively. The costs for truck transport are variable costs as these depend on the driven distance. The transportation cost is considered to be €1.50/km (Kostencheck, 2020). An unknown factor is how far these filling or charging stations will be constructed from the ports. It is assumed that for the Netherlands a distance of 50 km between port and filling or facility is reasonable. Therefore, the cost model will use a distance of 50 km between port and filling or charging facility by default.

Table 9: Truck parameters

	Unit	Values	Sources
Truck Investment	€	120,000	Reuß et al. (2021)
Lifetime	yr	8	Brückner et al. (2014), Reuß et al. (2017)
O&M	% of capital investment/yr	12	Brückner et al. (2014), Reuß et al. (2017)
Utilisation/ load hours	h/yr	2,000	Brückner et al. (2014), Reuß et al. (2017)
Average speed	km/ hr	50	Brückner et al. (2014), Reuß et al. (2017)

Table 10: Flatbed semi-trailer parameters

	Unit	Values	Sources
Trailer Investment	€	15,000	Boon Trucks & Trailers (2022)
Lifetime	yr	30	Boon Trucks & Trailers (2022)
O&M	% of capital investment/yr	4	Assumed
Possible containers that can be carried	#	2	Boon Trucks & Trailers (2022), Jungsbluth et al. (2021)

With the use of the equations in 2.2, the annual CAPEX, OPEX and annual replacement expenditures are calculated with an interest rate of 3% and a project lifetime of 20 years. The annual CAPEX, OPEX and annual replacement expenditures for the truck and flatbed semi-trailer are shown in Table 11 and Table 12 respectively.

Table 11: Annual CAPEX, OPEX and annual replacement expenditures for a truck

	Unit	Values
Annual CAPEX	€/yr	10,755
OPEX	€/yr	19,200
Annual replacement expenditures	€/yr	8,490

Table 12: Annual CAPEX, OPEX and annual replacement expenditures for a semi-trailer

	Unit	Values
Annual CAPEX	€/yr	1,008
OPEX	€/yr	600
Annual replacement expenditures	€/yr	415

4.2 Input parameters hydrogen bunkering infrastructure

For the bunkering infrastructure of hydrogen, a distinction is made between hydrogen bunkering by direct dispensing via a hose and by hydrogen containers. Bunkering with hydrogen containers requires hydrogen filling facilities and hydrogen containers. Hydrogen bunkering by hose requires bunkering stations with a dispensing unit.

A nationwide bunkering infrastructure can be achieved by the construction of several small or a few largee bunkering or filling facilities depending on how many bunkering locations are preferred. If many vessels bunker in one port, it might be preferable to place one large facility instead of several smaller ones. To test the cost difference between a multiple smaller and a single large facility, a list of the cost and performance parameters is made for of large and small facilities.

For the cost model, a simplified facility design is used that incorporates all the necessary components. A simplified facility design, applicable to both a hydrogen filling facility and a bunkering facility, is shown in Figure 18 and shows all the components needed to run a facility. Both facilities use a temporal low buffer storage and compressors. As described in Section 3.1.3.3, H_2 delivery by pipeline requires an extra cleaning process with a PSA unit. If hydrogen is produced on-site, an electrolyser is added to the facility. For the direct dispensing bunkering facilities an extra dispensing unit is installed.

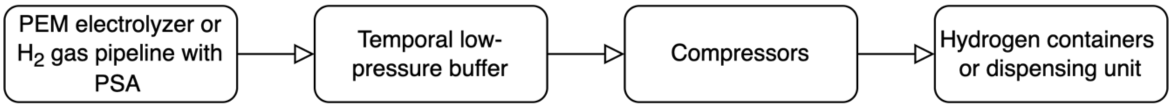

Figure 18: simplified facility design for large and small hydrogen filling and bunkering facilities.

The cost and performance parameters for different hydrogen filling facility and different hydrogen containers is shown in Table 13 and Table 14 respectively. The cost and performance parameters for different direct dispensing hydrogen bunker facilities is shown in Table 15. The maximum full load hours for the facilities are 8000 hours. The cost and performance parameters annual CAPEX, OPEX and annual replacement expenditures for the different components are shown in Appendix IV.

Table 13: Cost and performance parameters for different hydrogen container filling facilities

	Unit	Small facility with pipeline	Large facility with pipeline	Small facility with electrolyser	Large facility with electrolyser
PSA capital investment	€	2,769,918	8,078,928	0	0
PEM electrolyser capital investment	€	0	0	4,837,500	14,109,375
Low pressure buffer capital investment	€	500,000	500,000	500,000	500,000
Compressor capital investment	€	1,131,000	4,806,750	1,131,000	4,806,750
Total capital investment (excl. Grid connection)	€	4,400,918	13,385,678	6,468,500	19,416,125
Capacity	kg/hr	65	325	65	325
Average maximum output	kg/hr	59	297	59	297
Maximum output	ton/yr	520	2,600	520	2,600
Footprint	m^2	870	3,724	1,370	4,224
Electricity consumption	kWh/kg H_2	2.54	2.54	59.69	59.69
Water consumption	l/kg H_2	0	0	10	10
Total Electrical DC power	MW	0.86	12.54	55,408.36	19.40
Power grid connection	MVA	2	2	5.00	2x10
Power grid connection capital investment	€	43,478	43,478	228,887	576,576
O&M grid connection	€	729	729	1,728	17,490
Total capital investment (incl. Grid connection)	€	4,444,397	19,199,819	6,697,387	19,992,701
Electrolyser	Yes or No	No	No	Yes	Yes

Table 14: Parameters for different 20 ft hydrogen containers (Jungsbluth et al, 2021)

	Unit	20ft, Type II, 300 bar	20ft, Type IV, 300 bar	20ft, Type IV, 500 bar
Pressure	Bar	300	300	500
Storage capacity	kg CGH_2	312	371	518
Investment costs	€	150,000	250,000	380,000
Required containers on one vessel	#	7	6	4
footprint	m^2	14.88	14.88	14.88
Lifetime	yr	15	15	15
O&M	€/yr	26,667	26,667	26,667

The required containers on one vessel have been calculated and abstracted from the containers required for the average trip length provided by Abma et al. (2019b) and Jungsbluth et al. (2021). The dimensions of one 20 ft container are 6.1 x 2.44 m. Hence the footprint is 14.88 m^2.

Table 15: Cost and performance parameters for different hydrogen bunker facilities

	Unit	Small facility with pipeline	Large facility with pipeline	Small facility with electrolyser	Large facilitywith electrolyser
PSA capital investment	€	2,769,918	8,078,928	0	0
PEM electrolyser capital investment	€	0	0	4,837,500	14,109,375
Low pressure buffer capital investment	€	500,000	500,000	500,000	500,000
Compressor capital investment	€	1,131,000	4,806,750	1,131,000	4,806,750
Dispenser capital investment	€	95,000	190,000	95,000	190,000
Total capital investment (excl. Grid connection)	€	4,495,918	13,575,678	6,563,500	19,606,125
Capacity	kg/hr	65	325	65	325
Average output (with 8000 load hours)	kg/hr	59	297	59	297
Maximum output (with 8000 load hours)	ton/yr	520	2,600	520	2,600
Footprint	m^2	870	3,724	1,370	4,724
Energy	kWh/kg H_2	2.54	2.54	59.69	59.69
Water consumption	l/kg H_2	0	0	10	10
Total Electrical DC power	MW	0.86	0.83	3.88	19.40
Power grid connection	MVA	2	2	5.00	2x10
Power grid connection capital investment	€	43,478	43,478	228,887	576,576
O&M grid connection	€/yr	729	729	1,728	17,490
Total capital investment (incl. Grid connection)	€	4,539,397	19,389,819	6,792,387	20,182,701
Electrolyser	Yes or No	No	No	Yes	Yes
Berth places	#	1	1	2	2

Unfortunately, no optimalisation studies have been carried out towards the ideal ratio of vessels to the number of hydrogen containers in circulation. One condition that is crucial is the possibility to swap empty hydrogen containers immediately for full hydrogen containers in a port to ensure continuous sailing. Different approaches can be taken to provide the number of hydrogen containers required for the bunkering infrastructure of hydrogen containers. Hypothetically, if all vessels would enter the same port at once, the number of full hydrogen containers available in this port would have to be equal to all the hydrogen containers on all the vessels sailing. However, this situation is very unlikely. A more reasonable determination of hydrogen containers required to guarantee continues sailing has been proposed by Jungsbluth et al. (2021). Jungsbluth et al. (2021) stated that the following conditions for the number of hydrogen containers in circulation apply:

- Half the hydrogen container vessels are sailing, and half of the hydrogen container vessels are in a port. On every ship, the total number of hydrogen containers is equal to the required containers on one ship to sail.
- Of the vessels in ports half of those vessels are in upstream ports and half of those vessels are in downstream ports. Downstream ports are defined as ports downstream a river. Vessels departing from these kinds of ports will sail upstream a river. Vessels departing from upstream ports will thereby sail downstream a river.
- For a downstream port, the number of hydrogen containers is equal to half of the hydrogen containers on board of the vessels in the port. Assumed is that hydrogen container vessels

will require only half of the energy to sail downstream in comparison when sailing upstream. Therefore, if a vessel sails from an upstream port downstream only half of the containers on board will be used, whereas if a vessel sails upstream, all the containers have to be exchanged as all hydrogen containers are empty. Therefore, only half of the required containers have to be swapped for full hydrogen containers. If all the vessels in a downstream port at once would swap, only half of the hydrogen containers on board would have to be available in the port.

- At ports qualified as upstream ports, the number of hydrogen containers available in the port are equal to the number of hydrogen containers on the vessels. The reason for this is that if all vessels in an upstream port would swap hydrogen containers at the same time, enough hydrogen containers would be available.
- The total number of containers available at filling facilities is equal to the total number of hydrogen containers in ports.

The previously stated conditions are only valid for two ports. However, in this study, these conditions are valid for any given time in a year with every number of ports. To ensure any flexibility, the number of spare containers is equal to the following equation:

$$Spare\ hydrogen\ containers = 0.0329 \times hydrogen\ containers\ in\ circulation + 2.0033$$

The equation is derived from linear interpolation of the number of spare hydrogen containers required when there are 10 hydrogen containers in circulation (2 spare hydrogen containers), 50 hydrogen containers in circulation (4 hydrogen containers), 700 hydrogen containers in circulation (~25 spare hydrogen containers) (Jungsbluth et al., 2021)

4.3 Input parameters electricity

The main components for the bunkering infrastructure of battery electric containers are charging facilities with a grid connection and battery electric containers. Additionally, in cases of long distances from ports to charging stations truck transportation is required.

Piña Rodriguez (2021) and Interviewee 4 (personal communication, January 25, 2022) suggest that four different charging station designs can be implemented for charging battery electric containers. The cost and performance parameters for charging stations are shown in Table 16. Unfortunately, no costs for individual components of the charging station could be provided as this is competitively sensitive information (Interviewee 4, personal communication, January 25, 2022). Assumed is that the capital investment for the different charging stations includes the cost for construction and infrastructure.

Table 16: Cost and performance parameters for different charging stations

Info	Unit	Charging station with two 1000 kW charging spots	Charging station with two 500 kW charging spots	Charging station with one 750 kW charging spot	Charging station with one 1000 kW charging spot	Sources and notes
Investment	€/CF	1,350,000	1,080,000	840,000	950,000	Piña Rodriguez (2021), validated by Interviewee 4 (personal communication, January 25, 2022)
Charging power	kW	1,000	500	750	1,000	Piña Rodriguez (2021)
Charging spots	#	2	2	1	1	Piña Rodriguez (2021)
O&M	% of investment /yr	1	1	1	1	Abma et al. (2019a)
Footprint (incl. parking space)	m^2	400	400	400	400	Engie, 2020
Lifetime	yr	15	15	15	15	Engie, 2020
Capacity	MWh/yr	16,000	8,000	6,000	8,000	with 8000 full load hours

All charging stations in Table 16 require a grid connection of max. 2 MVA. As described in 3.2.2.1, the charging station is modular and can be expanded by the placement of more units to form a larger charging facility. A larger charging station would consist in theory of several smaller stations and would only require a grid connection with a large capacity in this situation.

The cost model implements batteries with a realistic 10-90% SOC charging strategy. The number of batteries in circulation is derived from the expansion plan by ZES. ZES expects a specific amount of battery electric containers in circulation with a specific amount of battery electric vessels for different business phases. This ratio is shown in Table 17 (Interviewee 4, personal communication, January 25, 2022).

Table 17: The number of battery electric containers and number of battery electric vessels for different phases (Interviewee 4, personal communication, January 25, 2022)

	Unit	Demonstration phase	Start-up phase	Scale up phase	Mature business
Battery electric containers	#	3	14	77	637
Battery electric vessels	#	1	8	45	400

By linear interpolating the data in Table 17, the number of containers in circulation can be derived for any given number of battery electric vessels sailing in the Netherlands. The number of containers in circulation is thereby calculated by the following equation:

$$Number\ of\ battery\ electric\ containers = 1.5918 \times number\ of\ battery\ electric\ vessels + 0.7905$$

It should be noted that determining the number of batteries in circulation is only valid when the 2 MWh battery is used. Less batteries or more batteries in circulation are expected when using batteries with higher or lower capacities respectively.

For battery electric containers in circulation, the distribution of battery electric containers in ports, on vessels or at charging facilities is the same as those of hydrogen containers in ports, on ships or at filling facilities. The cost and performance parameters for battery electric containers is shown in Table 18.

Table 18: Cost and performance parameters for different battery electric containers

Info	Unit	1.5 MWh battery	2MWh battery	2.5MWh battery	3MWh battery	Sources and notes
Investment	€	817,000	955,500	1,107,000	1,252,000	Piña Rodriguez (2021)
O&M	% of investment/yr	1	1	1	1	Abma et al. (2019a)
Capacity	MWh/container	1.5	2.0	2.5	3.0	Piña Rodriguez (2021)
Capacity with a SOC of 10-90%	MWh/container	1.2	1.6	2.0	2.4	80% of the capacity
Lifetime	yr	20	20	20	20	TLS container (2020)
Lifetime	cycles	10,000	10,000	10,000	10,000	TLS container (2020)
Number of containers required per ship (rounded off)	#	8	6	5	4	Obtained by dividing the average electricity consumption for a trip in Table 4 with the capcity of a container with a SoC fo 10-90%
Footprint	m^2	14.88	14.88	14.88	14.88	1 container = 6.1 x 2.44m

As a default, the cost model uses the lifetime in years instead of the lifetime in cycles for battery electric containers. The annual CAPEX, OPEX and annual replacement expenditures for the different components required for battery electric bunkering are shown in Appendix V.

4.4 Input parameters methanol

The cost and performance for the bunker installations and several delivery methods are determined for the bunkering infrastructure of methanol. As mentioned in 3.5, shore-ship or ship-to-ship bunkering is expected by 2030. A bunker installation is necessary for shore-ship bunkering and ship-to-ship happens with a bunker ship. Expected is that bunker ships will be retrofitted for bunkering methanol in the early stages of methanol adaption (Interviewee 3, personal communication, January 31, 2022). The cost and performance parameters for a shore-ship bunker installation and for a retrofitted bunker ship are shown in Table 19. With the data from Table 19, the annual CAPEX, OPEX and annual replacement expenditures for both shore-ship bunker installations and bunker ships can be calculated. The annual CAPEX, OPEX and annual replacement expenditures for a shore-ship bunker installations and bunker ships are shown in Table 20.

Table 19: Cost and performance parameters for methanol bunker installations and bunker ships

Info	Unit	Shore-ship bunker installation	Bunker ship	Sources and notes
Capital investment	€	5,000,000	220,000	ESMA (2016), ship-to-ship retrofit capital invesmentcomfirmed by Interviewee 3 (personal communication, January 31, 2022)
O&M	%	1	1	Ellis and Tanneberger (2016) and Zomer et al. (2020)
O&M	€/yr	50,000	2,200	Ellis and Tanneberger (2016) and Zomer et al. (2020)
Lifetime	yr	15	20	Zomer et al. (2020)
Average bunkering capacity	ton/day	600	40	Zomer et al. (2020)
Average bunkering capacity	l/hr	19,775	14,610	Density of methanol is 0.791kg/l
Footprint	m^2	20,000	0	Ellis and Tanneberger (2016) and Zomer et al. (2020)
Footprint incl. safety contour	m^2	27,696	625	Heitink and Mentink (2022) and Zomer et al. (2020)
Berth places	#	1	0	Zomer et al. (2020)

Table 20: Annual CAPEX, OPEX and annual replacement expenditures for methanol bunkering

		Unit	Shore-ship bunker installation	Bunker ship
Capital investment		€/yr	336,079	14,787
OPEX	**Total O&M facility**	€/yr	50,000	2,200
	Berth	€/yr	383,513	0
	Rent	€/yr	193,872	0
Capital investment		€/yr	215,716	8,187

Several delivery methods for methanol to a bunker facility are incorporated into the cost model. These are delivery by truck, rail short sea ship or inland ship. The cost parameters for these delivery modes are described in Table 21.

Table 21: Cost parameters for the delivery modes of methanol (Zomer et al., 2020)

	Unit	Rotterdam
Inland ship	€/ton	9.45
Short sea ship	€/ton	5.95
Rail	€/ton	10.60
Truck large	€/ton	37.50

4.5 Scenario development

For the energy carriers in this study there are four bunkering scenarios considered to be feasible by 2030. Different business cases are made for each bunkering infrastructure scenario A comparison can be made because these have the same fleet mix and demand for a certain energy carrier. The four bunkering infrastructure scenarios are considered in this thesis:

- A bunkering infrastructure with swappable hydrogen containers.
- A bunkering infrastructure for hydrogen bunkering with direct dispensing.

- A bunkering infrastructure with swappable battery electric containers.
- A methanol bunkering infrastructure.

For each bunkering infrastructure scenario, different business cases can be considered. For example, a viable business case for all scenarios is the development of relatively small, decentralized facilities to obtain a large network for a relatively low cost. However, according to Interviewee 2 (personal communication, January 21, 2022), the development of a few centralized filling stations for e.g., hydrogen containers and charging stations are options that are much more likely to occur in the begin stage than relatively smaller decentralized filling stations. However, these options would require truck transport to ports. The cost and performance of large, decentralized facilities are tested as well.

In the cost model, the necessary infrastructure for a nationwide bunkering infrastructure is calculated by the demand for a specific number of ships sailing in 2030 per energy carrier. A maximum of 8000 full load hours for hydrogen bunkering, hydrogen filling and battery electric charging facilities is assumed for all scenarios. The maximum output for methanol installations and bunkering ships is determined by Zomer et al. (2020) (see Table 19).

To meet the ambitions set in the Green Deal on Maritime, Inland Shipping and Ports, at least 150 vessels with a zero-emission power train are required in 2030. Therefore, to test if this feasible, the demand of 150 inland navigation vessels is used to determine the required bunkering infrastructure for each business case in each specific scenario.

4.5.1 Bunkering infrastructure scenarios for hydrogen container bunkering

Multiple viable scenarios for containerized hydrogen bunkering infrastructure are constructed in the model. The different viable scenarios are shown in table 22.

Table 22: Different business cases for the bunkering infrastructure scenario with containerized hydrogen

Business case	1A	1B	1C	1D	1E	1F
Size filling facilities	Small	Large	Large	Small	Large	Large
Hydrogen pipeline delivery or hydrogen produced with on-site electrolysers	Pipeline delivery	Pipeline delivery	Pipeline delivery	On-site electrolysers	On-site electrolysers	On-site electrolysers
Truck delivery	No	No	Yes	No	No	Yes

All options use the 20 ft type IV 500 bar hydrogen containers. For the scenarios with large hydrogen filling facilities that do not incorporate truck delivery, it is assumed that large filling facilities are placed in ports where there is high demand. For the scenarios where truck delivery is incorporated, the assumption is made that the large hydrogen facilities are placed in centralized locations for hydrogen container delivery at multiple ports. It is assumed that theoretically a large, centralized hydrogen facility with truck delivery has the same effect as several small filling facilities with a total equal output, because in both cases delivery of a small number of containers can be facilitated at multiple locations.

4.5.2 Bunkering infrastructure cases for direct dispensing hydrogen bunkering

Multiple viable business cases for the direct dispensing hydrogen bunkering infrastructure scenaio are constructed with the model. The different viable business cases are shown in Table 23. It is assumed that all bunkering stations have a berth place that is accessible for inland navigation vessels.

Table 23: Different scenarios for direct dispensing hydrogen bunkering infrastructure

Business case	2A	2B	2C	2D
Size bunkering facilities	Small	Large	Small	Large
Hydrogen pipeline delivery or hydrogen produced with on-site electrolysers	Pipeline delivery	Pipeline delivery	On-site electrolysers	On-site electrolysers

The difference between the scenario with the bunkering infrastructure for swappable hydrogen containers and the scenario with a bunkering infrastructure for bunkering through direct dispensing, is that a static hydrogen storage has to be installed in advance on vessels to be able to use hydrogen bunkering with direct dispensing. To be able to make an equal comparison between the two hydrogen scenarios, the cost for hydrogen storage on board of an inland navigation vessel is included in the business cases for the bunkering infrastructure scenario with hydrogen bunkering through direct dispensing. The investment, replacement expenditures and O&M for a hydrogen container are used as a reference for the compensation for a vessel owner. A static hydrogen storage equal to four 20ft type IV hydrogen containers is required on board of an inland navigation vessel to compete with the bunkering infrastructure scenario with swappable hydrogen containers.

4.5.3 The bunkering infrastructure scenario with battery electric container

Multiple cases for a bunkering infrastructure scenario with battery electric containers can be constructed with the model. The different viable scenarios are shown in Table 24. All scenarios have 2 MWh battery electric containers and uses base charging facility with two charging spots of each 1000 KW.

Table 24: Different cases for bunkering infrastructure scenario with battery electric containers

Business case	3A	3B	3C	3D
Size charging facilities	Small (Cat. 1)	Medium (Cat. 2)	Large (Cat. 3)	Large (Cat. 3)
Truck delivery	No	No	No	Yes

If in theory a cat 3. (10 MVA) grid connection cannot be filled with five charging facilities with each a capacity of 2MW, the grid connection type is changed to fit the number of stations to the minimum grid connection output. As an example, it is given that 33 charging facilities must be placed for the infrastructure required for battery electric charging. 30 charging facilities would require three cat. 3 grid connections leaving 3 charging stations without a grid connection. In this case, 2 charging stations are connected to a 5 MVA charging station and 1 to a 2 MVA charging station. In the case of a cat. 2 connection, the maximum of two charging facilities with two 1000 kW charging spots can be connected to a cat. 2 (max. 5 MVA) grid connection.

For large, charging facilities with truck delivery it is assumed that these charging facilities are placed in a centralized location.

4.5.4 Bunkering infrastructure scenarios with methanol bunkering

Two distinct bunkering methods are considered for the methanol bunkering infrastructure by 2030:

- STS bunkering is implemented for methanol bunkering (business case 4A)
- Shore-ship bunkering is implemented for methanol bunkering (business case 4B)

Both business cases use as a delivery method of inland ships for methanol.

5 Results cost model

The cost model provides an output for the capital investment, footprint, utility and hardware requirements and the EAC of each bunkering infrastructure. Moreover, the cost model calculated factors such as the minimum cost of energy service (€/km) and the minimum cost per energy carrier (€/GJ of that specific energy carrier). For each scenario, the price for the specific energy carrier to break-even with the EAC is provided. The cost model results are shown in Section 5.1. A sensitivity analysis is provided in Section 5.2. The effect of the demand for the different energy carriers is discussed in Section 5.3. An evaluation is provided in Section 5.4.

5.1 Model output

5.1.1 Capital investment and EAC

The lowest capital investment and EAC of different bunkering infrastructures is shown in Table 25.

Table 25:The cases with the lowest capital investment for each bunkering infrastructure scenario

		Bunkering infrastructure scenario			
	Unit	**Hydrogen containers**	**Hydrogen direct dispensing**	**Battery electric containers**	**Methanol**
Best performing business case	#	1B	2B	3A	4A
Capital investment for 150 vessels	M€	479.86	295.92	245.62	2.20
EAC for 150 vessels	M€/yr	92.31	56.45	34.58	1.10

The business case with the overall lowest capital investment and EAC is the business case with STS bunkering for the methanol bunkering infrastructure scenario. It should be noted that this case is based on the retrofitting of existing bunkering vessels. If solely new build infrastructure is used, the methanol bunkering infrastructure with shore-ship bunkering is the best solution based on the lowest capital investment and EAC.

5.1.2 Footprint

Business cases with the smallest footprint of each infrastructure scenario are shown in Table 26

Table 26: The business cases with the lowest footprint for each bunkering infrastructure scenario

		Bunkering infrastructure scenario			
	Unit	**Hydrogen containers**	**Hydrogen direct dispensing**	**Battery electric containers**	**Methanol**
Business case with the smallest footprint	#	1B and 1C	2B	3A, 3B, 3C and 3D	4A
Footprint for 150 vessels	Ha	83.38	1.86	0.74	0.00

The business case with the smallest footprint with 150 vessel demand is the STS bunkering business case for the methanol bunkering infrastructure scenario. As bunkering of methanol happens from a boat, the footprint required for methanol bunkering is in theory 0 ha.

Each business case for the battery electric bunkering infrastructure has the same footprint. The intrinsic properties of a small, medium or large charging facilities are that all charging facilities are made of smaller modular charging stations. As a result, the number of charging stations is the same in each scenario. Therefore, the footprint is the same in each battery electric scenario.

The smallest footprint for a bunkering infrastructure with hydrogen containers has a significantly large footprint requirement compared to the other bunkering infrastructures. The largest contribution to this relatively large footprint is from the storage of hydrogen containers including the required safety contour. The storage footprint for solely hydrogen containers is 75.8 ha with a demand from 100 vessels, whereas the storage space required for hydrogen containers with a demand from 150 vessels is 98.4 ha.

5.1.3 The cost of energy service and energy carrier

The comparison and breakdown in the cost of energy service for the different business cases is shown in Figure 19.

The total cost of energy service and energy carrier are broken down into the following cost components:

- Energy carrier base cost: consist of the base cost for buying the specific energy carrier.
- Facility cost: consist of all the costs (CAPEX, OPEX and replacement expenditures) involved in a bunkering, filling or charging facility. This includes the rent, grid connection costs and the electricity consumption. However, the costs involved with a PSA or electrolyser for both hydrogen scenarios are excluded in this component.
- PSA: includes the CAPEX, OPEX, replacement expenditures and the costs for the electricity.
- Electrolyser: includes the CAPEX, OPEX and replacement expenditures of the electrolyser, the costs for the electricity and water consumption. Moreover, this cost component includes the cost for the rent paid.
- Truck delivery or ship delivery: the delivery includes all the costs involved in the truck delivery of hydrogen containers or battery electric containers such as the CAPEX, OPEX and replacement expenditures of the trucks and trailers. Additionally, the cost for transport is included.
- Storage container: includes the CAPEX, OPEX and replacement expenditures of hydrogen or battery electric containers. Moreover, the handling, storage and rent of the storage place for these containers.
- Berth: consist of cost of berth.

A significantly large cost component is the cost for storage containers. It is noteworthy that the cost for the storage container in the business cases of the bunkering infrastructure scenario with hydrogen through direct dispensing (2A to 2D) represents the compensational cost for vessel owners as described in 4.5.2. By comparing the cost for storage containers, only half of the cost is required compensational costs of permanent hydrogen storage on board of vessels in the business cases for the bunkering infrastructure scenario with direct dispensing hydrogen compared to the business cases with swappable hydrogen containers. A storage of hydrogen containers is required in the business cases with a bunkering infrastructure for direct dispensing of hydrogen, whereas 1,087 swappable containers are in circulation for the bunkering infrastructure with hydrogen containers. Moreover, handling, storage and rent costs are also required in the business cases with swappable hydrogen containers.

For the hydrogen bunkering scenarios, hydrogen delivery by pipeline and the instalment of PSA's has a smaller impact on the cost of energy service than by on-site production of hydrogen with electrolysers. Additionally, the cost of a large bunkering or filling facility has a low total cost compared to multiple smaller facilities with the same output. Therefore, the business cases with lowest cost of energy service for the hydrogen scenarios are for both scenarios the cases with large, decentralized filling or bunkering facilities that are supplied by a pipeline (1B and 2B).

A business case with large, centralized filling facilities for hydrogen containers and truck delivery would be more beneficial instead of small filling facilities near bunker locations. Implementation of this transport will add €0.69/km to the total cost of energy service of the bunkering infrastructure that incorporates hydrogen containers. For centralized charging of battery electric containers, this is not the case. €3.50/km to the total cost of energy service to the bunkering infrastructure with battery electric containers.

STS bunkering of methanol would add the lowest cost towards the total cost of energy service of both business cases for the scenario with a bunkering infrastructure for methanol. However, as the cost for the base of methanol is significant, the business case with STS bunkering of methanol is not the best performing business case overall in terms of cost of energy service. Electricity has the lowest cost of energy service of all the energy carriers followed by the base cost of hydrogen.

The business case with the overall lowest cost for energy service is the battery electric bunkering scenario with small, decentralized charging facilities for battery electric containers (3A). The cost for energy service for this business case is €8.27/km.

All the business cases for the infrastructure scenario with the battery electric containers are superior to the hydrogen scenarios. As described in 4.2, no optimalisation studies have been carried out towards the ideal ratio of vessels to the number of hydrogen containers in circulation. However, even if the optimal ratio of vessels with the number of hydrogen containers in circulation would have been found, the hydrogen business cases would not compete to the business cases of the battery electric container scenario. The cost of energy service regarding the filling or bunkering facilities and cost for the purchase of energy carrier alone would be approximately equal to the total cost of energy service for the business cases with the bunkering infrastructure for battery electric containers.

The cost of energy for diesel is equal to 9.06, with the current bunkering cost of diesel is €1.30/l (at June 10, 2022) and a fuel economy of 6.95 l/km (Bunker Index, 2022). Therefore, implementing a bunkering infrastructure scenario with small, decentralized charging facilities for battery electric containers (3A) would achieve a lower cost of energy for vessel owners.

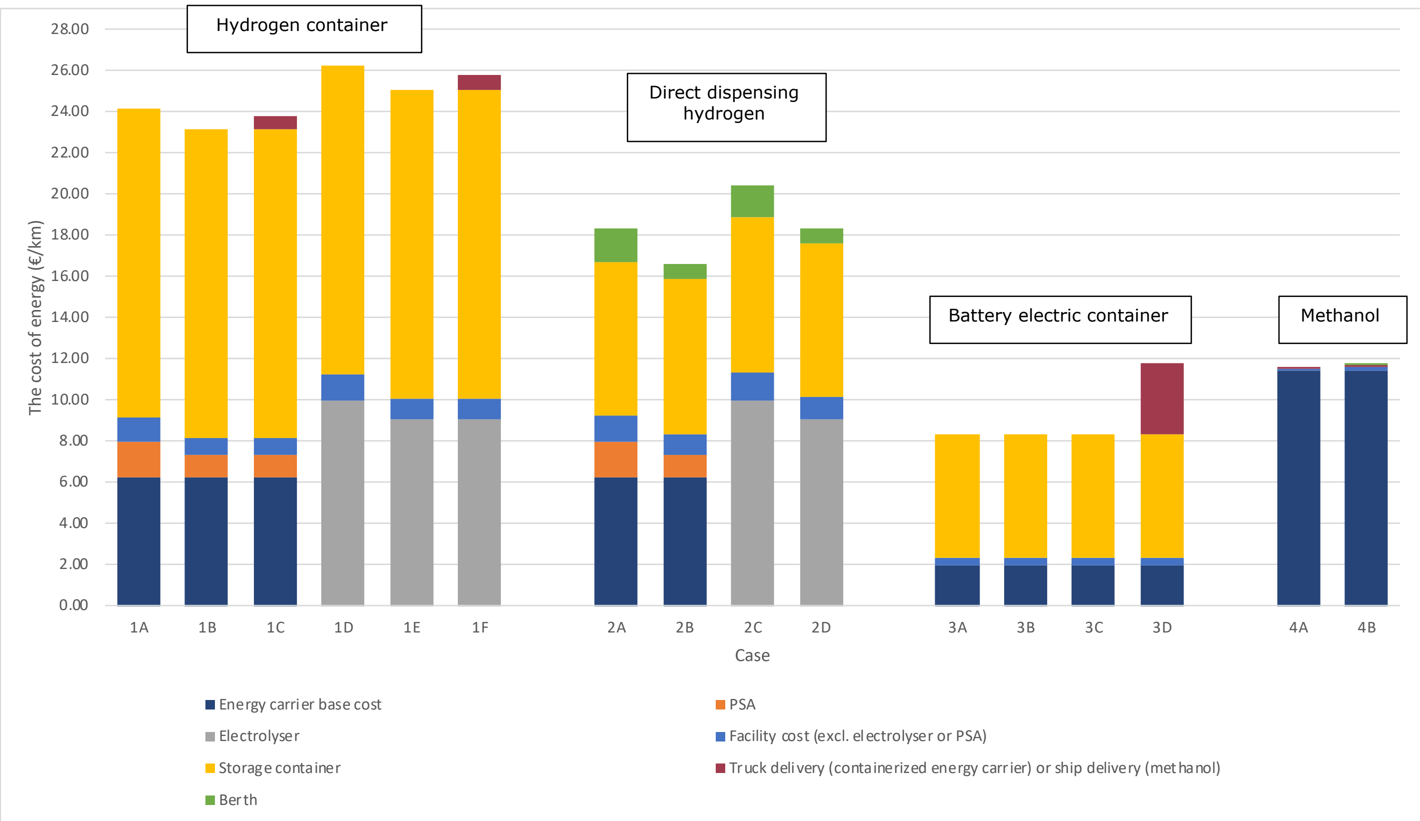

Figure 19: The comparison and breakdown of cost of energy service (€/km) for different cases with the energy demand of 150 vessels. The corresponding bunkering scenario is shown on top of the corresponding business cases

A comparison and breakdown of the cost per energy carrier for all the business cases is shown in Figure 20. The same breakdown of components applies as for Figure 19. A relatively high cost per energy carrier can be observed for the business cases for the different cases for the bunkering infrastructure scenario with battery electric containers. This is a result of a higher efficiency of battery electric vessels (8.46 km/GJ) compared to the hydrogen (3.38 km/GJ) and methanol propelled vessels (3.06 km/GJ).

The breakdown of the total capital investment, utility and hardware requirements of the different business cases is shown in Appendix VI.

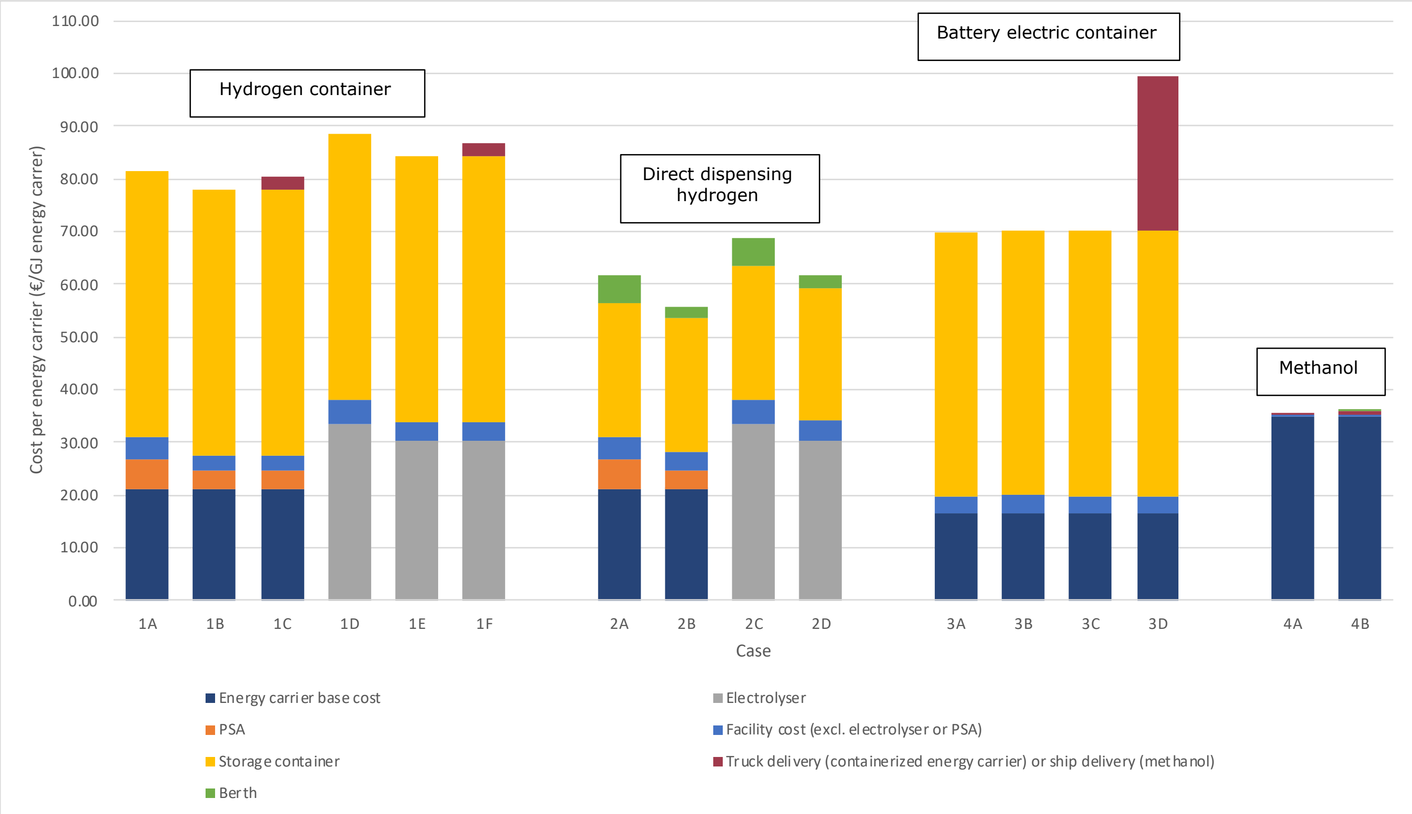

Figure 20: The breakdown and comparison of the cost per energy carrier (€/GJ) for different cases with an energy demand of 150 vessels. The corresponding bunkering scenario is shown on top of the corresponding business cases

5.2 Sensitivity analysis

For the best valued business cases of each bunkering scenario a sensitivity analysis has been conducted to analyse the uncertainties related to several key parameters for the different bunkering infrastructures. The sensitivity analysis shows how the uncertainty of the model's output can be allocated to the key parameters. An 80%-120% distribution has been chosen as the minimum and maximum ranges for all key parameters are respectively of the input value provided in the cost model.

Figure 21 shows the sensitivity analyses for business case 1B for the bunkering infrastructure scenario with hydrogen containers. The parameter that contributes most to the uncertainty of the model is the hydrogen container investment. A large number of hydrogen containers is required. Therefore, a small change in the cost and number of hydrogen containers has a large effect on the cost of energy service.

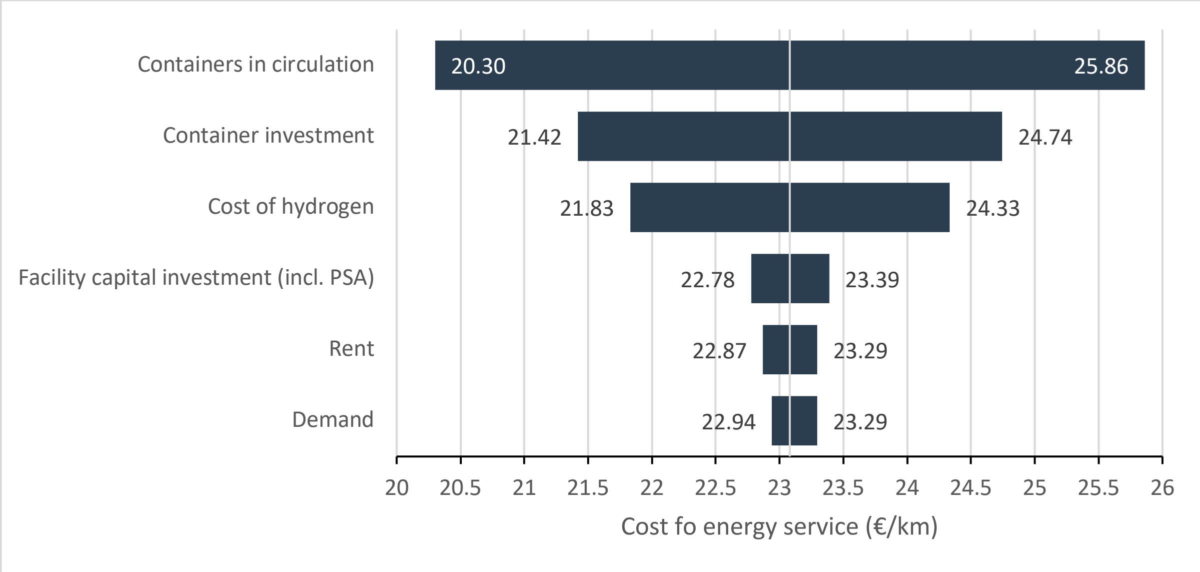

Figure 21: Sensitivity analysis of the bunkering infrastructure for hydrogen container bunkering (base cost of energy service: 23.08 €/km)

In Figure 22 the sensitivity analysis for the bunkering infrastructure for hydrogen bunkering via direct dispensing is shown. The cost of hydrogen in this business case provides the largest uncertainty to the outcome of the model. A remarkable feature is that a change in the demand of hydrogen has no effect on the cost of energy service. An increase or decrease of demand by 20% would lead to exactly an extra or one less facility placed with exactly the same used capacity. Therefore, the cost of energy service will stay the same.

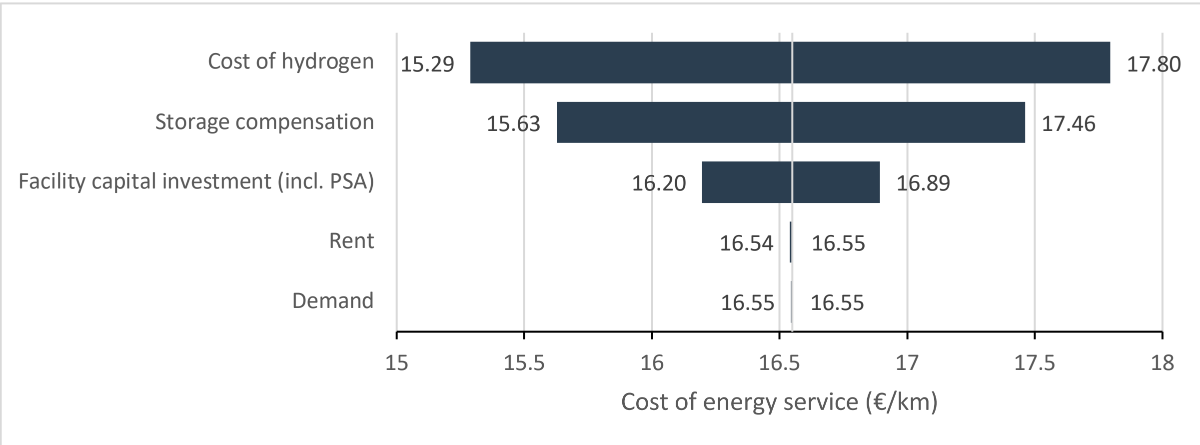

Figure 22: Sensitivity analysis of the bunkering infrastructure for hydrogen via direct dispensing (base cost of energy service: 16.55 €/km)

Figure 23 shows the sensitivity analysis for the bunkering scenario with battery electric containers. The investment into the battery electric containers is considered to generate the largest uncertainty in this scenario. A relatively large quantity of containers is required compared to other hardware such as charging facilities. Moreover, the investment into battery electric containers is significant, compared to the investment into other hardware required for the bunkering infrastructure of battery electric containers. A small reduction in the investment for a battery electric container would have a large effect on cost of energy service.

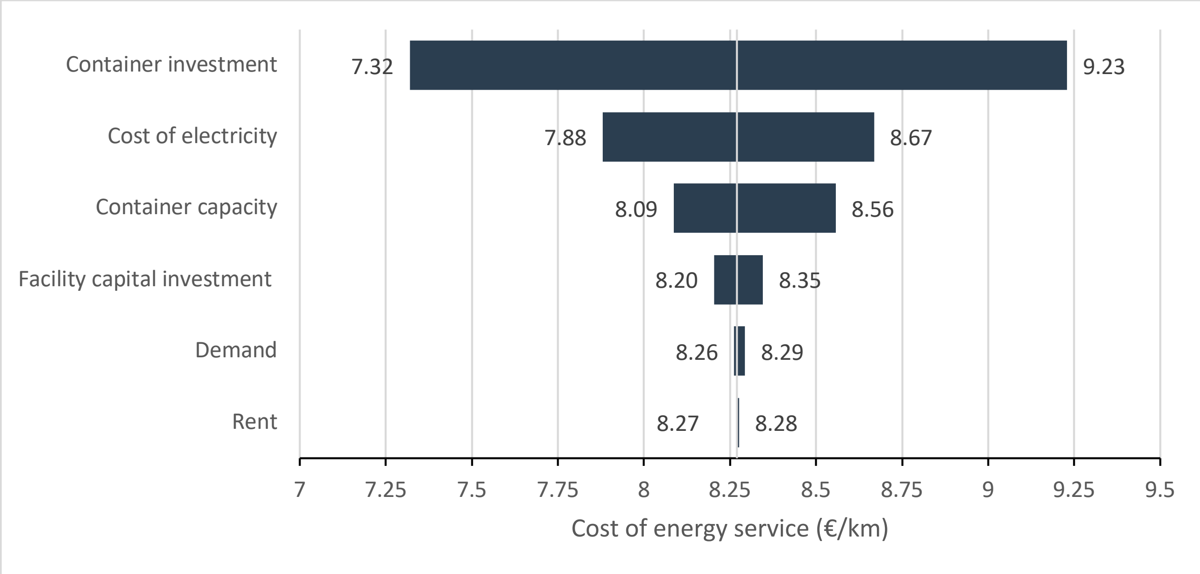

Figure 23: Sensitivity analysis of the bunkering infrastructure for battery electric containers (base cost of energy service: 8.27 €/km)

Figure 24 shows the sensitivity analysis of bunkering infrastructure for methanol in scenario 4. A lot of the uncertainty in the model can be allocated to the cost of methanol to a bunkering station or bunkering ship. However, even a 20% lowering in methanol base costs would not lead to a cost of energy service that can compete with the different business cases for a bunkering infrastructure scenario with swappable electric battery containers.

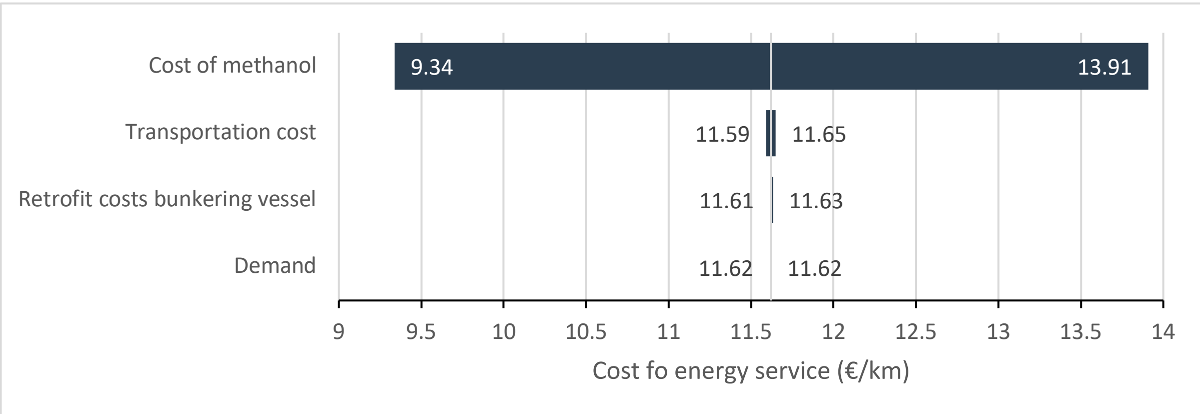

Figure 24: Sensitivity analysis of bunkering infrastructure for methanol (base cost of energy service: 11.62 €/km)

5.3 The impact on the total energy infrastructure

Several studies have been conducted towards the expected demand of different energy carriers by 2030. A relatively recent study by Gasunie, (2019) predicts that the demand for hydrogen in 2030 for a low, medium and high adoption scenario is respectively 200, 280 and 425 PJ/yr. This demand is equal to 1666 kton H_2/yr for a low adoption scenario, 2333 kton H_2/yr for a medium adoption scenario and 3541 kton H_2/yr for a high adoption scenario (with a LHV of 120 MJ/kg for hydrogen). The total demand for hydrogen for 150 vessels is 11,441 ton H_2/yr. The percentage of hydrogen demand for the inland navigation sector for the several adaption scenarios is shown in table 27. Only a small share of the total demand for hydrogen is expected to be used by the inland navigation sector. Depending on the scenario, only 0.69% to 0.32% is consumed by the inland navigation sector. However, an increase of hydrogen transportation by road (for e.g., business case 1C or 1F), would lead to increased safety risks as mentioned in section 3.1.3.1.

Table 27: Percentage of hydrogen demand compared to the total demand expected by 2030 for different adoption scenarios

	Low adoption scenario	Medium adoption scenario	High adoption scenario
The demand of 150 vessels sailing on hydrogen	0.69%	0.49%	0.32%

The demand for electricity in the Netherlands is expected to exceed 500 PJ/yr by 2030 (Afman et alk., 2017). This is approximately 1.389 x 10^8 MWh/yr. The demand of electricity in the scenario with the bunkering infrastructure for battery electric containers for 150 vessels is 180,175 MWh/yr. Even with the implementation of highly energy-consuming electrolysers for hydrogen production in scenario 3, only a fraction (0.13%) of the national demand would be allocated to the bunkering infrastructure for battery electric containers. However, as mentioned in section 3.2.3.2, grid congestion can become a major problem for the facilitation of electricity. Even relatively small projects could not be realised due to the lack of capacity on the electric grid.

Methanol is already used by the maritime sector. The demand for methanol in the Dutch maritime sector is expected to grow by 20%; the methanol demand as a maritime fuel is expected to grow from 110 PJ in 2017 to 132 PJ in 2030 (Zomer et al., 2020). With a LHV of 19.9 MJ/kg and a density of 0.791 kg/l for methanol, the expected demand in 2030 is equivalent to 8,386 million l/yr (Harmsen, 2021; Keera, El Sabagh, & Taman; 2011). The demand of methanol for 150 vessels is 113.7 million l/yr. Only a marginal share of 2.71% of the total demand for methanol in the maritime sector by 2030 would be from the inland navigation sector. This would not have a significant effect on the current production and distribution infrastructure of methanol. Even an increase of 20% for the maritime sector would not have a significant effect on the infrastructure. The increasing demand for methanol can initially be met with existing production plants, as the capacity is not fully utilized (Zomer et al., 2020).

5.4 Evaluation and interpretation

A methanol bunkering infrastructure scenario with STS bunkering (business case 4A) would be the most interesting from a capital budgeting decision point of view. The application of such infrastructure would have the lowest initial investment of all business cases. Additionally, this business case would have the lowest EAC, making the implementation of methanol bunkering infrastructure with STS bunkering the best cost-effective business case over the total project lifetime. In theory, a bunkering infrastructure scenario with STS bunkering has no footprint as all bunkering activities and components are on water.

The best performing business case in case of the lowest energy service would be a bunkering infrastructure with battery electric containers with small charging stations near ports (busines case 3A). This business case has an overall higher EAC, and a higher initial investment would be required compared to the business case with a bunkering infrastructure for methanol via STS bunkering but would be more beneficial for vessel owners in terms of the cost of energy.

To meet the 150 inland navigation vessels with zero-emission drivetrains as set by the Green Deal on Maritime and Inland Shipping and Ports, a bunkering infrastructure for methanol is excluded. Methanol is not a zero-emissive energy carrier on its own but is rather a carbon neutral energy carrier. For the 150 inland navigation vessels with zero-emission drivetrains, the implementation of a bunkering infrastructure for battery electric containers with small charging stations near ports would be of best solution. It has the lowest initial investment, EAC, and the lowest cost of energy service of all the business cases for with either a bunkering infrastructure for hydrogen or bunkering infrastructure for battery electric containers. Additionally, this business case has the best footprint of all the infrastructures that can supply an energy carrier for zero emission drive trains. The compact space required for the charging station and small footprint for container storage result in a relatively low footprint compared to the hydrogen bunkering business cases.

The roll-out of a bunkering infrastructure for hydrogen containers or via direct dispensing is not favourable according to the model. For both best performing hydrogen bunkering business cases, the cost of the total energy service is double to triple the amount compared to the cost of energy service for bunkering infrastructure scenario for battery electric containers.

In all the best performing business cases of each bunkering infrastructure scenario, one of the key parameters that causes the largest uncertainty in the model is the base cost of the energy carriers. Moreover, the cost of hydrogen or battery electric storage containers is also considered to be a key parameter that has a large effect on the uncertainty of the model.

When considering the output of the model, the overall best performing and future-proof business case is the implementation of a bunkering infrastructure with small charging stations near ports for swappable battery electric containers (business case 3A). The implementation of this business case would lead to a lower cost of energy (€8.27/km) compared to the current cost of energy for diesel (€9.06/km).

6 Discussion

The following section discusses the limitations and theoretical implications of this study. Moreover, recommendations are suggested for future research and steps to be taken.

6.1 Limitations

6.1.1 Input limitations

In this study there are certain simplifications and assumptions made for the input parameters, which affect the validity and the feasibility of the implementation of the bunkering infrastructure scenarios for the different energy carriers in the Netherlands.

An estimated and calculated average is provided for the different fuel economies and average sailing distance for inland navigation vessels that make use of the different energy carriers. However, the real fuel economy depends on multiple factors such as sailing upstream or downstream, weight, wind and the type of vessel. Moreover, the engine performance of a hydrogen and methanol inland navigation vessel is currently still unknown. The average distance travelled is based on CEMT 2, 4 and 5 vessels. However, there are more classes, such as CEMT 1, 3 and 6. Unfortunately, no data on the average sailing distance is known for these classes.

There are uncertainties in the number of battery electric containers and hydrogen container in circulation. For hydrogen containers, it is assumed that half of the ports are downstream ports and half of the ports are upstream ports. It is thereby assumed that a vessel upstream will always sail downstream and vice versa. However, if the port is a stopover, this will not be the case. Although the pilot studies provide a solid basis for the number of containers required, in reality the number of hydrogen containers may not match the needs of the vessels in an arbitrary port. In the model it is assumed that battery electric containers are equally distributed over ports, charging stations and vessels in the same way as for hydrogen containers. However, this may not be the case in real life as the speed of charging a battery electric container differs from the speed of filling a hydrogen container. Therefore, battery electric containers might circulate quicker and therefore would result in a different distribution over the ports, ships and storage.

It is assumed that the price for utility and energy carriers is always the same in the cost model. However, these are linked to dynamic commodity markets. The price and supply development over time is also uncertain and can deviate quickly from the price projections in a short period of time, as shown by the COVID-19 pandemic and the ongoing (geo)political conflict situated in Eastern Europe.

The interviews provided valuable input into different aspects involved in bunkering of hydrogen, electricity and methanol. A potential downside of the interviews conducted is that social desirability response bias might have occurred. Interviewees may have provided more socially acceptable answers in favour of their own interests rather than being truthful.

6.1.2 Model computation limitations

There are several limitations related to the model computation. The model is programmed to minimize the number of installations such as charging and bunkering facilities. In addition, the model incorporates reasonable full load hours for facilities. However, in a real-life scenario, more installations might be required to accommodate continuous sailing as the demand and supply are not equal for a certain energy carrier in an arbitrary location. An example is that a methanol bunker ship can only bunker one vessel at the time. If an inland navigation vessel arrives at a bunker ship where a vessel is already bunkering, seamless and continues sailing is not guaranteed. Moreover, the model solely incorporates an average bunkering, hydrogen filling or charging speed that is linked to the full load hours or average capacity of bunkering.

There are some conditions set regarding the supply and demand of energy carriers. It is assumed that the supply of utility or arbitrary energy carrier is always available. However, this availability cannot be guaranteed as the supply and availability of hydrogen, methanol or electricity depend on the development sustainable energy carriers. The development and implementation of green hydrogen production, e-methanol/biomethanol, and large scale sustainable and renewable electricity is uncertain. The large-scale deployment of these energy carriers depends on a stable policy framework over a large period of time. Furthermore, the demand is solely based on the needs of a specific number of vessels and not on where these vessels will sail in the Netherlands. A higher demand in certain locations might prefer one business case over another. Different locations or ports may not be suitable to implement a bunkering infrastructure for e.g., electric containers because of lack of storage space and capacity on the electric grid for charging.

6.1.3 Model output limitations

With the help of a supply chain analysis and expert input, a well-considered decision has been provided on the different bunkering techniques possible and used in 2030. However, the model is limited to certain distribution methods and types of bunkering and filling installations, whereas there is an uncertainty if these techniques will even develop. Although the interviews and literature have provided valuable input into what the bunkering techniques and capabilities may look like for the several energy carriers for 2030, it cannot be concluded that certain bunkering technologies and energy carriers will evolve in that particular way. Development of an energy carrier or bunkering technology may stagger due to external factors such as interference of political preference or lack of investment. Moreover, there are more energy carriers that can be considered as (transition) fuels for future inland navigation, such as NH_3 or LNG, that might compete with the energy carriers assessed in this study.

From an investing point of view, the scenario with the lowest capital investment or EAC (methanol bunkering infrastructure with STS bunkering) is interesting in case of a capital budgeting decision. This scenario would have the lowest investment upfront and overall cost over the project lifetime but achieves the same results as other scenarios. Note that this is presented in absolute terms, as it can supply the same number of vessels to be able to sail as any other scenario. However, other scenarios might be more interesting as these have other non-financial beneficial features such as more bunker locations and better overall supply of that specific energy carrier.

A holistic approach has been chosen to test the effect on the underlying infrastructure. The effect of the implementation of an arbitrary bunkering infrastructure to supply 150 vessels has little effect on the national demand of a given energy carrier. However, the effect on the underlying infrastructure is much more regionally depended. A single charging, bunkering or filling facility could have a large effect regionally as it requires a relatively large supply of a given energy carrier, whereas that would only be a small change on the total supply on a nationwide scale.

The model output is solely based on the requirements for an arbitrary bunkering infrastructure. However, vessels must be suitable to use a specific energy carrier as fuel. The investment by vessel owners for retrofitting a vessel, investing in an electric motor and/or fuel cell is not considered in this thesis. The cost for the use of hydrogen would be higher compared to battery electric as this requires an investment into fuel cells as well.

6.2 Theoretical implications

The study contributes to the research of the implementation of bunkering infrastructure of new energy carriers for the inland navigation sector in the Netherlands. This study provides an in-depth analysis in the possibilities of bunkering infrastructure required for hydrogen, electricity and methanol for the inland navigation. Compared to previous research on new energy carriers involving implementation of bunkering infrastructure (e.g. Perčić et al., 2021), this research shows the technical and cost parameters involved in different supply chains for hydrogen, electricity and methanol bunkering for the inland navigation sector. This results in improved understanding of how a bunkering infrastructure for inland navigation can be rolled out. A substantiated estimation on what is required for a certain infrastructure in terms of investment, cost of energy, hardware and utility is provided. Insights from experts and stakeholders provide accurate and specific values that are only valid for the Netherlands, whereas this information cannot be found in previous studies.

The study's model provides a tool for Rijkswaterstaat to play with different scenarios. If new projections are available, a quick calculation of the costs involved can be conducted. However, it is advised to update the values when new performance data of the input data is released. In addition, future research could be conducted on whether the model developed by this study would also be applicable in other countries. In doing so, a comparative analysis of the situation in the Netherlands and elsewhere could be executed. This might lead to generalization of the study's model.

Furthermore, the study provides the overall best performing business case for a bunkering infrastructure; a bunkering infrastructure with the bunkering of battery electric containers and small charging stations would be the best solution to reach the goals set by the Green Deal on Maritime and Inland Shipping and Ports. Based on this outcome, further research can be conducted towards locations, congestion and the implementation of smart grids. Furthermore, optimization studies towards optimizing the number of battery electric containers in circulation can be carried out. Exploring the optimized ratio for battery electric batteries in circulation could benefit the business case, as these containers contribute to most of the investment required for this particular bunkering infrastructure. Geolocation studies, towards which locations are suitable in terms of where vessels will bunker the most and if enough supply can be delivered, can be conducted. This can provide further insights in where net congestion might occur or where charging facilities may be built.

6.3 Managerial and policy implications

6.3.1 Decision making of the implementation of bunkering infrastructure for battery electric containers

Based on the model outcome, the overall best option is to build a bunkering infrastructure for battery electric containers with small charging facilities. Whether the implementation of such bunkering infrastructure is feasible depends on discissions taken, the willingness to invest and willingness to adapt by the involved stakeholders. Deciding if the implementation of such a bunkering infrastructure is feasible depends on the vessel owners, investors or bunkering operators, suppliers of the energy carrier i.e., grid operators and the government i.e., Rijkswaterstaat.

There has to be a willingness to invest into retrofitting vessels or building new vessels that can sail on alternative energy carrier by vessel owners. An investment into an electric motor is inevitable. Furthermore, vessel owners have to agree with the cost of energy for that specific energy carrier i.e., battery electric containers.

Whether a bunkering infrastructure is, on cost basis, feasible depends on how much an investor or operator is willing to invest. Extra financial aid from e.g., subsidies or higher CO_2 prices for conventional fuels could benefit the investment into a bunkering infrastructure for battery electric containers.

For grid operators it is important that they are assured of the purchase of electricity. Contracting can guarantee purchase of hydrogen can aid towards the feasibility of the implementation of a bunkering infrastructure for hydrogen. This is likewise the case for the delivery of electricity.

Rijkswaterstaat should act as a launching customer and stakeholder manager. They can develop a pilot project or a successful attempt into developing a part of the bunkering infrastructure for battery electric containers. This would be beneficial for investors as the first risks are explored and, in case of costs, are on the account of Rijkswaterstaat. Moreover, Rijkswaterstaat can demonstrate what benefits the use of alternative energy carriers provides. Investors are likely to be more interested in a project if these risks and benefits are known. Therefore, it is advised to go into discussion with all stakeholders about how much vessels owners and investors/ bunkering operators and grid operators are willing to invest to switch towards the use of bunkering infrastructure for battery electric containers. If it turns out that the costs for implementation are too high for vessel owners, investors/bunkering operators, or grid operators, a future study on the financial measurements can be conducted on how to promote and lower the costs for vessel owners to switch towards the use of battery electric containers as fuel. Additionally, Rijkswaterstaat can advise on permitting and initiating a subsidy scheme to aid the development of a bunkering infrastructure for battery electric containers.

6.3.2 Alternative option for a bunkering infrastructure

If the implementation of a bunkering infrastructure for battery electric containers is not feasible in the short term, the development of a bunkering infrastructure with STS bunkering of methanol seems to be a decent second choice with financial and non-financial benefits over the bunkering infrastructure of battery electric containers. The investment costs for a bunkering infrastructure for methanol bunkering are relatively low compared to the bunkering infrastructures of the other energy carriers. Furthermore, methanol is already used by the maritime and inland navigation sector. Hence, adaption would be easier compared to the other two energy carriers. Although methanol is not an emission-free energy carrier, it is thereby advised to use it as a quickly adaptable transitional energy carrier. Especially when financial aid is low.

7 Conclusion

The inland navigation sector in the Netherlands must become more sustainable through agreements contained in the Climate Agreement. In addition to making inland vessels more sustainable, an entire bunkering infrastructure is required. However, there is a lack in studies regarding the feasibility of the implementation of such bunkering infrastructure in the Netherlands. Therefore, this study had the objective to find out if a nationwide bunkering infrastructure for hydrogen, methanol and electricity for inland navigation in the Netherlands by 2030 is feasible. The research question was formulated as followed:

What is the technological and economic feasibility of a nationwide bunkering infrastructure for hydrogen, electricity and methanol for inland navigation in the Netherlands by 2030?

To provide an answer to the research question, an extensive techno-economic analysis has been conducted towards the methods and spatial requirements, technical components, the impact on the current energy infrastructure and cost components. A supply chain analysis has been conducted, to test the different technical components, methods and spatial requirements. The supply chain analysis conducted discussed the possible delivery and bunkering methods available by 2030 in the inland navigation sector. The delivery and bunkering methods of the reviewed energy carriers and technical components involved have been qualitatively described by bunkering and delivery speed, TRL, footprint and processable volume quantities i.e., capacity. Together with insights gained by expert interviews, the logical and possible bunkering and delivery methods by 2030 have been determined. These insights have been incorporated into a cost model. Expected is that bunkering of hydrogen is technologically feasible with swappable containers that contain CGH_2 and by direct dispensing (via a high-pressure hose). Bunkering of electricity is expected to be feasible with swappable battery electric containers with charging stations near ports. Methanol bunkering is probably technologically feasible by 2030 with bunkering ships or large bunkering installations on shore.

The cost model input parameters combine the technical components of delivery and bunkering of the different energy carriers with the cost parameters to develop an output in terms of cost, utility and hardware requirements and total footprint for different scenarios. Different business cases have been developed to test if a bunkering infrastructure for different energy carriers is feasible to supply 150 inland navigation vessels. The output of the model suggests that the implementation of a bunkering infrastructure for battery electric containers with small charging stations is the most feasible on cost basis. An even better business case can be obtained by implementing such infrastructure compared to the bunkering infrastructure of diesel. The second-best option would be the implementation of a bunkering infrastructure for methanol with STS bunkering. However, the latter cannot be used to meet the 150 inland navigation vessels with zero-emission drivetrains as set by the Green Deal on Maritime and Inland Shipping and Port as methanol is an energy carrier that generates emissions. Therefore, the development of a bunkering infrastructure for methanol should be used as a transitional model.

The feasibility of the implementation of a bunkering infrastructure is not only based on technological and economic parameters described in the study. There must be a consensus among stakeholders such as ship owners, investors/bunkering operators and suppliers/grid operators to invest into external factors such as retrofitting inland navigation vessels or facilitating and supplying electricity. Besides that, external factors such as competition of other energy carriers or the total capacity on the underlying infrastructure i.e., electric grid must be considered as well.

8 Acknowledgement

I would like to thank Prof. Dr. Gert Jan Kramer for the supervision of this project. I am grateful for the valuable feedback that directed me into the right ways.

This project would not have been possible without Evelien Korbee and Sacha Scheffer. I am grateful for the opportunity they provided me to do an internship at Rijkswaterstaat. Without their supervision and didactic feedback this would not have come to the product that it is. Furthermore, I like to thank my colleagues at Rijkswaterstaat who provided me valuable feedback and contacts during meetings. Especially, I would like to thank the interviewees who provided me with valuable information.

I would like to thank my friends and family for always showing interest into my work. Last but definitely not least, I would like to thank Nicole for always showing interest and supporting me throughout the years.

The past 7 months have been challenging as working from home and online meetings became the norm. I would like to express my thanks to all the people showing interest and guiding me through difficult times like these.

9. References

Abma, D., Atli-Veltin, B., & Verbeek, R. (2019a). *Feasibility study for a zero emission, battery-electric powertrain for the Gouwenaar II.* Den Haag: TNO.

Abma, D., Atli-Veltin, B., Verbeek, R., & van der Groep, R. (2019b). *Feasibility study for a zero emission, hydrogen fuel cell powertrain for the Gouwenaar II*. Den Haag: TNO.

Adam, P., Engelshove, S., Heunemann, F., Thiemann, T., & Bussche, C. V. D. (2020). Hydrogen infrastructure-the pillar of energy transition: The practical conversion of long-distance gas networks to hydrogen operation. *Siemens Energy, Gascade Gastransport GmbH, Nowega GmbH.*

Adolf, J., Balzer, C. H., Louis, J., Schabla, U., Fischedick, M., Arnold, K., ... & Schüwer, D. (2017). Energy of the future?: Sustainable mobility through fuel cells and H2; Shell hydrogen study.

Afman, M. R., Hers, S., & Scholten, T. (2017). *Energy and electricity price scenarios 2020-2023-2030: Input to Power to Ammonia value chains and business cases*. CE Delft.

Andersson, K., Marquez Salazar, C. (2015). *Methanol as a marine fuel report*. FCBI energy/Methanol Institute. Retrieved from https://www.methanol.org/wp-content/uploads/2018/03/FCBI-Methanol-Marine-Fuel-Report-Final-English.pdf

Aroundoffice. (n.d.) Containerstapler. Retrieved from https://www.aroundoffice.de/gabelstapler/containerstapler/

Blok, K., & Nieuwlaar, E. (2016). *Introduction to energy analysis*. Routledge.

Blue Roadmap. (n.d.). The Blue Road Map. Retrieved from https://blueroadmap.nl/#/

Boon Trucks & Trailer. (2022). Schmitz Cargobull SGF*S3. Retrieved from https://www.boontrucks.nl/nl/aanbod/30100040-schmitz-cargobull-sgf-s3

Brey, J. J., Carazo, A. F., & Brey, R. (2018). Exploring the marketability of fuel cell electric vehicles in terms of infrastructure and hydrogen costs in Spain. *Renewable and Sustainable Energy Reviews, 82, 2893-2899.*

Brückner, N., Obesser, K., Bösmann, A., Teichmann, D., Arlt, W., Dungs, J., & Wasserscheid, P. (2014). Evaluation of Industrially applied heat-transfer fluids as liquid organic hydrogen carrier systems. *ChemSusChem*, *7*(1), 229-235.

Bunker Index. (2022, June 10). Rotterdam - Port Bunker Prices - BUNKER INDEX. Retrieved from https://www.bunkerindex.com/prices/portfreels_xmdo.php?port_id=637

Burg, L. van der. (2020). *Hydrogen webinar 2: Next generation electrolysers* [Video]. TNO. Retrieved from https://youtu.be/5zxpykde2O8

Burgers, I. (2020). Novel Technology for Hydrogen Separation from Natural Gas using Pressure Swing Adsorption (Doctoral dissertation, University of Melbourne).

CBS. (2021). Hoeveel goederen worden er in Nederland vervoerd*? Centraal Bureau voor de Statistiek*. Recieved from https://www.cbs.nl/nl-nl/visualisaties/verkeer-en-vervoer/goederen/transportsector/goederen

Chang, C. K. (2019). Factors affecting capacity design of lithium-ion stationary batteries. *Batteries, 5*(3), 58.

Chrysochoidis-Antsos, N., Liu, C., & Van Wijk, A. (2018, September). On-site wind powered hydrogen refuelling stations-From national level to a case study in Germany. In 2018 International Conference on Smart Energy Systems and Technologies (SEST) (pp. 1-6). IEEE.

Connekt (2021). Richtlijn 6 – Binnenvaart bulk Droog en vloeibaar. *Connekt/Topsector logistiek.* Retrieved from https://carbonfootprinting.org/richtlijnen/

Cummins. (2020). ELECTROLYZERS 101: WHAT THEY ARE, HOW THEY WORK AND WHERE THEY FIT IN A GREEN ECONOMY. *Cummins Inc., Global Power Leader.* Retrieved from https://www.cummins.com/news/2020/11/16/electrolyzers-101-what-they-are-how-they-work-and-where-they-fit-green-economy

Demir, M. E., & Dincer, I. (2018). Cost assessment and evaluation of various hydrogen delivery scenarios. International Journal of Hydrogen Energy, 43(22), 10420-10430.

Dijkhuizen, B. (2014). *Van Uden wil distributiecentrum bouwen bij Alpherium*. Logistiek.nl

DNV (2021). *SuAc A3 & B3: Guidance for safety distances for bunkering hydrogen in the Netherlands & Germany. Det Norske Veritas* /RH_2INE

DNV, G. (2015). The fuel Trilemma: Next generation of marine fuels. *Strategic Research and Innovation position paper*, 03-2015.

DOE. (2015). Fuel Cell technologies office multi-year research, development and demonstration plan Department of Energy. Retrieved from https://www.energy.gov/sites/prod/files/2015/08/f25/fcto_myrdd_delivery.pdf

ECER. (2021). Fit-for-55-pakket van Europese Commissie moet leiden tot bereiken van klimaatdoelen door de EU. *Expertisecentrum Europees Recht*. Retrieved from https://ecer.minbuza.nl/-/fit-for-55-pakket-van-europese-commissie-moet-leiden-tot-bereiken-van-klimaatdoelen-door-de-eu

EICB (2020). *Waterstof in binnenvaart en short sea - een inventarisatie van innovatieprojecten.* Expertise- en InnovatieCentrum Binnenvaart

Ellis, J., & Tanneberger, K. (2016) *Study on the use of ethyl and methyl alcohol as alternative fuels in shipping*. European Maritime Safety Agency.

Engie. (2020). Introductie Energie Transport Hub's

European Commission. (2014). Commission Decision C (2014) 4995, Horizon 2020–Work Programme 2014–2015, Annex G: Technology Readiness Levels (TRL).

European Commission. (2020). *Inland waterway*. Retrieved from https://ec.europa.eu/transport/modes/inland_en

European Commission. (2021a). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality.* COM/2021/550 final.

European Commission. (2021b). *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU of the European Parliament and of the Council*. COM/2021/559 final

European Parliament. (2014). *Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the deployment of alternative fuels infrastructure (Text with EEA relevance).* Document 32014L0094, 2014.

European Parliament. (2021). *European Parliament resultion of 14 September 2021 towards future-proof inland waterway transport in Europe.* 2021/2015(INI)

Eurostat. (2021). Modal split of freight transport. Retrieved from https://ec.europa.eu/eurostat/databrowser/view/tran_hv_frmod/default/table?lang=en

FPS. (2021). *Holland Shipyards Group will Retrofit Future Proof Shipping's "Maas" to Sail on H2 Power*. Future Proof Shipping. Retrieved from https://futureproofshipping.com/news/2021/holland-shipyards-group-will-retrofit-future-proof-shippings-maas-to-sail-on-h2-power/

Frank, S., & Bachmeier, M. (Oktober 2020). Mission Hydrogen GmbH
Fuel Cell Technologies Office. (2017). Hydrogen Storage. Retrieved from https://www.energy.gov/sites/prod/files/2017/03/f34/fcto-h2-storage-fact-sheet.pdf

Future Proof Shipping. (2021). The Maas. Retrieved from https://futureproofshipping.com/the-maas/

Gangoli Rao, A., Yin, F., & Werij, H. G. C. (2020). Energy transition in aviation: the role of cryogenic fuels. *Aerospace — Open Access Aeronautics and Astronautics Journal*, 7(12), 1-24.

Gardner, E. (2018). Lithium-ion Batteries: a new safety issue for ships? *Ship technology*. Retrieved from https://www.ship-technology.com/features/lithium-ion-batteries-new-safety-issue-ships/

Gasunie. (2019). Waterstof vraag en aanbod nu – 2030. Retrieved from https://www.hyway27.nl/gelieerde-rapporten-en-beleidsbrieven

GEFCO. (n.d.). Downstream logistics. Retrieved from https://www.gefco.net/en/glossary/definition/downstream-logistics/

Geyer, R., Knöttner, S., Diendorfer, C., Drexler-Schmid, G., & Alton, V. (2021). 100% renewable energy for austria's industry: Scenarios, energy carriers and infrastructure requirements. *Applied Sciences, 11*(4), 1819.

GIIGNL. (2009). Basic Properties of LNG. *International Group of Liquefied Natural Gas Importers*. Retrieved from http://www.kosancrisplant.com/media/5648/1-lng_basics_82809_final_hq.pdf

Gondal, I. A., & Sahir, M. H. (2012). Prospects of natural gas pipeline infrastructure in hydrogen transportation. *International journal of energy research, 36*(15), 1338-1345.

Green Deal. (2019). *C-230 Green Deal on Maritime and Inland Shipping and Ports Retrieved from* https://www.greendeals.nl/sites/default/files/2019-11/GD230%20Green%20Deal%20on%20Maritime%20and%20Inland%20shipping%20and%20Ports.pdf

Harmsen, J. (2021). Green Maritime Mehanol. Towards a zero emission shipping industry. *TNO.*

Harmsen, J., van Meijeren, J., & Croes, N. (2014). *Quick wins voor verlegging van vervoer gevaarlijke stoffen van spoor naar water en buis*. Delft: TNO.

Héder, M. (2017). From NASA to EU: the evolution of the TRL scale in Public Sector Innovation. *The Innovation Journal, 22*(2), 1-23.

Heitink, J., & Mentink, L. (2022). Rapport / Clean Energy Hubs binnenvaart, veiligheidsaspecten. *AVIV*

Hübner, J. H., Douma, J. (2021). *SuAc 1.1c Hydrogen Demand Study.* DNV/ RH_2INE. Retrieved from https://www.rh2ine.eu/wp-content/uploads/2021/10/RH2INE-Kickstart-Study-Scenario-building-Hydrogen-Demand-Scenarios.pdf

Hyde, K., Ellis, A., & Power, I. T. M. (2019). Feasibility of hydrogen bunkering. *Interreg North Sea Region Dual Ports.*

Hyster. (n.d.) *RS46 Reachstacker Heavy-duty Applications*. Retrieved from https://www.hyster.com/en-gb/europe/container-handlers/rs46/

Iannuzzi, L., Hilbert, J. A., & Lora, E. E. S. (2021). Life cycle assessment (LCA) for use on renewable sourced hydrogen fuel cell buses vs diesel engines buses in the city of rosario, argentina. *International Journal of Hydrogen Energy*

IEA. (2020). *CO2 emissions by sector, Netherlands 1990-2018*. Retrieved from https://www.iea.org/data-and-statistics/data-browser?country=NETHLAND&fuel=CO2%20emissions&indicator=CO2BySector

Incer-Valverde, J., Mörsdorf, J., Morosuk, T., & Tsatsaronis, G. (2021). Power-to-liquid hydrogen: exergy-based evaluation of a large-scale system. *International Journal of Hydrogen Energy*.

IVR. (2018). Samenstelling Nederlandse vloot - aantal schepen. Retreived from https://binnenvaartcijfers.nl/samenstelling-nederlandse-vloot/

Jungsbluth, J., Lemken, D., Koch, F., & Olvis, C. (2021). RH_2INE Kickstart Study – Design Study. *Rhine Hydrogen Integration Network of Excellence*. Retrieved from https://www.rh2ine.eu/wp-content/uploads/2021/10/RH2INE-Kickstart-Study-Design-Study.pdf

Keera, S. T., El Sabagh, S. M., & Taman, A. R. (2011). Transesterification of vegetable oil to biodiesel fuel using alkaline catalyst. *Fuel, 90*(1), 42-47.

KiM. (2020). Het kleine drogeladingschip op de radar

König, A., Nicoletti, L., Schröder, D., Wolff, S., Waclaw, A., & Lienkamp, M. (2021). An Overview of Parameter and Cost for Battery Electric Vehicles. *World Electric Vehicle Journal, 12*(1), 21.

Kostencheck (n.d.). Container transport: What are the costs? Retreived from https://kostencheck.de/container-transport-kosten

Kumar, S. S., & Himabindu, V. (2019). Hydrogen production by PEM water electrolysis–A review. *Materials Science for Energy Technologies, 2*(3), 442-454.

Kunze, K., & Kirchner, O. (2012). Cryo-compressed Hydrogen Storage. Cryogenic Cluster Day.

Lee, Y., Lee, U., & Kim, K. (2021). A comparative techno-economic and quantitative risk analysis of hydrogen delivery infrastructure options. *International Journal of Hydrogen Energy, 46(27), 14857-14870.*

Liander. (2021). Tarieven 2022 voor grootzakelijke klanten. Retrieved from https://www.liander.nl/grootzakelijk/tarieven-facturen/onze-tarieven?ref=22611

Liemberger, W., Groß, M., Miltner, M., & Harasek, M. (2017). Experimental analysis of membrane and pressure swing adsorption (PSA) for the hydrogen separation from natural gas. Journal of Cleaner Production, 167, 896-907.

Liu, X., Guo, R., Ni, K., Xia, F., Niu, C., Wen, B., ... & Mai, L. (2020). Reconstruction-Determined Alkaline Water Electrolysis at Industrial Temperatures. Advanced Materials, 32(40), 2001136.

Lloyd's Register, U. M. A. S. (2020). Techno-economic assessment of zero-carbon fuels. *Lloyd's Regist.*

Lucas, A., Neto, R. C., & Silva, C. A. (2013). Energy supply infrastructure LCA model for electric and hydrogen transportation systems. *Energy, 56*, 70-80.

Methanol Institute. (2017). *Methanol Safe Handling Manuel* (4^{th} ed.). Retrieved from https://www.methanol.org/wp-content/uploads/2017/03/Safe-Handling-Manual.pdf

Ministerie van Infrastructuur en Waterstaat. 2020. *Monitoringsverslag AFID richtlijn*. Retrieved from https://www.rijksoverheid.nl/documenten/rapporten/2020/10/05/bijlage-3-afid-rapportage-nl

Moirangthem, K., & Baxter, D. (2016). *Alternative fuels for marine and inland waterways.* European Commission.

Moreno-Blanco, J., Camacho, G., Valladares, F., & Aceves, S. M. (2020). The cold high-pressure approach to hydrogen delivery. *International Journal of Hydrogen Energy, 45*(51), 27369-27380.

Netbeheer Nederland. (2019). Basisinfromatie over energie-infrastructuur. Retrieved from https://www.netbeheernederland.nl/_upload/Files/Basisdocument_over_energie-infrastructuur_143.pdf

Netbeheer Nederland. (2021). Capaciteitskaart afname elektriciteitsnet. Retrieved from https://capaciteitskaart.netbeheernederland.nl/

NPRC. (2021). *Subsidie voor nieuwbouw eerste waterstof aangedreven vrachtschip*. Nederlandse Particuliere Rijnvaart-Centrale Coöperatie U.A. Retrieved from https://nprc.eu/subsidie-voor-nieuwbouw-eerste-waterstof-aangedreven-vrachtschip/

Oirsouw, P. van, & Cobben, J. F. G. (2011). *Netten voor distributie van elektriciteit.* Phase to Phase.

Panteia. (2019). Op weg naar een klimaatneutrale binnenvaart per 2050 - Transitie- en rekenmodel binnenvaart

Panteia. (2020). Cost Figures for Freight Transport - final report.

Perčić, M., Vladimir, N., & Fan, A. (2021). Techno-economic assessment of alternative marine fuels for inland shipping in croatia. *Renewable and Sustainable Energy Reviews, 148*, 111363.

Petitpas, G., Simon, A. J., Moreno-Blanco, J., & Aceves, S. M. (2017). Liquid hydrogen infrastructure analysis. *DOE Hydrogen and Fuel Cells Annual Merit Review. Washington DC LLNL-PRES-727907. Project ID: PD135.*

PGS 35. (2020). *PGS 35: Waterstofinstallaties voorhet afleveren vanwaterstof aan voertuigen en werktuigen*. Publicatiereeks Gevaarlijke Stoffen 35. Retrieved from https://content.publicatiereeksgevaarlijkestoffen.nl/documents/PGS35/PGS_35_v0.2_april_2020.pdf

PGS 37-1. (2022). *Lithium-houdende energiedragers: Energie Opslag Systemen – EOS. Concept version 0.1 (Februari 2022).* Publicatiereeks Gevaarlijke Stoffen 37

Piña Rodriguez, M. (2021). Optimal exchangeable battery distribution and docking station location for electric sailing in IWW shipping: The case study of ZES.

Port of Rotterdam. (2021a). Jaarverslag 2020. Retrieved from https://jaarverslag2020.portofrotterdam.com/jaarverslag-2020/5-jaarrekening/toelichting-op-de-winst-en-verliesrekening/11-som-der-bedrijfsopbrengsten

Port of Rotterdam. (2021b). First emission-free inland shipping vessel on energy containers in service. Retreived from https://www.portofrotterdam.com/en/news-and-press-releases/first-emission-free-inland-shipping-vessel-on-energy-containers-in-service

Port of Rotterdam. (n.d.). *Pipeline network.* Retrieved from https://www.portofrotterdam.com/en/logistics/connections/intermodal-transportation/pipeline-network

Prussi, M., Scarlat, N., Acciaro, M., & Kosmas, V. (2021). Potential and limiting factors in the use of alternative fuels in the European maritime sector. *Journal of Cleaner Production*, *291*, 125849.
Randall, C. (2021). *World's largest electric ferry launches in Norway*. Electrive.com. Retrieved from https://www.electrive.com/2021/03/02/worlds-largest-electric-ferry-yet-goes-into-service-in-norway/

Rashid, M. D., Al Mesfer, M. K., Naseem, H., & Danish, M. (2015). Hydrogen production by water electrolysis: a review of alkaline water electrolysis, PEM water electrolysis and high temperature water electrolysis. International Journal of Engineering and Advanced Technology
Research and Innovation for Vehicle efficiency and Energy sustainability. Retrieved from https://www.energy.gov/sites/prod/files/2017/08/f36/hdtt_roadmap_July2017.pdf

Reuß, M., Dimos, P., Léon, A., Grube, T., Robinius, M., & Stolten, D. (2021). Hydrogen Road Transport Analysis in the Energy System: A Case Study for Germany through 2050. *Energies, 14*(11), 3166.

Reuß, M., Grube, T., Robinius, M., Preuster, P., Wasserscheid, P., & Stolten, D. (2017). Seasonal storage and alternative carriers: A flexible hydrogen supply chain model. *Applied energy*, *200*, 290-302.

RH_2INE. (2021) RH_2INE Kickstart Study – Main Findings & Strategic Roll-Out Plan. *Rhine Hydrogen Integration Network of Excellence*. Retrieved from https://www.rh2ine.eu/wp-content/uploads/2021/10/RH2INE-Kickstart-Study-Roll-Out-Plan-def.pdf
Rieske, J., & Scheffer, S. (2021) Uitrol bunkerinfrastructuur voor duurzame energiedragers binnenvaart. *Rijkswaterstaat*

Rijksoverheid. (2019) *Klimaatakkoord*. Retrieved from https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/klimaatakkoord

Rijksoverheid. (n.d.) *Inland shipping*. Retrieved from https://www.government.nl/topics/freight-transportation/inland-shipping

Rivard, E., Trudeau, M., & Zaghib, K. (2019). Hydrogen storage for mobility: a review. *Materials, 12*(12), 1973.

Rogelj, J., Den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., . . . Meinshausen, M. (2016). Paris agreement climate proposals need a boost to keep warming well below 2 C. *Nature, 534*(7609), 631-639.

SafeRack. (n.d.). Methanol (CH3OH) Handling Design, Loading, and Installation. Retrieved from https://www.saferack.com/bulk-chemical/methanol/

Schmidt, O., Gambhir, A., Staffell, I., Hawkes, A., Nelson, J., & Few, S. (2017). Future cost and performance of water electrolysis: An expert elicitation study. International journal of hydrogen energy, 42(52), 30470-30492.

Shusheng, X., Qiujie, S., Baosheng, G., Encong, Z., & Zhankuan, W. (2020). Research and development of on-board hydrogen-producing fuel cell vehicles. *International Journal of Hydrogen Energy, 45*(35), 17844-17857.

Siemens Energy. (2020) Overview of the PEM Silyzer Family. Retrieved from https://4echile-datastore.s3.eu-central-1.amazonaws.com/wp-content/uploads/2020/10/10132733/20200930-SE-NEB-PEM-Electrolyzer-and-Applications_EW.pdf

Stedin (2021). Tarieven grootzakelijk. Retrieved from https://www.stedin.net/zakelijk/betalingen-en-facturen/tarieven

Stefenson, P. (2014). The use of biofuel in the marine sector or Methanol, the marine fuel of the future. *European Biofuels Technology Platform Brussels, 15.*

Taylor, M. (2009). What is sensitivity analysis. *Consortium YHE: University of York*, 1-8.

TenneT. (n.d.). *Our high-voltage grid*. Retrieved from https://www.tennet.eu/our-grid/our-high-voltage-grid/our-high-voltage-grid/

Tian, W. (2013). A review of sensitivity analysis methods in building energy analysis. Renewable and Sustainable Energy Reviews, 20, 411-419.

TLS container. (2020). Battery energy storage system container | BESS container. Retrieved from https://www.tls-containers.com/energy-storage-container.html

Turconi, R., Boldrin, A., & Astrup, T. (2013). Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. *Renewable and Sustainable Energy Reviews, 28*, 555-565.
U.S. Drive. (2017). Hydrogen delivery technical team roadmap. *United States Driving*

Undertaking, H. J. (2017). Study on early business cases for H2 in energy storage and more broadly power to H2 applications.

Vermij, H., & De Vries, K. (2019). *Gevolgen grote transities en wereldhandel voor de binnenvaart 2020-2040*. Retrieved from https://www.topsectorlogistiek.nl/wptop/wp-content/uploads/2020/02/24012020-Binnenvaart-RHDHV.pdf

Viktorsson, L., Heinonen, J. T., Skulason, J. B., & Unnthorsson, R. (2017). A step towards the hydrogen Economy—A life cycle cost analysis of A hydrogen refueling station. *Energies*, *10*(6), 763.

Vorobyov, A. A., Bityutsky, N. A., Krutko, A. A., & Sedykh, D. A. (2021, December). Optimization of the operating fleet of tank cars. In *AIP Conference Proceedings* (Vol. 2412, No. 1, p. 030026). AIP Publishing LLC.

Wartsila. (2022). Improving efficiency. Retrieved from https://www.wartsila.com/sustainability/innovating-for-sustainability/improving-efficiency

Waterfront Shipping. (2020). *Waterfront Shipping takes leadership role in demonstrating simplicity of methanol bunkering to marine industry*. Waterfront shipping Limited. Retrieved from https://www.waterfront-shipping.com/news/2021/05/waterfront-shipping-takes-leadership-role-demonstrating-simplicity-methanol-bunkering

Weeda, M., & Segers, R. C. (2020). The Dutch hydrogen balance, and the current and future representation of hydrogen in the energy statistics.

Weihua. (n.d.). Ship-to-Shore Gantry Crane. Retrieved from https://www.weihuacraneglobal.com/product/Ship-to-Shore-Gantry-Crane.html

Weyenberg, S. P. R. A. van (2021, December 2). Rapportage ketenstudie omgevingsveiligheid van duurzame waterstofrijke energiedragers [Letter of government]. Retrieved from https://www.tweedekamer.nl/kamerstukken/brieven_regering/detail?id=2021Z22398&did=2021D47589

Wulf, C., Reuß, M., Grube, T., Zapp, P., Robinius, M., Hake, J. F., & Stolten, D. (2018). Life Cycle Assessment of hydrogen transport and distribution options. *Journal of cleaner production,* 199, 431-443.

Xiong, R., Pan, Y., Shen, W., Li, H., & Sun, F. (2020). Lithium-ion battery aging mechanisms and diagnosis method for automotive applications: Recent advances and perspectives. *Renewable and Sustainable Energy Reviews, 131*, 110048.

Zero Emission Services. (2021). Zero Emission Services start met operatie eerste emissievrije binnenvaartschip op energiecontainers in de vaart. Retrieved from https://zeroemissionservices.nl/eerste-emissievrije-binnenvaartschip-op-energiecontainers-in-de-vaart/

Zero Emission Services. (n.d.). *ZESpack*. Retrieved from https://zeroemissionservices.nl/zespack

Zomer, G. R., Finner, S. P., Harmsen, J., Vredeveldt, A. W., & van Lieshout, P. S. (2020). *Green Maritime Methanol; operation aspects and the fuel supply chain* (No. TNO 2020 R11105). TNO.

Zou, J., Han, N., Yan, J., Feng, Q., Wang, Y., Zhao, Z., ... & Wang, H. (2020). Electrochemical compression technologies for high-pressure hydrogen: current status, challenges and perspective. *Electrochemical Energy Reviews*, 1-40.

Appendix I: Technology Readiness Level

The technology readiness levels (TRLs) are first introduced by NASA in the late 1970s and are formally and theoretically defined in 1989 (Héder, 2017). However, the original TRLs defined by NASA are applicable to the aviation and space technology. The commonly used definition of the TRLs is defined by the European Commission, that implemented TRLs in proposals for EU-funded innovation and research projects. The TRLs defined by the European Commission are (European Commission, 2014):

- TRL 1 – basic principles observed
- TRL 2 – technology concept formulated
- TRL 3 – experimental proof of concept
- TRL 4 – technology validated in lab
- TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7 – system prototype demonstration in operational environment
- TRL 8 – system complete and qualified
- TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Appendix II: Different electrolysis techniques

The different electrolysis technologies are shown in Figure 25.

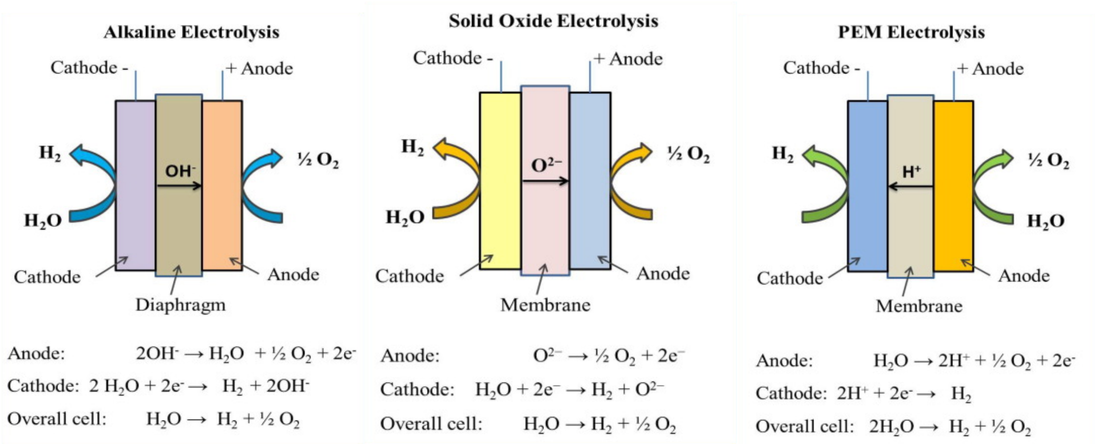

Figure 25: the different commercial electrolysis techniques (Kumar & Himabindu, 2019)

Within the AEC process there are two molecules of an alkaline solution (KOH/NaOH) reduced to one hydrogen molecule (H_2) and two hydroxyl ions (OH^-) at the cathode. The hydrogen is released at the cathode surface as a gas. With an electrical circuit between the anode and cathode, OH^- is transferred to the cathode where it is discharged in the form of half a molecule of oxygen (O_2) and one molecule of water (H_2O) (Kumar & Himabindu, 2019). An electrolyser based on the AEC process operates at industrial temperatures of 50-80 °C (323-353 K) (Liu et al., 2020). The negative aspect of AEC is that this electrolysis happens under low pressure (<30bar) and thus requires compressors to be used in a filling or bunkering facility (Rashid et al., 2015).

The SOE uses a solid ceramic material as the electrolyte. SOE operates by providing electrons from the electrical circuit at the cathode that combine with H_2O to form hydrogen gas and negative charged ions. Oxygen is transferred to the anode by passing through the membrane and forms oxygen gas and electrons (Cummins, 2020). The SOE advantages over the other electrolysis processes are that it has the potential to become more efficient and that the operating temperatures are very high (500-1000 °C) (Cummins, 2020; Kumar & Himabindu, 2019; Rashid et al., 2015).

PEM electrolysis uses solid polysulfonated membranes as electrolytes. When current is applied, water is split into hydrogen ions and oxygen molecules. The hydrogen ions pass through the membrane and react at the cathode to form H_2 gas (Cummins, 2020). When compared to other electrolysis techniques, PEM and AEC have very similar environmental effects (Wulf et al., 2018). However, PEM is superior to the other techniques because it has a compact design, lower power consumption, relatively high efficiency and is able to ramp up and down very quickly (Hyde et al., 2019; Kumar & Himabindu, 2019, Rashid et al., 2015). Moreover, PEM produces ultrapure hydrogen (99.999% pureness) (Cummins, 2020). A disadvantage is that a state-of-the-art PEM electrolyser uses costly noble metals in the electrocatalysts, making it more expensive than an AWE electrolyser.

A comparative analysis has been made by Van der Burg (2020) and this concluded that the highest overall scored is PEM. The PEM electrolysis technology scored the highest in simplicity, response time, safety, peak power and minimum power.

Appendix III: Sailing profile calculations

Table 28 shows the average sailing profiles per CEMT class and commodity class. Each CEMT class shows the maximum dimensions a vessel can have. CEMT 2 is categorized as small, CEMT 4 as medium and CEMT 5 as large vessels. The average distance per commodity and CEMT class are abstracted from Panteia (2020). Unfortunately, no data about the average distance per commodity for CEMT 1,3 and 6 is not published or publicly available. The number of vessels is abstracted from KiM (2020). The number of wet and dry divisions is calculated by the share of dry and wet cargo vessels in the inland navigation sector (79% dry and 21% wet) (IVR, 2018).

Table 28: Average sailing profile per CEMT class and commodity class

CEMT class	Type of commodity	Sailing profile (km/yr)	Type of cargo	Average sailing profile per CEMT with a specific cargo type (km/yr)	Number of vessels	Number of vessels in the wet and dry division per CEMT class	Overall average sailing profile (km/yr)
2	Agricultural and food products	19,869	Dry	21,102	555	555	36,574
	Coal, brown coal and cokes	19,835	Dry				
	Ores	19,858	Dry				
	Salt, sand, gravel and clay	22,007	Dry				
	Containers	23,943	Container (dry)				
4	Agricultural and food products	24,642	Dry	27,580	741	588	
	Coal, brown coal and cokes	24,848	Dry				
	Ores	27,583	Dry				
	Salt, sand, gravel and clay	26,826	Dry				
	Containers	34,002	Container (dry)				
	Crude oil and natural gas	26,826	Wet	26,773		153	
	Chemical	26,853	Wet				
	Miscellaneous minerals	26,639	Wet				
5	Agricultural and food products	32,315	Dry	36,575	1,338	1,062	
	Coal, brown coal and cokes	32,143	Dry				
	Ores	32,161	Dry				
	Salt, sand, gravel and clay	35,690	Dry				
	Containers	50,565	Container (dry)				
	Crude oil and natural gas	46,348	Wet	46,509		276	
	Chemical	46,751	Wet				
	Miscellaneous minerals	46,427	Wet				

The overall average distance is obtained by adding the multiplied product of each average distance per CEMT class and cargo type (5th column) with the number of vessels with that CEMT class and cargo type (7th column) and divide it by the total number of vessels in the fleet.

The model also includes an option that includes the average sailing profile for solely vessels with container cargo. To calculate the average sailing profile for vessels with container cargo, the different sailing profiles of vessels with container cargo per CEMT class (3rd column) have to be multiplied by the number of vessels in that particular CEMT class first (7th column). The result is divided by the total number of vessels with dry cargo 40,296 km/yr. Unfortunately, the exact number of vessels with container transport is unknown. Therefore, the absolute number for dry vessels for a particular CEMT class is used to calculate the average sailing profile of vessels with container cargo.

Appendix IV: Extra parameter info for hydrogen bunkering

Temporal low-pressure buffer

For the storage of hydrogen, a buffer with a capacity of 1000 kg of hydrogen is used for the large and small hydrogen filling and bunkering facilities. The relevant input parameters are shown in Table 29. Assumed is that the start-up time for compressors can proceed the supply of hydrogen without totally emptying the buffer capacity.

Table 29: Cost and performance parameters for temporal low-pressure buffer

	Unit	Values	Sources and notes
Capital investment	€/kg H_2	500	Chrysochoidis-Antsos et al. (2018) & Jungsbluth et al. (2019)
Deprecation period	yr	30	Undertaking (2017)
O&M	%	1	Chrysochoidis-Antsos et al. (2018)
Low pressure buffer capital investment	€	500,000	A multiplication of the capital investment with 1000 kg

Compressors

Jungsbluth et al. (2021) mentioned that the capital investment of a 50 kg/h compressor is €700,000, which is equal to a capital investment of €14,000/kg/hr. Chrysochoidis-Antsos et al. (2018) mentioned that the capital investment of a compressor with a capacity of 34 kg/hr would be €20,800/kg/hr. The average investment is thereby €17,400/kg/hr.

Compressors with a combined capacity of 65 and 325 kg/hr are installed in small and large facilities respectively. The cost and performance parameters for the compressors used are shown in Table 30. More compressors are needed for a large facility compared to a small facility and not larger compressors. Therefore, deduction in capital investment is not included.

Table 30: Cost and performance parameters for the compressors

	Unit	Compressors in small facilities	Compressors in large facilities	Sources and notes
Rated output	kg/hr	65	325	
Investment	€/kg H2/h	17,400	17,400	
Compressor capital investment	€	1,131,000	4,806,750	compressors in large facilities have a discount of 15% according to Jungsbluth et al. (2016).
O&M compressor	%/yr	4	4	Reuß et al. (2017) & Chrysochoidis-Antsos et al. (2018)
O&M compressor	€/yr	45,240	192,270	
Lifetime	yr	15	15	Reuß et al. (2017)
Electricity Demand	kwh/kg H_2	2	2	Abma et al. (2019b)
Electrical DC power	MW	0.13	0.65	Electricity demand multiplied with the rated output

Dispenser units

The cost and performance parameters for the dispenser units are shown in Table 31. The cost and performance parameters for dispenser units in small and large facilities are derived from Table 31 and shown in Table 32.

Table 31: Cost and performance parameters for dispenser units

	Unit	Values	Sources and notes
Dispenser cost	€	95,000	Average of €130000 and €60000/unit found in DOE (2015) and Chrysochoidis-Antsoset et al. (2018) respectively
O&M dispenser unit	% of investment/yr	2.0	DOE (2015) and Chrysochoidis-Antsoset et al. (2018)
Lifetime	yr	10	Reuß et al. (2017) and DOE (2015
Dispenser speed	kg/hr	216	Chrysochoidis-Antsoset et al. (2018)

Table 32: Cost and performance parameters for dispenser units in small and large direct dispensing facilities

	Unit	Small	Large
Dispensers required	#	1	2
Dispenser capital investment	€	95,000	190,000
O&M	% of investment/yr	2.0	2.0
O&M	€/yr	1,900	3,800
Lifetime	yr	10	10

Footprint

The footprint of the total plant has been received from a small and large existing hydrogen facility for road vehicles or trains by Linde (Frank & Bachmeier, 2020). Unfortunately, there are no bunkering facilities or filling facilities for containerized hydrogen for the inland navigation sector. Therefore, no reference can be taken from such facilities. The footprint with the safety contour is shown in Table 33.

Table 33: Footprint for small and large facilities

	Unit	Small	Large	Sources and notes
Footprint	m2	650	3,252	Frank and Bachmeier (2020)
Footprint incl. safety contour	m2	870	3,724	Frank and Bachmeier (2020) with safety contours from PGS 35 (2020)

PEM electrolyser

PEM electrolysers will be the dominant electrolyser type in 2030 according to Schmidt et al. (2017). The cost and performance parameters for the electrolysers in small and large facilities are shown in Table 34. Values are based on Syllizer 200 electrolysers by Siemens Energy.

Table 34: Cost and performance parameters for an electrolyser in small and large facilities

	Unit	Small	Large	Sources and notes
Rated output	kg/hr	65	325	Chrysochoidis-Antsoset et al. (2018)
Production	kg/hr	59	297	With 8000 full load hours
Capital investment	€/kW	1,200	700	Average of Abma et al. (2019b) and Chrysochoidis-Antsoset et al. (2018) for an electrolyser for a small facility, capital investment for a large facility is Abma et al. (2019b).
Capital investment	€	4,500,000	13,125,000	
Investment construction/ infra	€	337,500	984,375	Retrieved from linear cost extrapolation made from investment construction/ infra on Jungsbluth et al. (2021) (investment 8.4, construction 1.08 and 3.6 investment with 0.72 construction)
PEM electrolyser capital investment	€	4,837,500	14,109,375	
Electrolyser O&M	% of investment/ yr	2	2	Minutillo, Perna, Forcina, Di Micco, & Jannelli (2021) and Jungsbluth et al. (2021)
O&M grid connection	€/yr	729	8,745	See Input data battery electric
Lifetime	yr	20	20	Siemens Energy (2020)
Water consumption	l/kg H_2	10	10	Siemens Energy (2020)
Electrical DC power	MW	3.75	18.75	Abma et al. (2019b)
Power grid connection	MVA	5	2x10	Abma et al. (2019b)
Electricity Demand	kwh/kg H_2	58	58	Multiplication of rated output and electrical DC power
Required space (footprint incl. safety contour)	m^2	500	1,000	Jungsbluth et al. (2021)

Pressure swing absorption (PSA) unit

The pressure swing absorption unit is necessary for hydrogen delivery by a nationwide pipeline network as the purity of this hydrogen would not be high enough for a fuel cell to operate. Burgers (2020) found out that a PSA unit with a capacity of 700 kg/day (~29.2 kg/hr) has a capital investment of 1,883,200 AUD, which is equal to € 1,242,912 (retrieved with the €/AUD = 0.66/1 on 2 March 2022). This is equal to a capital investment cost of €42,614/kg H_2/hr. The capital investment cost for PSA in small facilities is determined by €42,614/kg H_2/hr. However, it is assumed that the PSA unit in the large facilities has the same cost reduction in terms of percentage as for the electrolysers in the large facilities. This leads to a 24,858/kg H_2/hr capital investment for the PSA unit in a large facility.

The cost and performance parameters for PSA units in small and large facilities are shown in Table 35.

Table 35: Cost and performance parameters for PSA units in small and large facilities

PSA	Unit	Small	Large	Sources and notes
PSA capital investment	€	2,769,918	8,078,928	Burgers (2020)
Rated output	kg/hr	65	325	
Maintenance	% of investment/ yr	2	2	Burgers (2020)
Maintenance	€	55,398	161,579	
Lifetime	yr	10	10	Burgers (2020)
Electricity consumption	kWh/kg H_2	0.54	0.54	Liemberger et al. (2017) stated that H_2 uses on average ~1.15 kWh/m³ at 25.81 bar. Density of H2 is 0.08376 kg/m3 at 1.01325 bar
Electrical DC power	MW	0.04	0.18	
Power grid connection	MVA	2	2	

The Equivalent Annual Cost (EAC)

With the given cost and performance parameters for each component, a project lifetime of 20 years and an interest rate of 3%, the EAC can be calculated. Table 36, Table 37 and Table 38 show the annual CAPEX, OPEX and annual replacement expenditures for different hydrogen container filling facility respectively. Table 39 shows the annual CAPEX, OPEX and annual replacement expenditures for different hydrogen containers. Table 40, Table 41 and Table 42 show the annual CAPEX, OPEX and annual replacement expenditures for different hydrogen bunkering facility respectively. It should be noted that the data applies to a capacity of 8000 full load hours. In certain scenarios, some facilities will not run on full capacity i.e., 8000 full load hours. The total OPEX in these scenarios will thereby be lower, as there are fewer expenditures for utilities such as water, electricity and/or hydrogen. The cost for the different grid connections is discussed in 4.3.

Table 36: Annual CAPEX for different hydrogen container filling facility

	Unit	Small facility with pipeline	Large facility with pipeline	Small facility with electrolyser	Large facility with electrolyser
PSA capital investment	€/yr	186,182	543,031	0	0
PEM electrolyser capital investment	€/yr	0	0	325,156	948,372
Low pressure buffer capital investment	€/yr	33,608	33,608	33,608	33,608
Compressor capital investment	€/yr	76,021	323,089	76,021	323,089
Total capital investment (excl. grid connection)	€/yr	295,811	899,728	434,785	1,305,069
Power grid connection capital investment	€/yr	2,922	2,922	15,385	38,755
Total annual CAPEX	€/yr	298,733	902,650	450,170	1,343,824

Table 37: OPEX for different hydrogen container filling facility

	Unit	Small facility with pipeline	Large facility with pipeline	Small facility with electrolyser	Large facility with electrolyser
PSA O&M	€/yr	55,398	161,579	0	0
PEM O&M	€/yr	0	0	90,000	262,500
Buffer O&M	€/yr	5,000	5,000	5,000	5,000
Compressor O&M	€/yr	45,240	192,270	45,240	192,270
Dispenser O&M	€/yr	0	0	0	0
Grid connection O&M	€/yr	729	729	1,728	17,490
Total O&M facility (excl. Grid connection)	€/yr	105,638	358,849	140,240	459,770
Electricity consumption	€/yr	79,217	396,084	1,862,400	9,312,000
Water consumption	€/yr	0	0	52,000	260,000
Rent	€/yr	6,093	26,069	9,593	29,569
H2 cost	€/yr	1,560,000	7,800,000	0	0
Total annual OPEX	€/yr	1,751,677	8,581,731	2,065,961	10,078,830

Table 38: Annual replacement expenditures for different hydrogen container filling facilities

	Unit	Small facility with pipeline	Large facility with pipeline	Small facility with electrolyser	Large facility with electrolyser
PSA capital investment	€/yr	138,537	404,066	0	0
PEM electrolyser capital investment	€/yr	0	0	180,031	525,090
Low pressure buffer capital investment	€/yr	13,846	13,846	13,846	13,846
Compressor capital investment	€/yr	48,795	0	48,795	207,379
Dispenser capital investment	€/yr	0	0	0	0
Total capital investment (excl. grid connection)	€/yr	201,178	417,912	242,672	746,315
Power grid connection capital investment	€/yr	1,618	1,618	8,518	21,458
Total annual replacement expenditures	€/yr	202,796	419,530	251,190	767,773

Table 39: Annual CAPEX, OPEX and annual replacement expenditures for different hydrogen containers

	Unit	20ft, Type II, 300 bar	20ft, Type IV, 300 bar	20ft, Type IV, 500 bar
Annual CAPEX	€/yr	10,082	16,804	25,542
OPEX	€/yr	26,667	26,667	26,667
Annual replacement expenditures	€/yr	6,471	10,786	16,394

Table 40: Annual CAPEX for different hydrogen bunkering facility

	Unit	Small facility with pipeline	Large facility with pipeline	Small facility with electrolyser	Large facility with electrolyser
PSA capital investment	€/yr	186,182	543,031	0	0
PEM electrolyser capital investment	€/yr	0	0	325,156	948,372
Low pressure buffer capital investment	€/yr	33,608	33,608	33,608	33,608
Compressor capital investment	€/yr	76,021	323,089	76,021	323,089
Dispenser capital investment	€/yr	6,385	12,771	6,385	12,771
Total capital investment (excl. grid connection)	€/yr	302,196	912,499	441,170	1,317,840
Power grid connection capital investment	€/yr	2,922	2,922	15,385	38,755
Total annual CAPEX	€/yr	305,119	915,421	456,555	1,356,595

Table 41: OPEX for different hydrogen bunkering facility

	Unit	Small facility with pipeline	Large facility with pipeline	Small facility with electrolyser	Large facility with electrolyser
PSA O&M	€/yr	55,398	161,579	0	0
PEM O&M	€/yr	0	0	90,000	262,500
Buffer O&M	€/yr	5,000	5,000	5,000	5,000
Compressor O&M	€/yr	45,240	192,270	45,240	192,270
Dispenser O&M	€/yr	1,900	3,800	1,900	3,800
Grid connection O&M	€/yr	729	729	1,728	17,490
Total O&M facility (excl. grid connection)	€/yr	107,538	362,649	142,140	463,570
Electricity consumption	€/yr	79,217	396,084	1,862,400	9,312,000
Water consumption	€/yr	0	0	52,000	260,000
Rent	€/yr	6,093	26,069	9,593	33,069
Cost H2	€/yr	1,560,000	7,800,000	0	0
Total annual CAPEX	€/yr	193,577	785,531	2,067,861	10,086,130

Table 42: Annual replacement expenditures for different hydrogen bunkering facility

	Unit	Small facility with pipeline	Large facility with pipeline	Small facility with electrolyser	Large facility with electrolyser
PSA capital investment	€/yr	138,537	404,066	0	0
PEM electrolyser capital investment	€/yr	0	0	180,031	525,090
Low pressure buffer capital investment	€/yr	13,846	13,846	13,846	13,846
Compressor capital investment	€/yr	48,795	207,379	48,795	207,379
Dispenser capital investment	€/yr	4,751	9,503	4,751	9,503
Total capital investment (excl. grid connection)	€/yr	205,929	634,793	247,423	755,818
Power grid connection capital investment	€/yr	1,618	1,618	8,518	21,458
Total annual replacement expenditures	€/yr	207,547	636,411	255,942	777,275

Appendix V: EAC for battery electric bunkering components

The annual CAPEX, OPEX and annual replacement expenditures for different grid connections, charging stations and batteries are shown in Table 43, Table 44 and Table 45. The electricity consumption costs only apply for 8000 full load hours

Table 43: The annual CAPEX, OPEX and annual replacement expenditures for different grid connections

Info	Unit	Cat. 1	Cat. 2	Cat. 3
Annual CAPEX	€/yr	2,922	15,385	19,377
OPEX	€	729	1,728	8,745
Annual replacement expenditures	€/yr	1,618	8,518	10,729

Table 44: The annual CAPEX, OPEX and annual replacement expenditures for charging stations

		Unit	Charging station with two 1000 kW charging spots	Charging station with two 500 kW charging spots	Charging station with one 750 kW charging spot	Charging station with one 1000 kW charging spot
Annual CAPEX		€/yr	90,741	72,593	56,461	63,855
OPEX	**Total O&M facility**	€/yr	13,500	10,800	8,400	9,500
	Electricity consumption	€/yr	960,000	480,000	360,000	480,000
	Rent	€/yr	2,800	2,800	2,800	2,800
Annual replacement expenditure charging station		€/yr	58,243	46,595	36,240	40,986

Table 45: The annual CAPEX, OPEX and annual replacement expenditures for different battery electric containers

Info	Unit	1.5 MWh battery	2MWh battery	2.5MWh battery	3MWh battery
Annual CAPEX	€/yr	54,915	64,225	74,408	84,154
OPEX	€/yr	8,170	9,555	11,070	12,520
Annual replacement expenditures	€/yr	30,405	35,560	41,198	46,594

Appendix VI: Detailed cost model output

Table 46: The breakdown of the cost of energy service for each business case

		Bunkering infrastructure scenario with:															
		Hydrogen containers				Hydrogen, direct dispensing				Battery electric containers				Methanol			
Business case	**Unit**	**1A**	**1B**	**1C**	**1D**	**1E**	**1F**	**2A**	**2B**	**2C**	**2D**	**3A**	**3B**	**3C**	**3D**	**4A**	**4B**
Facility cost (excl. electrolyser or PSA)	€/km	1.23	0.80	0.80	1.32	1.05	1.05	1.29	1.01	1.37	1.08	0.37	0.39	0.38	0.38	0.05	0.14
PSA		1.66	1.08	1.08	0.00	0.00	0.00	1.66	1.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Electrolyser	€/km	0.00	0.00	0.00	9.94	9.02	9.02	0.00	0.01	9.94	9.02	0.00	0.00	0.00	0.00	0.00	0.00
Storage container	€/km	14.95	14.95	14.95	14.95	14.95	14.95	7.50	7.50	7.50	7.50	5.93	5.93	5.93	5.93	0.00	0.00
Truck delivery (containerized energy carrier) or ship delivery (methanol)	€/km	0.00	0.00	0.69	0.00	0.00	0.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.50	0.15	0.15
Berth	€/km	0.00	0.00	0.00	0.00	0.00	0.00	1.61	0.70	1.61	0.70	0.00	0.00	0.00	0.00	0.00	0.07
Energy carrier purchase	€/km	6.26	6.26	6.26	0.00	0.00	0.00	6.26	6.26	0.00	0.00	1.97	1.97	1.97	1.97	11.42	11.42
Total (break even)	€/km	24.10	23.08	23.77	26.21	25.02	25.71	18.31	16.55	20.42	18.29	8.27	8.29	8.28	11.78	11.62	11.78

Table 47: The breakdown of the cost of energy for each business case

		Bunkering infrastructure scenario with:															
		Hydrogen containers				Hydrogen, direct dispensing				Battery electric containers				Methanol			
Business case	**Unit**	**1A**	**1B**	**1C**	**1D**	**1E**	**1F**	**2A**	**2B**	**2C**	**2D**	**3A**	**3B**	**3C**	**3D**	**4A**	**4B**
Facility cost (excl. electrolyser or PSA)	€/GJ	4.16	2.69	2.69	4.44	3.54	3.54	4.34	3.41	4.63	3.63	3.13	3.27	3.19	3.19	0.14	0.41
PSA	€/GJ	5.61	3.64	3.64	0.00	0.00	0.00	5.61	3.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Electrolyser	€/GJ	0.00	0.00	0.00	33.56	30.45	30.45	0.00	0.02	33.56	30.45	0.00	0.00	0.00	0.00	0.00	0.00
Storage container	€/GJ	50.49	50.49	50.49	50.49	50.49	50.49	25.34	25.34	25.34	25.34	50.19	50.19	50.19	50.19	0.00	0.00
Truck delivery (containerized energy carrier) or ship delivery (methanol)	€/GJ	0.00	0.00	2.34	0.00	0.00	2.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	29.60	0.47	0.47
Berth	€/GJ	0.00	0.00	0.00	0.00	0.00	0.00	5.43	2.36	5.43	2.36	0.00	0.00	0.00	0.00	0.00	0.21
Energy carrier purchase	€/GJ	21.13	21.13	21.13	0.00	0.00	0.00	21.13	21.13	0.00	0.00	16.67	16.67	16.67	16.67	35.00	35.00
Total (break even)	€/GJ	81.38	77.95	80.28	88.49	84.47	86.81	61.84	55.89	68.95	61.77	69.98	70.12	70.05	99.64	35.62	36.10

Table 48: The utility and hardware requirements hydrogen bunkering infrastructure scenarios

		Business case									
	Unit	**1A**	**1B**	**1C**	**1D**	**1E**	**1F**	**2A**	**2B**	**2C**	**2D**
Hydrogen/ battery electric containers in circulation	#	1,087	1,087	1,087	1,087	1,087	1,087	0	0	0	0
Number of facilities	#	23	5	5	23	5	5	23	5	23	5
Electricity required	MWh/yr	29,049	29,049	29,049	682,947	682,947	682,947	29,049	29,049	682,947	682,947
Water consumption	l/yr	0	0	0	114,411,214	114,411,214	114,411,214	0	0	114,411,214	114,411,214
H_2 required	Ton H2/yr	11,441	11,441	11,441	11,441	11,441	11,441	11,441	11,441	11,441	11,441
Electricity cost	M€/yr	1.74	1.74	1.74	40.98	40.98	40.98	1.74	1.74	40.98	40.98
Water cost	M€/yr	0.00	0.00	0.00	1.14	1.14	1.14	0.00	0.00	1.14	1.14
H_2 cost	M€/yr	34.32	34.32	34.32	0.00	0.00	0.00	34.32	34.32	0.00	0.00
Footprint	Ha	83.38	83.24	83.24	84.53	83.49	83.49	2.00	1.86	3.15	2.36
Capacity usage facilities	%	95.66	88.01	88.01	95.66	88.01	88.01	95.66	88.01	95.66	88.01

Table 49: The utility and hardware requirements battery electric and methanol scenarios

		Business case					
	Unit	**3A**	**3B**	**3C**	**3D**	**4A**	**4B**
Hydrogen/ battery electric containers in circulation	#	240	240	240	240	0	0
Number of facilities	#	0	0	0	0	10	1
Electricity required	MWh/yr	180,175	180,175	180,175	180,175	0	0
Methanol required	1000 l/yr	0	0	0	0	113,745,143	113,745,143
Electricity cost	M€/yr	10.81	10.81	10.81	10.81	0.00	0.00
Methanol cost	M€/yr	0.00	0.00	0.00	0.00	62.67	62.67
Footprint	Ha	0.74	0.74	0.74	0.74	0.00	2.00
Capacity usage facilities	%	93.84	93.84	93.84	93.84	98.43	65.62

Table 50: A breakdown of the capital investment for each bunkering infrastructure

		Bunkering infrastructure scenario with:															
		Hydrogen containers				Hydrogen, direct dispensing				Battery electric containers				Methanol			
Business case	**Unit**	**1A**	**1B**	**1C**	**1D**	**1E**	**1F**	**2A**	**2B**	**2C**	**2D**	**3A**	**3B**	**3C**	**3D**	**4A**	**4B**
Total capital investment filling facility (excl. grid connection)	M€	101.22	66.93	66.93	148.78	97.08	97.08	103.41	67.88	150.96	98.03	16.20	16.20	16.20	16.20	2.20	5.00
Total capital investment grid connection	M€	0.04	0.04	0.04	5.31	2.93	2.93	0.04	0.04	5.31	2.93	0.52	1.37	0.81	0.81	0.00	0.00
Capital investment energy carrier container	M€	412.89	412.89	412.89	412.89	412.89	412.89	228.00	228.00	228.00	228.00	228.90	228.90	228.90	228.90	0.00	0.00
Capital investment truck	M€	0.00	0.00	1.92	0.00	0.00	1.92	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.12	0.00	0.00
Capital investment trailer	M€	0.00	0.00	0.18	0.00	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.00	0.00
Total capital investment	M€	514.15	479.86	481.96	566.97	512.90	515.00	331.45	295.92	384.27	328.96	245.62	246.47	245.91	255.88	2.20	5.00

Table 51: The equivalant annual cost and break-even price for bunkering hydrogen for different business cases

		Business case									
	Unit	**1A**	**1B**	**1C**	**1D**	**1E**	**1F**	**2A**	**2B**	**2C**	**2D**
Equivalant annual cost (excl. bought H_2)	M€/yr	97.89	92.31	96.10	103.02	96.49	100.28	66.15	56.45	71.27	59.61
Break-even bunkering price for H_2	€/kg	11.56	11.07	11.40	12.57	12.00	12.33	8.78	7.93	9.79	8.77

Table 52: The equivalant annual cost and break-even price for bunkering battery electric containers and methanol for different business cases

		Business case					
	Unit	**3A**	**3B**	**3C**	**3D**	**4A**	**4B**
Equivalant annual cost (excl. bought energy carrier)	M€/yr	34.58	34.67	34.62	53.82	1.10	1.98
Break-even bunkering price for electricity	€/MWh	251.94	252.44	252.16	358.72	-	-
Break-even bunkering price for methanol	€/l	-	-	-	-	0.56	0.57

Appendix VII: Cost model excel sheet

The attached file “cost_model_inland_navigation_bunkeringinfra_RWS_RD.xlsx” is the cost model which provided the calculations for this research.