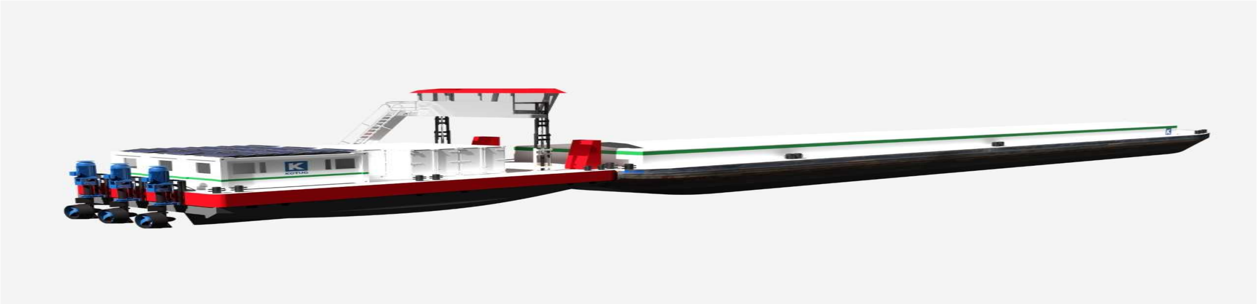
Potential of the E-Pusher as Transport Mode in the Dutch Carbon Capture and Storage System

M.E.J. (Maikel) Blom

MSc Thesis



Delft University of Technology

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Potential of the E-Pusher as Transport Mode in the Dutch Carbon Capture and Storage System

by

M.E.J. Blom

to obtain the degree of **Master of Science Transport, Infrastructure & Logistics**
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PREFACE

Dear reader,

Writing this thesis allowed me to fulfil the final step towards obtaining a degree in Master of Science Transport, Infrastructure, and Logistics at the TU Delft. The final step of this thesis is executed in collaboration with KOTUG, a company ahead in maritime excellence.

First of all, I would like to show my gratitude to my committee from the TU Delft. Jaap and Wouter, I would like to thank you both for supervising me from an academic perspective through this research. Also, the chair of my thesis contributed on a similar basis. Therefore, I would like to thank you, Dingena.

Second, I would like to thank KOTUG for providing me with the opportunity to execute this graduation project and the opportunity to experience the atmosphere at the office. Especially, I am grateful to Patrick and Vibhanshu for their supervision from KOTUG. Next to that, I should thank Myron and Martijn who let me feel very comfortable when I joined the company. Also, I highly appreciate the input from the company's perspective in my thesis, provided by my direct colleagues Almar, Bas and Koos. Of course, I feel also obliged to thank my other colleagues from the office in Rotterdam for the amazing experience.

Third, to all the representatives of companies that were willing to deliver input for my thesis I would like to show my gratitude, thank you all. In particular, Leen Schipper from SHIFT should receive a high appreciation for providing input to modelling part of barges within CCS within this thesis.

Lastly, I am in debt to my friends and family for their support throughout my student career in the last couple of years. My mother and grandparents should be recognised as the biggest supporters of achieving my Master's Degree.

By summarising all my gratitude to the ones that helped me to the point where I am now, I hope that you will enjoy reading this thesis.

Blom, M.E.J. (4671260)

Culemborg, December 2022

Lists of Abbreviations and Relevant Companies

Abbreviation or Stakeholder	**Definition**
Aramis	Dutch CCS Project
CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CE Delft	Research Organisation in Energy and Transport
Continuous flow	Transport Flow continuously over time
CO2next	Liquid CO2 Terminal in the Port of Rotterdam
Discontinuous flow	Transport flow in discrete time steps
DTL	Dangerous Toxic Load
ETS	European Trading Scheme
General Barge	Considered as Barge that is Diesel-driven
IMO	International Maritime Organization
KOTUG	Maritime Company and Commissioner of this Thesis
LCA	Life-Cycle-Assessment
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MARIN	Maritime Research Institute
MTPA	Mega Ton per Annumm
Northern Lights	Norwegian CCS Project
NRW	North Rhine Westphalia
OPEX	Operational Expenditures
Port of Rotterdam	Global recognised Port and Potential CCS hub
Porthos	Dutch CCS Project
QRA	Quantitative Risk Assessment
SIMIE	Systems Engineering Process
SHIFT	Zero-Emission Battery Service Provider
SLOT	Indication of DTL
SLOD	Indication of the significant Likelihood of Death
SOG	Speed over Ground
STW	Speed through Water
TNO	Research Organisation
TTW	Tank-to-Wheel
WTT	Well-to-Tank
WTW	Well-to-Wheel
ZEP	Zero Emissions Platform

EXECUTIVE SUMMARY

KOTUG International is a towage company operating globally in the maritime industry. A new innovative push-boat concept that is introduced by KOTUG to the transportation market is the E-Pusher. This modular and scalable electric pusher tug is powered by swappable energy containers and operates zero-emission, Tank-to-Wheel (TTW). KOTUG is discovering new transportation markets for the E-Pusher, such an interesting transportation market might be the onshore transportation market of Carbon Capture and Storage (CCS).

In the Netherlands, **CCS** is considered a solution to decrease CO2 emissions. The expected contribution of CCS to the decrease of CO2 emissions on a global level is estimated at 30% (Rijksoverheid, 2021). The concept of CCS is that emitted CO2 will be captured, and then transported to collection points where it will be further transported to an offshore location. At this offshore location, the CO2 captured will be injected under the seabed. For the onshore transportation of carbon, several studies compared pipelines and ships for different trajectories. The advantages and disadvantages of both transportation modes in CCS are widely identified. An example, for instance, is that longer shipping distances have an impact on the real amount of CO2 captured and stored. Because of the fuel combustion and boil-off of ships. A **knowledge gap** is found in the literature review, concerning the potential of zero-emission vessels in CCS chains, and what the impact is to the emitted CO2 during transportation if zero-emission vessels are used.

Objective and Method Following the pursuit of climate targets by implementing CCS chains and the ambition of KOTUG to contribute to sustainable transportation provided by the E-Pusher, it is attempted to fill in the identified knowledge gap in this thesis. The goal of this thesis is to have a scientific contribution to the field of determining the potential of electrified ship transport modes in CCS chains. The findings are also expected to form insightful advice for KOTUG about the potential role of the E-Pusher in CCS chains.

Pursuing this goal is by approaching an answer to the main research question, which is formulated as follows: *"Which requirements and conditions determine to what extent the E-Pusher could be a suitable inland transport mode for liquid carbon within the transport stage of a CCS chain, and what are the emission effects to the CCS transportation chain if the E-Pusher is deployed?"*. Several sub-questions are formulated and answered sequentially to approach the answer to the main question. The Systems Engineering approach, in particular following the SIMIE process whereby each sign indicates a process step, led to a clear strategic approach for executing this research. After the knowledge gap, research objectives, and research scope were defined and the literature review was performed to determine KPIs and CCS transportation requirements, it was possible to model the system. Thereafter, the model was simulated for different scenarios, more specific for realistic CCS trajectories, in Microsoft Excel. The obtained results were validated and a sensitivity analysis

was performed, before conclusions and recommendations could be given.

Scope This research is in several ways bounded by the scope. First, the cargo assumed is liquid CO2 because liquefaction of CO2 is required for carbon transportation by ship. Second, regarding transportation, the main focus is orientated to the onshore transportation stage of CCS, see Figure 3. The geographical scope is orientated to the industrial clusters in the Netherlands and the surrounding European region, that can be connected to the Port of Rotterdam. The time dimension is bounded by the coming decades because of the finite amount of storage capacity for CCS.

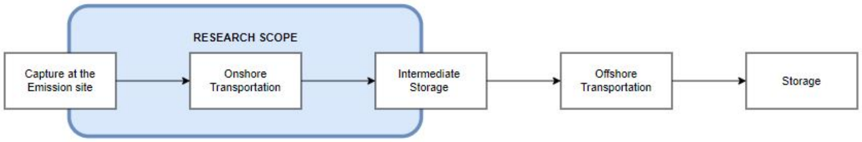

Figure 3: Visual depiction of the scope of this research

KPIs Before modelling the current state, a literature review was performed to define the KPIs for modelling and evaluating a barge transportation network. The existing framework of Konings (2009) is adapted in such a way that it was possible to formulate KPIs that can be considered in this research from a network perspective, whereby both traditional KPIs from operators and shippers are considered as well as a sustainability KPI, which has significant importance nowadays. The KPIs considered are **Operational Impact** and **Sustainability**.

Current state analysis In the current state analysis it was found that the CCS market is developing but not in the implementation stage yet. Demand for CCS from different industrial clusters is observed. Some barriers and drivers in the stakeholder field are influencing the implementation degree of CCS and its infrastructure. Based on the findings in the current state analysis, the network typology in Figure 4 is proposed. Also, a more detailed overview of the E-Pusher is presented in the current state analysis. Thereafter, a model was designed to allow for simulating CO2 transport by different modes. Furthermore, scenarios were generated based on realistic destinations for CO2 capture sites. The scenarios were different from each other with respect to the distance between the emissions site and the Port of Rotterdam. Each scenario is further divided into four configurations allowing an analysis of each considered transport mode. Which were as follows: general barge, truck, pipeline and E-Pusher.

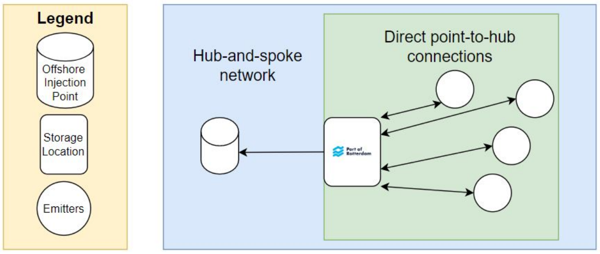

Figure 4: Proposed Network Typology in a Dutch CCS system
Note. Own Figure

Results In the Integrate part of this research, the simulation experiments were executed and the results were obtained. Concerning the costs per ton, the barge performs the best in most scenarios. The difference with the E-Pusher for the costs per ton is not very high. Regarding the emissions, it could be concluded that the E-Pusher has direct savings compared to general barge and truck transport. Two different methods for calculating the emissions were used, namely based on expected fuel consumption and based on the transport performance in tonne-kilometres. The pattern for the barge and truck emissions per ton over the different distances was similar in both methods. But the calculation method based on the tonne-kilometres led to values that were slightly more than one and a half times higher than the method based on the fuel consumption. Figure 5 and Figure 6, present the overall results. More detailed results for each scenario are presented in Chapter 8.

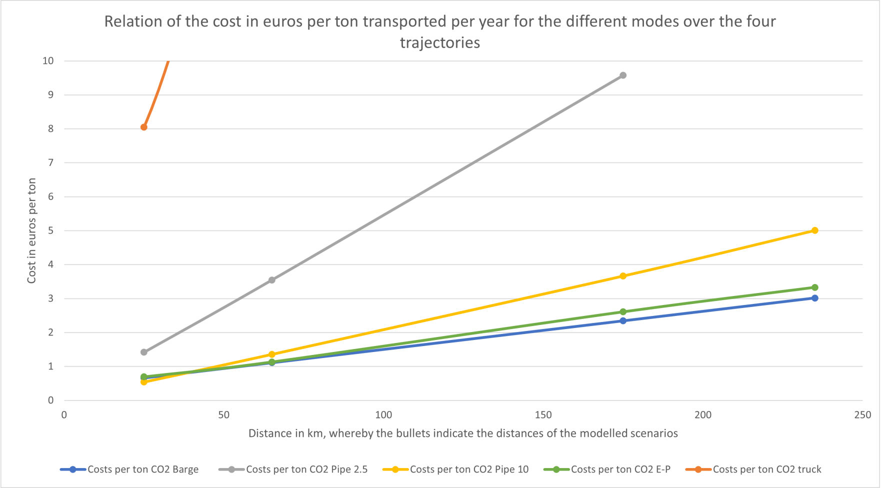

Figure 5: Relation of the cost per ton over the distances

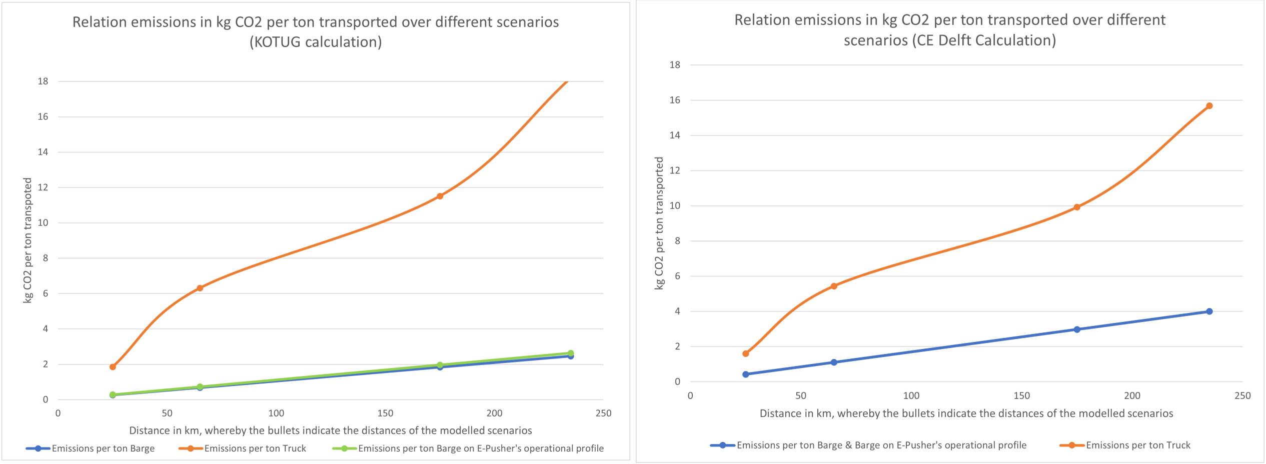

Figure 6: Relations of the Emissions per ton over the different scenarios

Evaluation In the evaluation part, the way modelling and corresponding assumptions were validated. Following the formed discussion bullet points in Chapter 9.1, the fluctuations of several discussed volatile parameters were analysed in the sensitivity analysis. About the robustness of the results for the E-Pusher in CCS, the following can be concluded: A halved CAPEX for a pipeline of 10 MTPA would change the advantageous position of the E-Pusher in the base case results to this pipe for the lowest costs per ton, negatively. In practice, this might be a realistic possibility when an already implemented pipeline will be used. Pricing developments like increased fuel prices or halved electricity prices have a small, but favourable, impact on the E-Pushers position compared to the other modes, regarding the costs per ton. Other, findings about the sensitivity of the results from the base case scenarios are presented in Chapter 9.

Conclusions This thesis has created insights into the potential of a zero-emission push-boat concept in a CCS chain. The observed developments of CCS implementation in itself is an aspect that might danger the possibility to deploy the E-Pusher in CCS. Regarding, the competitive position of the E-Pusher to other transport modes for the considered scenarios and configurations, it can be concluded that mainly the general barge would perform with the lowest costs per ton over all distances, but the E-Pusher is not completely outperformed. Next to that, the direct TTW emissions savings are found for the deployment of the E-Pusher in a CCS chain.

Recommendations for further academic research It is recommended to perform a more in-depth analysis of the specific trajectory characteristics that are not intensively studied in this research. Furthermore, pipeline modelling should be reconsidered by performing the method of Knoope et al. (2015). Also regarding the reporting of emissions in CCS chains, it is recommended, to identify what type of method is the most accurate and suitable to use. Lastly, it is recommended to study the outcomes of this network typology to the outcomes of a similar study for other network typologies.

Recommendations for KOTUG For KOTUG, it is recommended to validate the operational configuration given based on simulation results by performing a thorough analysis of the reliability and robustness of the operational configuration of the E-Pusher. Furthermore, it is recommended to perform a more detailed commercial study to determine the value of CO2 transport and the possibilities and the corresponding value for KOTUG to collaborate with potential allies in a CCS transport network. Lastly, it is recommended to identify the possibilities to design and evaluate a charging infrastructure for electric vessels in CCS chains.

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Part I

STATE OF THE PROBLEM

1 Introduction

In line with the worldwide transition, also Dutch companies are identifying possibilities to reach the global climate goals. One particular temporary solution to decrease CO2 emissions is Carbon Capture and Storage (CCS). CCS consists of different stages, the main stages could be divided into capture, transportation and storage. A company that is identifying their potential rol in CCS is KOTUG. The towage service provider developed the E-Pusher, a zero-emission tug. KOTUG desires to discover the possibilities to deploy the E-Pusher in new transportation markets. In this thesis, the possibility to deploy the E-Pusher in the onshore transportation stage of CCS will be discovered.

1.1 Carbon Capture and Storage

CCS is a way to decrease CO2 emissions and has an expected contribution of a 30% decrease in CO2 emissions on a global level. In the Netherlands, CCS is observed as an essential technology to reach the CO2 reduction goals (Rijksoverheid, 2021). The CO2 value chain within CCS is composed of five main steps. First, the CO2 will be captured at the storage site. Second, CO2 will be transported to a collection point. Third, the CO2 flows will be collected at a location near an offshore pipeline. Then, the collected CO2 will be transported to an offshore location. Finally, the CO2 will be stored under the seabed at the offshore location. To achieve a full-scale CCS deployment, it is required that in all different stages of the value chain efficient and reliable solutions are available (Størset et al., 2018). The development of infrastructure and transport services is therefore of high importance.

1.1.1 Onshore Transportation within the CCS Chain

Multiple transport modes are available for inland transportation of carbon. Generally, pipelines and ships are the most viable solutions to transfer the captured CO2 (Kjärstad et al., 2016; Roussanaly et al., 2013). Pipelines are especially preferred for short distances and a large emission capacity. However, the existing pipeline infrastructure in the Netherlands is not as established as in for example the United States. As a result, ships and vessels are expected to offer higher flexibility on a short-term solution for areas with no existing pipeline infrastructure (Kjärstad et al., 2016). Next to that, ships are more effective and cost-competitive in the case of longer distances and a lower emission capacity. Moreover, the flexibility of ships is also an advantage for temporary storage, regarding the collection of CO2 from sites with intermittent emissions (Ansaloni et al., 2020). Because of this inherent flexibility, shipping can contribute to the scale-up stages of a CCS project (Weihs et al., 2014). Nevertheless, longer shipping distances could increase the CO2 emissions from fuel combustion and boil-off. Consequently, the real amount of CO2 injected and avoided will be reduced over longer transport distances (Weihs et al., 2014). Regarding the costs aspects, the motive to deploy ships or pipelines heavily depends on the distance and quantity transported. In the case of pipelines, costs depend also on the congestion in areas and whether mountains, large rivers, or frozen ground on the route exist. On the other hand, the costs of ship transport depend on the tanker volume and the characteristics of the transhipment systems (IPPC, 2005).

1.1.2 Transport Processes and Liquefaction

Another main difference between ship or pipeline transport is the process of the handled carbon. Transportation of CO2 by ship requires liquefaction for economical reasons (Seo et al., 2016). Regarding the entire CCS chain, it is important to consider the transportation in addition to the liquefaction and injection processes. The advantage of pipeline transportation is that a limited number of steps are involved in the transport process. As Figure 7 indicates, pipeline transport requires only compression, transfer through an onshore pipeline, pumping and transfer through an offshore pipeline to the destination. In contrast, ship transportation of CO2 requires multiple steps (Geske et al., 2015).

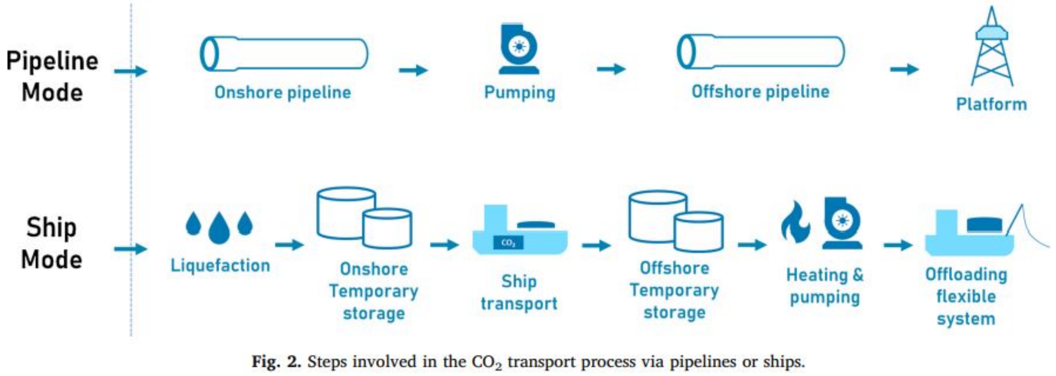


Fig. 2. Steps involved in the CO_2 transport process via pipelines or ships.

Figure 7: Comparison between pipelines and ship of the involved steps of CO2 transport
Note. From Ansaloni et al. (2020)

Seo et al. (2016), illustrated a general ship-based CCS chain, with the following steps, see Figure 8. First, the CO2 is captured at the emission point. Second, it is transported to a liquefaction system. Third, the captured CO2 is liquified in the liquefaction system and then temporarily stored in storage tanks. Thereafter, the liquified CO2 is loaded and transported by a CO2 carrier to an intermediate terminal. At the intermediate terminal, the liquefied CO2 is compressed by a pumping system where it finally will be transported by a pipeline to the offshore destination. The steps within the Aramis project, a Dutch CCS project, correspond with the proposed ship-based CCS chain from Seo et al. (2016).

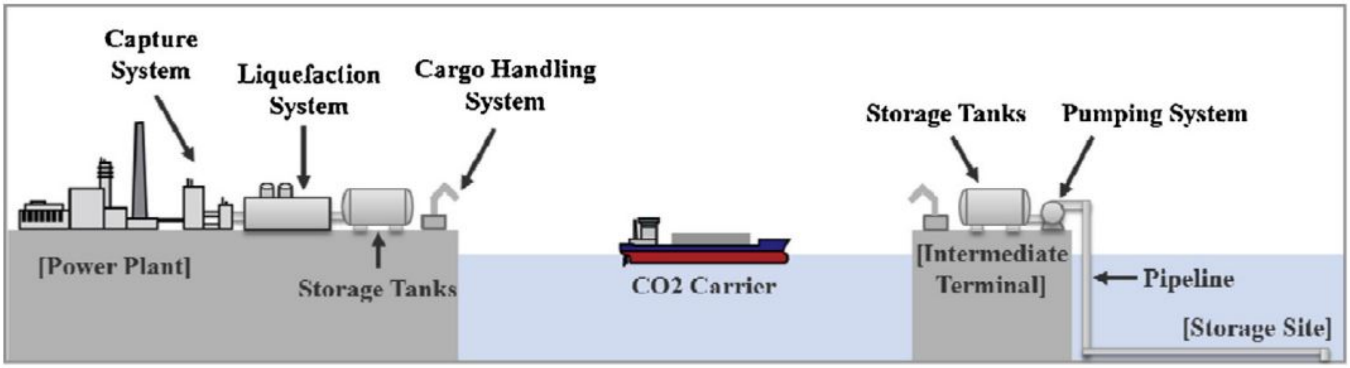


Figure 8: Proposed ship-based CCS chain
Note. From Seo et al. (2016)

As mentioned, the two main possibilities to transport carbon from industrial emitters to collection points are pipelines and ships. The characteristics and suitability of both transport modes are widely researched. Kjärstad et al. (2016) stated that pipelines are more suitable for short distances and a large emission capacity, whereas ships are more effective over longer distances and lower emission capacities. Next to that, the transport processes are different for both modes. Pipeline transport consists of limited process steps compared with ship transport where liquefaction of CO2 is required because of economical reasons (Seo et al., 2016). An aspect that is not explored yet is the impact on the CO2 emissions if conventional ships or pipelines are replaced by electrified ships. The knowledge gap that can be derived is the effect of using electrified ships as a transport mode in CCS on the decrease in CO2 emissions. The main goal of this thesis is to fill in the identified knowledge gap and thus determine to what extent electrified ship transport can play a role in the onshore transportation stage of CCS. By pursuing this goal, it is assumed that this thesis will contribute to the existing literature about electrified ships and transport modes within CCS. Furthermore, it is expected that insightful advice about the potential of the E-Pusher as a transport mode within CCS systems to KOTUG will be provided.

1.2 Research Questions

Derived from the knowledge gap, the following research question is formulated:

"Which requirements and conditions determine to what extent the E-Pusher could be a suitable inland transport mode for liquid carbon within the transport stage of a CCS chain, and what are the emission effects to the CCS transportation chain if the E-Pusher is deployed?"

The approach to answering the main research question is by answering the following sub-questions:

1. How are barge transport networks designed and what are the performance indicators to evaluate a barge transport network?

2. What are the technical, operational and economical requirements for onshore transport of carbon dioxide by ship?

3. What is the current state of carbon capture (utilisation) and storage inland shipping chain?
   (a) What are the possible areas to transport liquefied CO2 from and to, and what are the corresponding volumes and time-span?
   (b) How can a CCS transportation network be modelled?
   (c) In what way are stakeholders supporting or blocking certain objectives and requirements of carbon transport within CCS?

4. What are the technical-operational characteristics of the E-Pusher?

5. What is the impact of deploying the E-Pusher in the transportation stage of CCS, to the outcomes of the KPIs and trade-off between the KPIs of other possible transport modes?

6. Which potential developments have an impact related to the feasibility of deploying the E-Pusher in CCS?

1.3 Research Scope

The E-Pusher is a ship transport mode. Because liquefaction of carbon is required to transport CO2 in CCS systems by ship, the considered cargo is mainly liquefied CO2. Next to that, CCS consist of different stages. The stage that will be focused on in this research is the onshore transportation stage of CO2, see Figure 9. The scope will be orientated to industrial clusters in the Netherlands and the surrounding European region that can be connected to the carbon collection point in the Port of Rotterdam. The possibilities to deploy the E-Pusher will be analysed for short-term (coming years) and long-term. The time dimension of this investigation will be bounded by 2050, since the underlying motives for decarbonization lies in the climate goals till 2050 and a finite amount of storage space of CO2 is available.

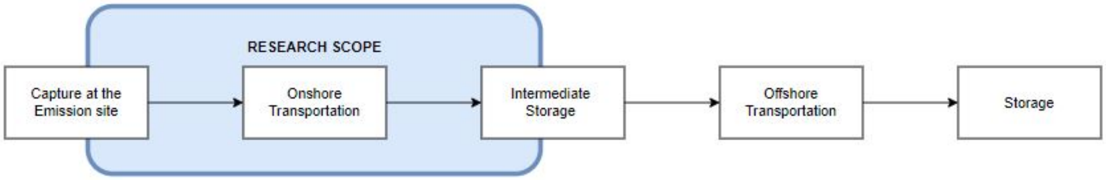


Figure 9: Visual depiction of the scope of this research

1.4 Report Outline

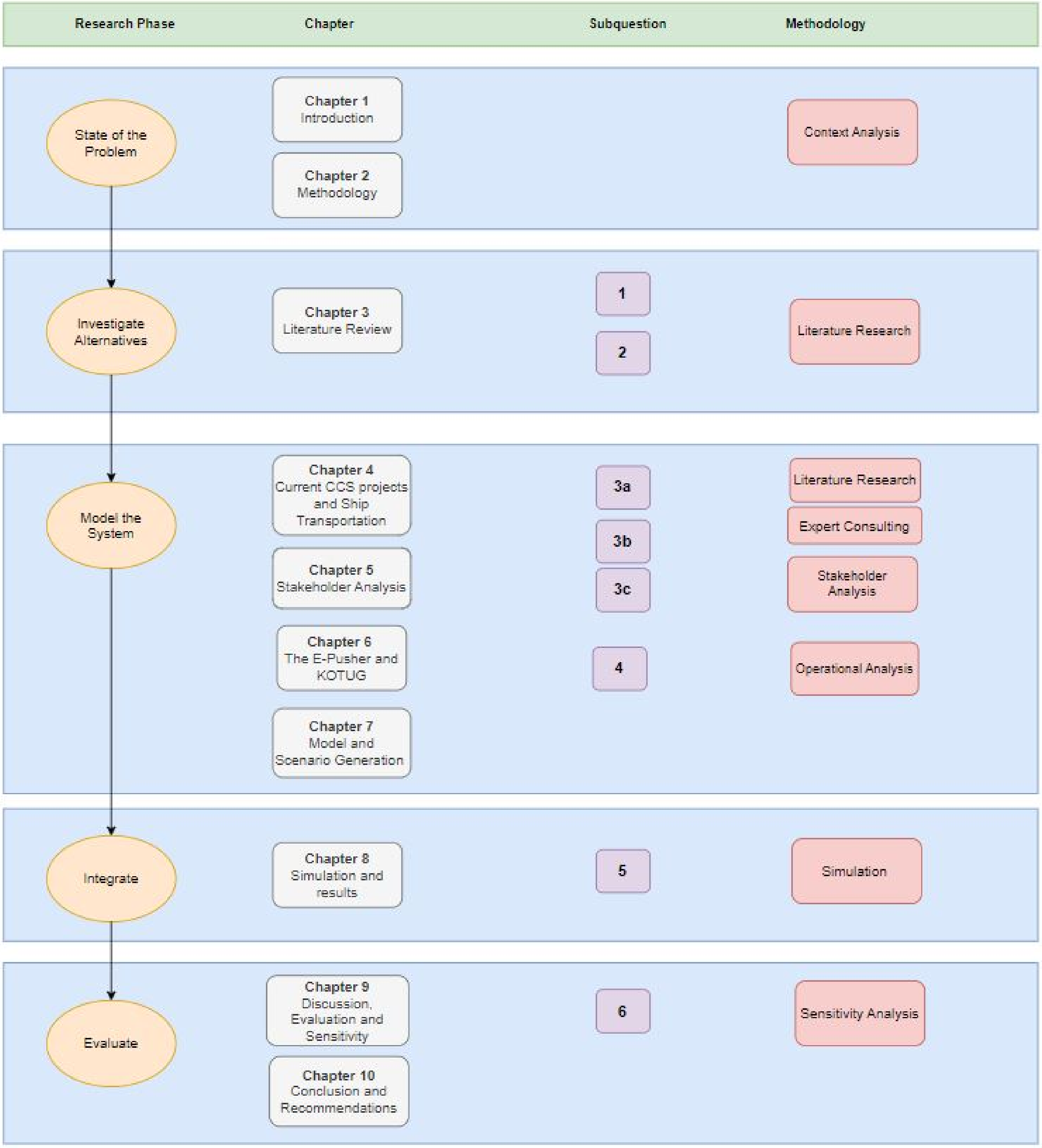


Figure 10: SIMIE Approach in this Research

2 Research Methodology

In the previous section, the goal of this research was outlined. Namely, to determine to what extent electrified ship transport can play a role in the onshore transportation stage of CCS. From a higher perspective, CCS can be considered the main system. Whereby, electrified ship transport can be considered a sub-system of CCS. Both CCS and electrified ship transport has some pilots running but are not (widely) implemented yet. Therefore, it is required to start from scratch, determine a current state and make possible designs whereby CCS and electrifies ship transport are integrated. This methodology section, reveals which methods are contributing to designing possible system concepts and approaching an answer to the main question. First, in Section 2.1, the motives for the Systems Engineering approach and SIMILAR process are explained. Second, in Section 2.2, the underlying methods will be elaborated. Finally, in Section 2.3, the role of the analyst in this research will be outlined.

2.1 Systems Engineering Approach

Systems Engineering can be defined in different ways and the approach is also applied to different areas. One way to define systems engineering concerning designing new systems is the following: "an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem" (INCOSE, 2014). Systems Engineering can be executed in different methods. In this research, an adapted version of the SIMILAR process will be used as a method. The SIMILAR process can be seen as an iterative process roadmap, where each sign indicates a part of the process. The sequence of the processes is as follows: State of the problem, Investigate the alternatives, Model the System, Integrate, Launch the System, and Re-evaluate. Because the expected time horizon for launching a certain system is far beyond the execution time of this research, the last steps are combined. Therefore, in this research, an adapted version of the SIMILAR process will be used, namely, SIMIE. Below, each process step of the SIMIE process dedicated to this research will be outlined.

1. **State of the Problem:** In this stage, the purpose of a project is identified, and realistic and measurable goals are set. The customer needs should be identified to make a clear definition of the project and formulate an appropriate strategy to use in the research. In this research, also the knowledge gap is found in this part.

2. **Investigate:** In this research, the knowledge gap is already found in the previous stage. But the remaining part of the literature review is performed in this stage. Also, methodologies for designing and evaluating barge transport networks will be discovered. Furthermore, the transportation requirements are investigated in this stage.

3. **Model the System:** In this phase of the research, the goal is to describe the current state. It is essential to describe the current state clearly and well understood before making confident choices about future state configurations. This process will therefore be used to describe the current state of CCS within the defined scope. Also, the E-Pusher will be analysed from an operational perspective. To fulfil this process literature review, expert consulting, stakeholder analysis and an operational analysis will take place. After the mentioned processes, the final goal of this stage is to incorporate the sourced information from the previous steps to create a selected design or selected designs. The impact of deploying the E-Pusher in a certain reference case will be evaluated in the next stage. A model is needed to approach a representation of the system and its environment. The model should allow for building different scenarios and experimenting with the different scenarios. Required for modelling the scenarios is that assumptions and requirements must be defined on forehand. Associated with literature findings and consultation with experts the assumptions and requirements will form the fundamentals for modelling scenarios.

4. **Integrate:** In this stage, the simulation of the build model and generated scenarios will take place to obtain the results. The results will be presented in this stage. The interpretation of the results will take place in the next stage.

5. **Evaluate:** The last phase of the SIMIE approach is the evaluation phase. The model, scenarios and outcomes will be validated to guarantee that the conclusions and recommendations are of academic and practical importance. In this research, it is not possible to test a scenario design for a real-world application because the time-span of this project is shorter than the duration to implement a new system or transport service. Therefore, verification and validation will be limited to reviewing the designs by experts. The goal is to fill in the identified knowledge gap and thus give an answer to the main research question. Then, the research will be finished with a conclusion and recommendation section. In the conclusion, all the sub-questions and the main answer will be answered. In the recommendations, both the recommendations for further academic research and practical recommendations for KOTUG will be provided.

2.2 Underlying Methods

CCS is considered the fundamental system in this research. First, it will be attempted to discover all requirements for CCS. Second, it will be attempted to discover the stakeholder dynamics behind the CCS system in this research. To discover these aspects literature review, expert consulting and a combined stakeholder analysis will be used as underlying methods. Literature research provides a significant amount of useful information in defining the system outline. However, it is not guaranteed that consensus between researchers is found, and represents viable information for successful CCS implementation. To validate the information found in the literature research, expert consulting will be executed. Experts that will be approached include industrial emitters, governmental authorities, research institutions and CCS project members. The expert consulting will be executed by taking interviews. The interviews will be semi-structured organised. This allows the interviewer to adjust the sequence of the questions and add new questions based on the contexts of the interviewed person's responses (Zhang and Wildemuth, 2009). A stakeholder analysis is useful in this context because it allows for analysing the involvement, means, and possible actions to take for each stakeholder in detail (Enserink et al., 2010). Because, different stakeholders can have different requirements, which should be considered in generating designs, it is important to perform the stakeholder analysis. The module of Enserink et al. (2010) will be the guideline to perform the stakeholder analysis. This module is chosen because it provides a well-structured basis to analyse multi-stakeholder problems. Therefore, regarding the fact that CCS implementation requires support and initiatives from different types of stakeholders this module fits best. Another underlying method is the operational analysis of the E-Pusher. This analysis contributes by defining the operational design and the technical specification of the E-Pusher.

2.3 Role of the Researcher

As mentioned in Section 2.2, the module of Enserink et al. (2010) will be used to perform the stakeholder analysis. Following from this module, it is important to position the role of the analyst because the analyst has to make deliberate choices in the role he wants to play and consequently the skills and methods he wants to use. The extended framework of Mayer et al. (2004) combines different analytical activities and styles in a hexagon. The hexagons' activities and styles covered in this research, see Figure 11 will be explained below.

The purpose of this research is two-folded. First, the effects of electric barge transport in a CCS chain on the CO2 emissions in CCS stages will be investigated for the TU Delft. Second, the potential of the E-Pusher as a transport mode to apply for onshore carbon transport will be explored for KOTUG. The analysis for the TU Delft will be performed through a rational style. The rational style assumes that the system is empirically knowable and measurable. Scientific methods will be used to generate insights into causes, effects, nature, and scale of matters of the system. The corresponding clusters are *research and analysis* and *design and recommend.* The *research and analysis* activities will focus on the gathering of data. Research questions will be formed about the facts, causes and effects, and calls because of that for scientific research. In case sufficient data and information are gathered, it is possible to apply the *design and recommend* activities to come up with solutions and recommendations. Mostly, the recommendations consist of a set of generated alternative strategies and corresponding tactics. Regarding, the analysis for KOTUG, a client advice style will be the perspective of the research. This style assumes that the systems' environment is chaotic with numerous players and corresponding interests and strategies. As a result, it is essential to gain insight into the various interests, objectives and means of the involved actors. Similarly as for the TU Delft research, also for KOTUG, one cluster is *design and recommend.* Furthermore, *advise strategically* is the other involved cluster. In this style, the client will be advised about the most effective strategy to deploy for reaching certain goals given certain conditions. It can be concluded that there is some overlap between the two-folded purposes of this research. The most logical sequence is to first analyse the whole system from a scientific perspective and then give strategic advice to the client. The sequence and overlap are illustrated in Figure 11.

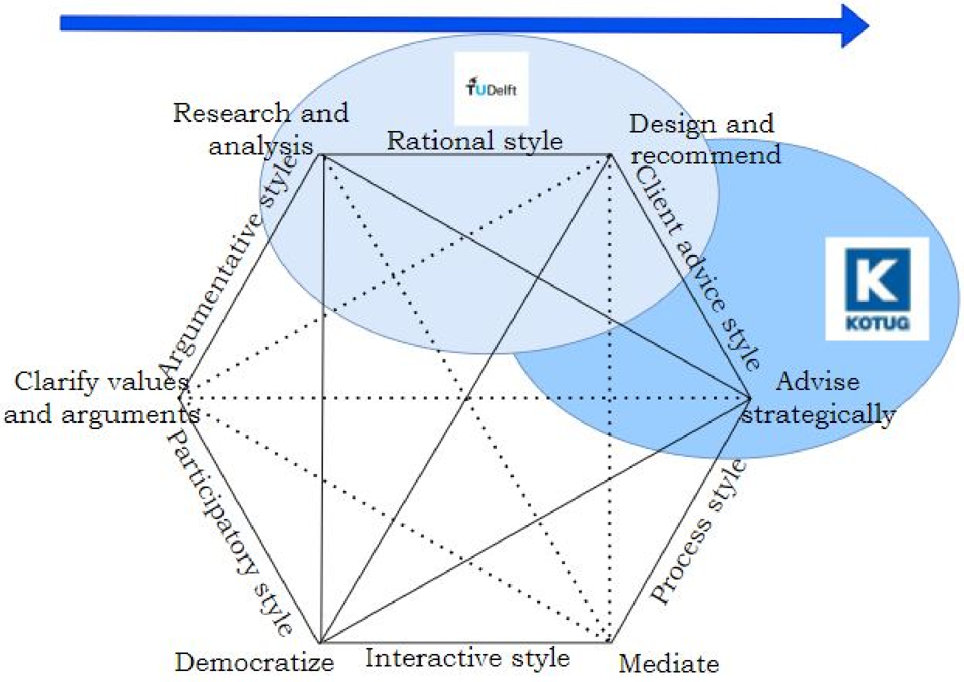


Figure 11: Analytical clusters and styles of this research
Note. Adapted From Mayer et al. (2004)

Part II

Investigate Alternatives

3 Literature Review

In this chapter, the main part of the literature review will be performed. The literature about transport networks for barges, in general, will be reviewed in Section 3.1 and Section 3.2. Furthermore, literature about the technical and economical conditions to transport CO2 by ship or barge will be reviewed in Section 3.3 . This chapter ends in Section 3.4, with the answers to the two sub-questions, formulated as:

1. *How are barge transport networks designed and what are the performance indicators to evaluate a barge transport network?*
2. *What are the technical, operational and economical requirements for onshore transport of carbon dioxide by ship?*

3.1 General Design of Inland Transport Networks

Barge transport plays an important role in the transportation of freight in countries with a large transport capacity and high quality inland waterways. Mainly, the freight in a barge network system is transported between seaports and the hinterland. Countries with an extensive network, have the ideal opportunity to carry cargo between the seaports and the hinterland. Examples of cargo that is suitable to transport by barge are liquid cargo, dry bulk, and containers (Wiegmans and Konings, 2007). To develop and assess barge transport networks the framework from Konings (2009) could be used. Konings (2009), developed a framework for an intermodal barge network design, see Figure 12. This framework is suitable to use in this thesis because the whole network design of CCS can be considered as an intermodal transport network. Inland transport operations can be performed by pipeline, barge, truck or rail, while offshore transport can be pipeline or ship only. Because in this thesis the main focus of the transport modes is barges, the framework of Konings (2009) is used as starting point.

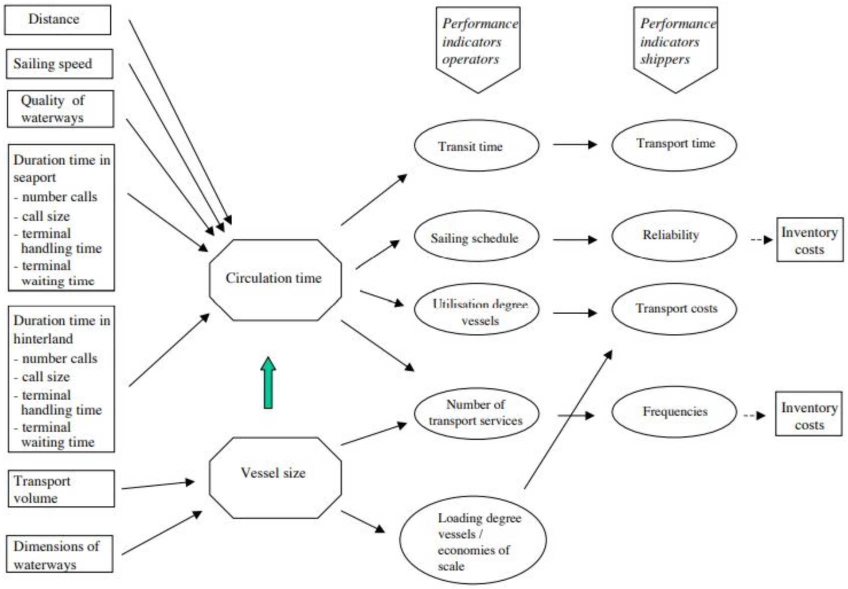


Figure 12: Framework for barge network design
Note. From Konings (2009)

The performance of the barge transport system can be measured by the low-cost operations, which is determined by two major factors, namely the circulation time and the vessel size (scale of operation). Both factors should be optimised to achieve low-cost levels. Noticed should be that both factors impact the costs differently. The circulation time has an impact on the cost per unit load by reducing the fixed cost share, while the scale of operation can result in lower cost per unit load because of the reduced fixed and variable costs per unit. Both the scale of operation and the circulation time of a vessel are related to specific quality features. These features are frequency and transit time of services. Next to that, for barge operators, it is important to consider the trade-off costs, quality features and relevant external conditions. Dimensions and the quality of the waterways are typical external factors (Konings, 2009). The focus on sustainability within performance measures was at the time this framework was published, in 2009, not so present as it is nowadays. Therefore, an adapted framework is built where sustainability is considered. Different types of propulsion are expected to have an opportunity in the future. Therefore, this factor is included in the framework. Because in this research the focus is on electrification, also the establishment of infrastructure allowing for electrified ship transport is included as a major factor. The KPIs in this research will be the sustainability impact measured in the number of emissions per year and the operational impact. This last KPI can be further specified in the transport time, reliability, transport costs, and frequencies, which were already present as performance indicators in the base framework. Because, the focus in this research is more orientated to the trade-off between the operational impact and emissions in case electrified propelled barges are implemented, the green arrow is replaced by a general arrow. The highlighted relation between vessel size and circulation time is expected to capture less attention in this research. Derived from the adaptations and the explanation above, it can be concluded that in this research the perspective is more orientated from a network point of view instead of the operators' or shippers' perspective. Therefore, the KPIs are categorised as *Performance indicators network perspective*. It should be noted that the framework and the adapted version of the framework both are conceptual models. At all times, it can be discussed whether an arrow should be present or not for each existing or non-existing relation. The adapted version of the framework is presented in Figure 13, below.

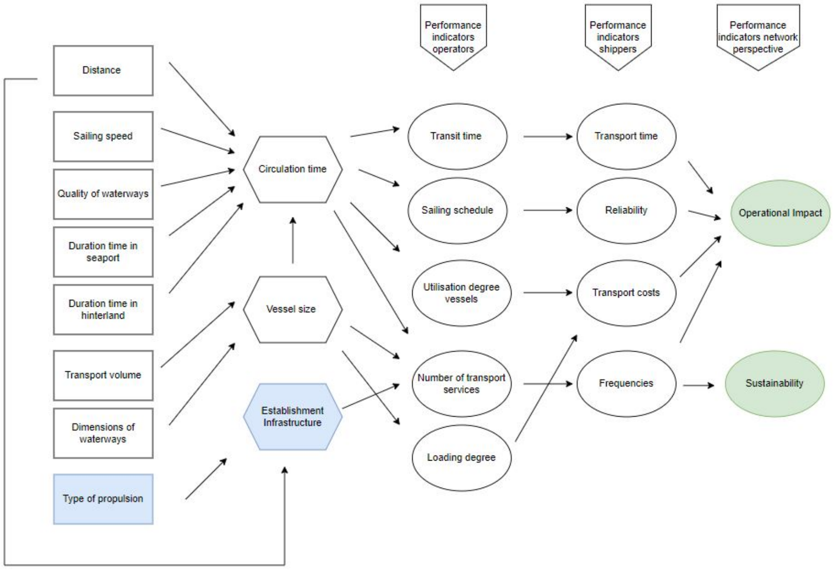


Figure 13: Adapted framework for barge network design
Note. Own figure, adapted from Konings (2009)

The KPIs considered assessing the performance of a barge network are derived from the adapted framework. In this research, the operational impact and sustainability will be the KPIs to assess. In Table 1, the KPIs are presented with corresponding units. It is chosen to combine the frequency and transport time in the operational capacity of a vessel. This KPI will be expressed in cycles/year. Associated with the number of cycles/year it is also important to express the amount of volume transported. The KPI will be thus, transported volume expressed in ton/year, or a more commonly used unit in CCS chains is Mega Ton per Annum (MTPA). The costs KPI will be divided into OPEX and CAPEX. Both will be expressed in euros/year. The sustainability KPI, emissions, will be expressed in kg CO2 emitted / year. Reliability expresses how reliable a system is. This KPI will not be calculated quantitatively. The reliability aspects for each transport mode will be covered in literature research and thus it will not be considered in a model later in the research. In the validation phase, reliability aspects can be considered during the evaluation of the results.

Table 1: KPIs to asses the E-Pushers' potential

KPI	**Indicator**		**Unit**
Operational Impact	*Operational capacity*		Cycles/year
	Transported volume		MTPA
	Costs	*OPEX*	Euros / year
		CAPEX	Euros / year
Sustainability	*Emissions CO2*		kg CO2 / year

The KPIs presented above can be differently modelled and calculated. For the first KPI, operational capacity, it is important to distinguish two types of speeds used. The type of speed used can influence the sailing time, where the cycle time, and thus the operational capacity depends on. Yang et al. (2020), found in the literature that presenting the sailing time is uniformly calculated by the waterway distance divided by the sailing speed. However, a differentiation should be made between speed over water (STW) and speed over ground (SOG). STW is the speed relative to the water, while SOG is the speed relative to the earth. For calculating the sailing time, it is required to use the SOG to estimate the actual sailing time. Choosing one of the two concepts has not only an impact on the first KPI, operational capacity, but also on the second KPI, annual transported volume. The annual transported volume depends on the number of cycles that can be made, which is dependent on the cycle time.

As mentioned, the costs will be expressed as total costs in euro per year. This is the sum of CAPEX and OPEX. For the CAPEX, the average depreciation per year and the average interest per year will be calculated based on several financial factors, such as purchase price, and residual value. The OPEX will be calculated based on annual crew costs, operational depreciation per year, fuel costs and overhead.

Determining one of the two mentioned speeds has also an influence on the last KPI, emissions. In the case of estimations for the ships' required propulsion, the STW should be used to obtain correct calculations of fuel consumption. Another concept that is important to outline when calculating the emissions is which phase of the Life-Cycle-Assessment (LCA) is considered. Three main types of emissions can be distinguished in the LCA. The first one is called Well-to-Tank (WTT). The second one is called Tank-to-Wheel (TTW). The last one is called Well-to-Wheel (WTW). CE Delft (2021), provided the following definitions for the three types of emissions:

- **WTT:** *'Emissions arising during extraction, transport and refinery of fuels or during electric power generation and transmission. In the case of biofuels, TTW emissions are taken to be zero, In line with IPCC protocols, and net supply-chain emissions cited under WTT.'*
- **TTW:** *'Emissions arising from fuel combustion during vehicle use. Under the heading 'TTW*

emissions' the tables in this report also include PMw emissions occurring during vehicle use.'

- **WTW:** *'The sum total of WTT and TTW emissions.'*

Below, in Figure 14, the different concepts of emissions are explained in a graphical overview.

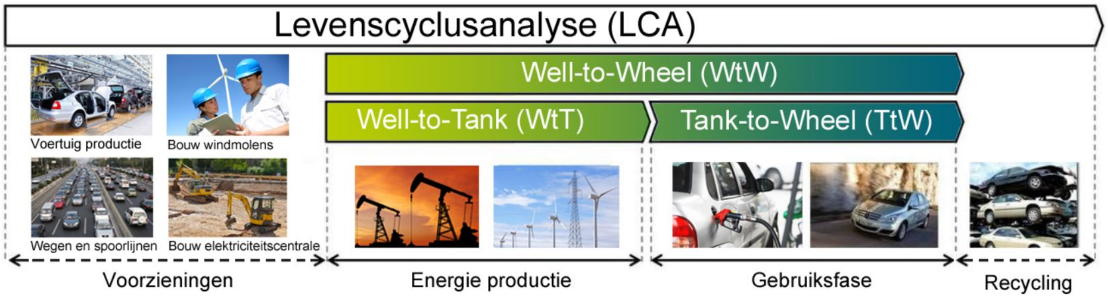


Figure 14: Life-Cycle-Assessment Emissions, in Dutch
Note. Retrieved from CO2 Emissiefactoren (nd)

3.2 Network typology

Different types of networks exist for freight bundling. Kreutzberger (2008), distinguished four main basic principles, as can be seen in Figure 15. Network A is a point-to-point network, whereby freight is directly shipped from origin to destination. Network B is a collection/distribution network whereby a central collections hub receives the freight from different companies and then ships the freight to a distribution hub. This network is mainly used in international networks. Network C is similar to B, however, only one centralised hub is used to receive, sort, and distribute the freight. Network D is a line network, whereby each company has its transport network. In barge transport, mainly networks A and D are used. This is because in ports the freight is already bundled so mainly direct transports are preferred. Extra bundling concepts are considered unnecessary. The line network has still the advantage that it enables a barge to fulfil multiple intermediate stops, allowing for more cargo to transport. The disadvantage is that multiple stops increase the transit time. A typical example of a line network is the barge transport on the Rhine River (Kreutzberger, 2008).

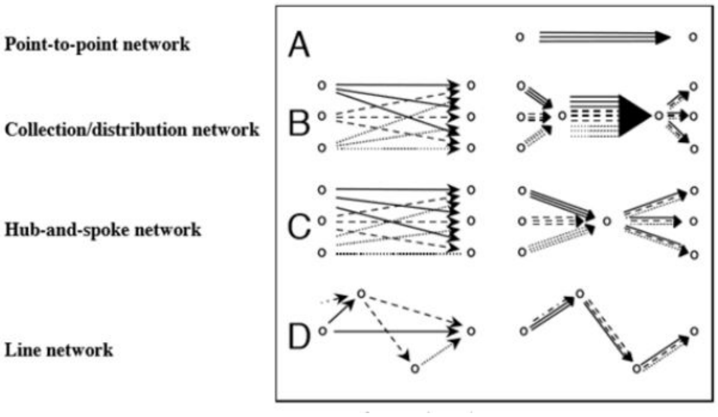


Figure 15: Four basic principles of freight bundling
Note. From Kreutzberger (2008)

3.3 Onshore transport requirements within CCS

Before CO2 can be transported it should be captured at the emission site. The main approaches to capture CO2 will be outlined briefly, in Section 3.3.1. Then, the transport requirements for CO2 will be presented, in Section 3.3.2. Also, the safety measures and regulations to transport CO2 will be discussed in 3.3.3.

3.3.1 Carbon Capture Approaches

Three main approaches capturing carbon from fossil fuels exist, namely, post-combustion, oxy-fuel combustion and oxy-fuel combustion. The methods are schematically illustrated in Figure 16

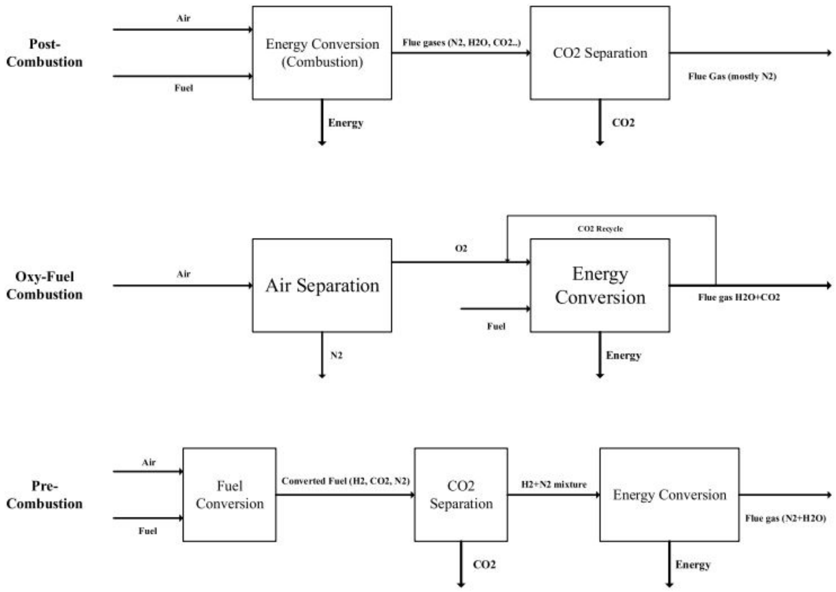


Figure 16: Carbon capture techniques

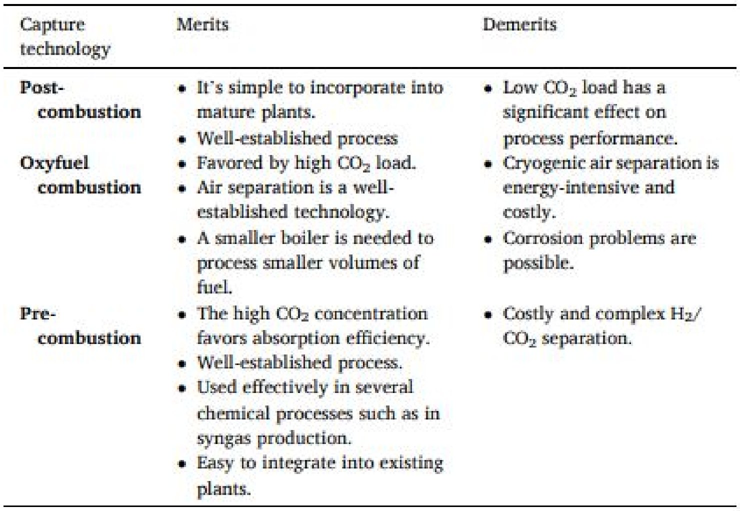
Note. From Olabi et al. (2022)

In the post-combustion capture method, carbon emissions are captured from combustion flue gases. In many cases, a solvent is used to capture the CO2 from the flue gases. However, other methods also exist, such as cryogenic carbon capture. Because, in this thesis, the focus is more orientated to the potential transport possibilities of CCS, the different sub-methods for post-combustion will not be discussed in detail.

In the oxyfuel combustion method, the combustion air is replaced by pure oxygen. The result is a flue gas where nitrogen is removed and mostly carbon and water remain (Rubin, 2008). Cooling and compressing the flue gas is the most convenient way to remove the water and obtain pure CO2.

In the pre-combustion capture method, the present carbon is the fuel that will be separated from the hydrogen before the combustion takes place. This is done by deploying a sequence of chemical reactions. As a result, carbon can be obtained before the combustion, while hydrogen is used for the combustion.

As mentioned, the applications of the three capture methods will not be discussed in detail. However, Figure 17 is presented to give an overview of the advantages and disadvantages of each method.



Capture technology	Merits	Demerits
Post-combustion	• It's simple to incorporate into mature plants. • Well-established process	• Low CO_2 load has a significant effect on process performance.
Oxyfuel combustion	• Favored by high CO_2 load. • Air separation is a well-established technology. • A smaller boiler is needed to process smaller volumes of fuel.	• Cryogenic air separation is energy-intensive and costly. • Corrosion problems are possible.
Pre-combustion	• The high CO_2 concentration favors absorption efficiency. • Well-established process. • Used effectively in several chemical processes such as in syngas production. • Easy to integrate into existing plants.	• Costly and complex H_2/CO_2 separation.

Figure 17: Merits and demerits of carbon capture technologies

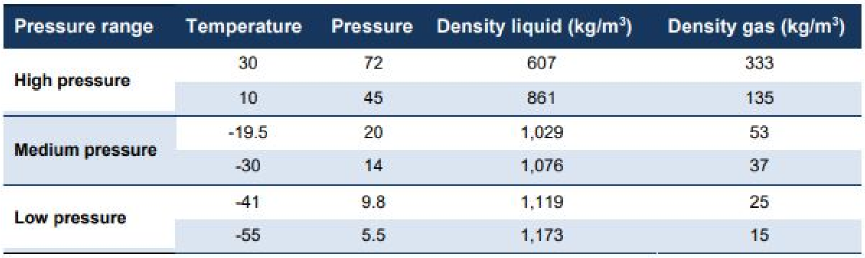
Note. From Leung et al. (2014)

3.3.2 Transport Requirements of CO2

Next to the transport steps in providing carbon transport in a CCS system, it is also important to consider the load of the carrier. Buirma (2020), identified two main options, namely fixed tanks or containerization. Fixed tanks are technically feasible and can meet safety requirements. Similarly, as designing LNG tanks also CO2 tanks can be built. However, the disadvantage is that tanks should be incorporated into the design from the beginning, otherwise vessels should be retrofitted. Therefore, it is also not very scalable. In contrast, containers are in terms of compatibility, flexibility and scalability suitable to use for transporting liquefied CO2. The containers are widely available on the market and could also be used for the transport of other liquids, such as liquid oxygen. Furthermore, the containers can also be used for other transport modes such as rail or truck. An example of a standardised CO2 container tank that could be used is depicted in Figure 18.

Figure 18: 20ft CO2 tank
Note. From COMTECSWISS (nd)

For liquefied CO2, the density depends on the liquefaction pressure. The pressure types could be distinguished into three types, namely, low, medium and large pressure. The characteristics of these three are depicted in Figure 19.



Pressure range	Temperature	Pressure	Density liquid (kg/m^3)	Density gas (kg/m^3)
High pressure	30	72	607	333
	10	45	861	135
Medium pressure	-19.5	20	1,029	53
	-30	14	1,076	37
Low pressure	-41	9.8	1,119	25
	-55	5.5	1,173	15

Figure 19: Density of CO2 liquid and gas at different pressures and temperatures considered for shipping transport
Note. From Elementenergy (2018)

Seo et al. (2016), experimented with different liquefaction pressures to determine the optimal liquefaction pressure. The results showed that an increase in liquefaction pressure leads to a decrease in the costs of the liquefaction and pumping system. However, the costs of the storage tanks and the CO2 carrier increased. In Figure 20, the CO2 phase diagram is depicted. The triple point of CO2 is at 5.18 bar given a temperature of -56.6°C. This indicates that under atmospheric pressure, CO2 only exists as a gas or solid. Consequently, storing CO2 as a liquid requires a pressure of at least 5.18 bar. In CCS, the CO2 is transported in large volumes, relatively. As a result, ship transport conditions close to the triple points (7 to 9 bar and - 55 °C) are desired to guarantee high fluid densities and lower overall transport costs (Xu et al., 2018). However, the safety risk of shipping low-pressure CO2 near the triple point, is that formation of hydrates or dry ice can occur. Because of these solid substances, clogging and pressurization of pipes, valves and vessels can appear (Equinor, 2019). Therefore, it is required to store the CO2 well above its triple point.

Seo et al. (2016), found that given a cost-effective perspective, an optimal liquefaction pressure is at 15 bar (-27○C). ZEP and CCSA (2022), surveyed multiple ship owners and designers to determine the primary transport conditions for liquid CO2 applied nowadays. The ship size also influences the preference of shippers and designers to determine the transport conditions. Vessels smaller than 10,000 m3, operate at approximately 15 bar and -30°C, mainly. While vessels larger than 10,000 m3 operate at lower pressure around 7 bar, at a temperature of -50°C. The smaller vessels and corresponding transport conditions are expected in the inland shipping chains of CCS. As presented in Figure 18, containers could be used to transport the CO2 by rail or truck. Becattini et al. (2022), stated that the CO2 is transported in such containers under liquid form at a pressure of 22 bar and a temperature of -35. The unit capacity in this configuration is 20t CO2 (COMTECSWISS, nd).

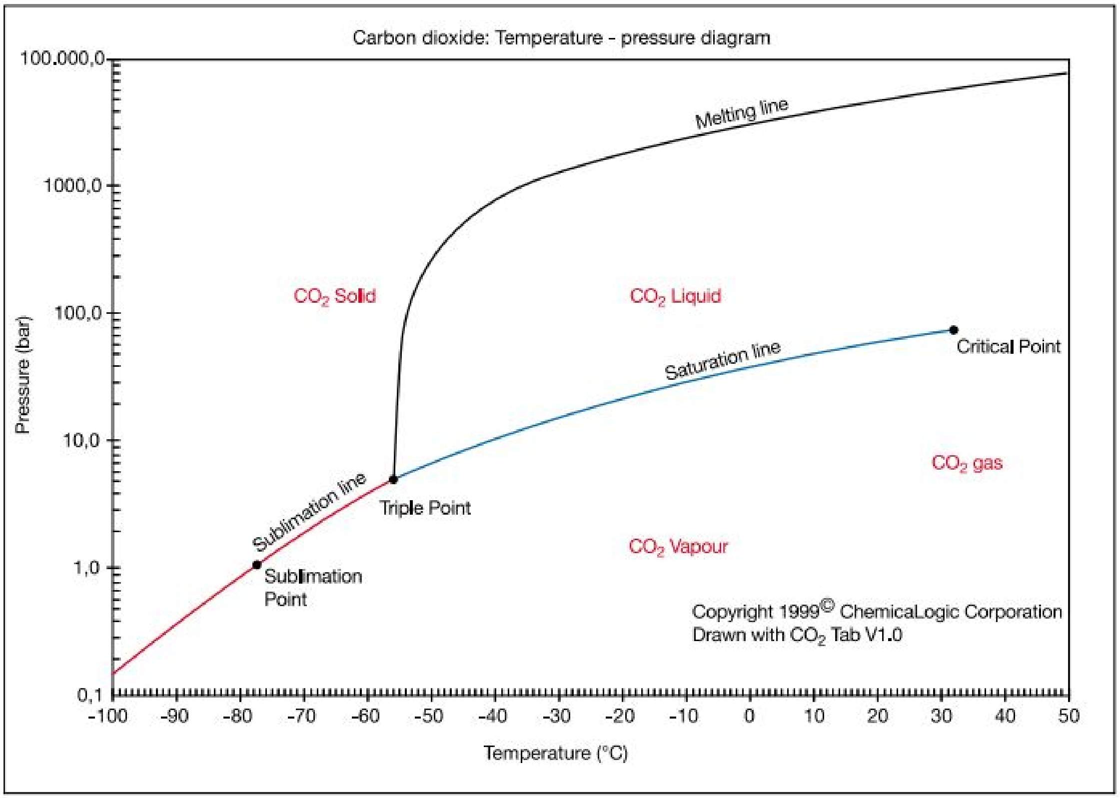


Figure 20: Phase Diagram

Note. From Metz et al. (2005)

3.3.3 Transport Safety of CO2

Global CCS Institute (ndb), claims that CO2 transport by pipelines and ships poses no higher risk than the transport of hydrocarbons, for instance, natural gas and oil. The related risks are abrupt or gradual leakage of CO2. International standards are developed to promote safe and efficient CO2 operations. In populated areas, it is required for pipeline transport of CO2 to pay attention to the design factors, such as overpressure protection and leak detection. No indication exists that pipeline transport for carbon dioxide is more challenging than hydrocarbon through pipelines (Metz et al., 2005). Regarding the safety aspects of ship systems, different ways a ship system can fail exist. Fire is not a high risk for CO2 tankers. Nevertheless, an asphyxiation risk appears when a collision causes a ruptured tank. ZEP and CCSA (2022) stated that CO2 has high threats to human life at concentrations of only 15 % in air. This is because of the toxicological impact on the human body during inhaling. In Figure 21, the dangerous toxic load limits for CO2 are outlined in a graph. The specified level of toxicities is SLOT and SLOD. SLOT indicates the dangerous toxic load (DTL) and SLOD indicates the significant likelihood of death. The methods are performed by extrapolating toxicity data and then determining the dangerous toxic load.

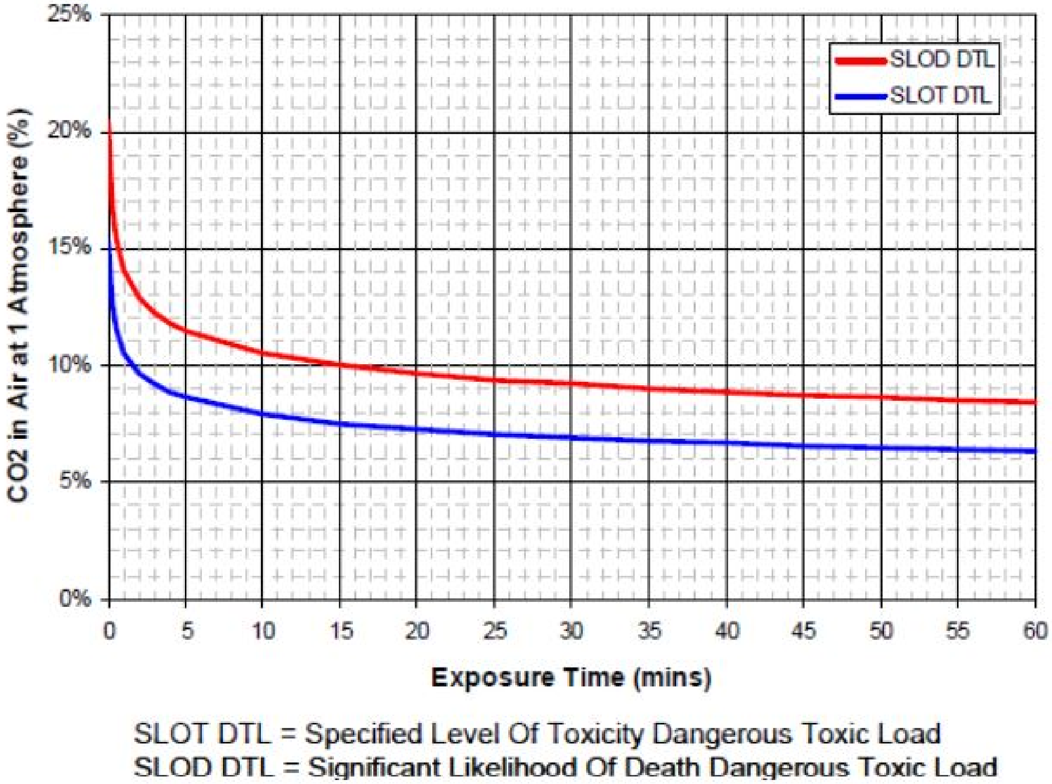


Figure 21: Dangerous Toxic Load Limits for CO2
Note. From DNV (nd)

High standards of construction and operation, nowadays already applied to LPG, could minimize this risk for CO2 transport by ships. The Act on the transport of hazardous substances, in Dutch called 'Wet vervoer gevaarlijke stoffen', is formulated to provide rules on the transport of hazardous substances, including CO2 (Boekholt, 2014). Ter Mors (2011), executed a Quantitative Risk Assessment (QRA) of CO2 shipping in infrastructure in the port area of Rotterdam. Ter Mors (2011), found that the CO2 shipping risk stays within the acceptance levels according to the Dutch criteria. This means that for international transport it should be investigated whether international CO2 transport is possible. Currently, the Dutch government is investigating establishing bilateral agreements (Ministry of Economic Affairs and Climate Policy, 2021).

3.4 Conclusion

A potential barge network design within the CCS chain is not implemented yet. Before, making scenarios for a barge network design, it is essential to explore the general approach to design and evaluate barge network designs. Therefore, the answer to the first sub-question contributes to this thesis by providing a fundamental basis to assess the performance of a potential barge network design in CCS.

The answer to the second sub-question in this chapter contributes to the aim of this thesis by providing an overview of the requirements to transport carbon in an inland barge transport network.

In this chapter, the two following sub-questions are answered:

1. *How are barge transport networks designed and what are the performance indicators to evaluate a barge transport network?*

   A barge network design and assessment could be considered from different perspectives. Konings (2009), developed a framework to design and assess a barge network from operators' and shippers' perspectives. In the period the framework was developed, no attention was given to sustainability. Therefore, in this thesis, an adapted version of the framework of Konings (2009) is developed. The advantage of the adapted framework is that it allows the researcher of this thesis to consider important KPIs already present in the base framework of Konings (2009) and also sustainability as a KPI, which is nowadays an important KPI to consider. The new layer of KPIs is categorised as KPIs from a network perspective, whereby the following KPIs are considered in this research: The **KPI Operational Impact** can be divided into operational capacity expressed in cycles per year, transported volume expressed in MTPA, and transportation costs in euros per year. Whereby, the costs can be further divided into CAPEX and OPEX. The other **KPI Sustainability**, can be defined by the CO2 emissions expressed in kg CO2 per year.

2. *What are the technical, operational and economical requirements for onshore transport of carbon dioxide by ship?*

   Required for CO2 transport by ship is liquefaction. The two main identified options to transport the CO2 by ships are fixed tanks and containers. The liquefied CO2 can be transported under different pressures and temperatures. From an economical point of view, it is desired to transport the CO2 under pressure and temperature conditions close to the triple point. Regarding a safety point of view, the transport conditions close to the triple point increase the risks of hydrate formation or dry ice. As a result, it is needed to store the CO2 well above its triple point during transportation. In literature, it is found, that an optimal liquefaction pressure is 15 bar under a temperature of -27 degrees. This pressure and temperature are the most cost-effective under the condition that safety risks are limited. Also found in the literature, is that the ship size can influence the preference of shippers to determine the optimal transport conditions.

Part III

Model the System

4 Current CCS Projects and Ship Transportation

In this chapter, the current state of the system to be modelled will be analysed and determined. Sub-questions 3a and 3b will be answered to describe a part of the current state. The CCS projects that are operating currently or soon will be discussed, concerning the shipping conditions of these projects.

The sub-question was formulated as follows:

3. What is the current state of carbon capture (utilisation) and storage inland shipping chain?
    (a) What are the possible areas to transport liquefied CO2 from and to, and what are the corresponding volumes and time-span?
    (b) How can a CCS transportation network be modelled?
    (c) In what way are stakeholders supporting or blocking certain objectives and requirements of carbon transport within CCS?

4.1 Current CCS Projects

- **Northern Lights:** The first discussed project is the Northern Lights project. This is a commercial project whereby CO2 is cross-border transported between several countries. From the connected CCS initiatives the CO2 will be captured and then transported by ship to the destination, a Norwegian storage site (Reyes et al., 2021). Regarding the transport of the captured CO2 in the Northern Lights Project, an adapted ship design for liquefied petroleum gas (LPG) is used. This is done by adding a carriage system for liquefied CO2 and adding insulation for maintaining temperatures to keep the CO2 as a liquid. Under the conditions of 15 barg and equilibrium temperature, the liquid CO2 will be transported. The cargo size of the ships is 7500m3, allowing transport of approximately 7500 tons of CO2. The length of the ship is 130m, where LNG is used as fuel. Dalian Shipbuilding is the ship builder and announced that the ships will be ready for delivery by mid-2024 (Northern Lights, 2021). As mentioned above, Northern Lights will use LNG as a primary fuel for ship transport. Comparing LNG to other fuels, it can be concluded that LNG has a lower environmental footprint. Yet, should other alternatives as means of propulsion be investigated and developed for further minimizing the environmental footprint. One of the alternatives that is being investigated is the use of batteries (Reyes et al., 2021).

- **Aramis:** The Dutch project Aramis focuses on the establishment of a new infrastructure for CO2 transport from the capture onshore to the storage offshore. Aramis is collaborating with two other projects to supply CO2. The first one is CO2next, which is a collaboration for the development of a terminal for receiving and supplying liquefied CO2 by ships. CO2next and Aramis are in respect of the supply of CO2 both dependent on the decisions that will be made by other industrial clusters, in particular the emitters. Currently, it is not certain how and when the CO2 will be supplied from these industrial clusters, especially abroad (Ministry of Economic Affairs and Climate Policy, 2021). The second project is Porthos, for a compressor station and the transport of CO2 from the Port of Rotterdam to the offshore location (Rijksoverheid voor Ondernemend Nederland, 2022). However, the transport mode involves an offshore pipeline thus no ship transport is provided in this project.

- **Carbon Collectors:** Carbon Collectors is a Dutch commercial project offering a service for the collection of captured CO2 and the transport of CO2 from industrial clusters near the North Sea to the depleted offshore gas fields. Transport conditions for the liquefied CO2 are expected to be 40 bar and 5 degrees Celsius. The transport capacity is estimated at 5500m3, corresponding with approximately 4700 tons of CO2. A tug-barge combination will be deployed, whereby the barge has a length of 130 m and the tug-barge combination has a length of 150m (Reyes et al., 2021). The expected distances of the shipping routes are estimated between 100km up to 250km (Carbon Collectors, nd). Carbon collectors assume that the best option for barge transport is in case the emitter is not located near an existing or planned CO2 pipeline.

4.2 CCS Network Typology

As mentioned in the previous chapters, one of the barriers to a full-scale CCS implementation is that a business case is lacking for industrial emitters to consider the application of CCS. A solution to overcome this problem is clustering, in which CCS infrastructure is shared resulting in reduced costs for companies. Global CCS Institute (2016) compared a point-to-point network to a hub clustering network in the CCS value chains. Where in a point-to-point network the individual industrial emitters are directly connected to the storage facilities, in a hub clustering network, the industrial facilities share the CCS infrastructure and knowledge. Consequently, the costs will be reduced for the involved companies in comparison with companies with an individual approach. A cluster is a centralised network of smaller emitters. A cluster consists of several hubs, the hubs will be the central collection or distribution points for CO2. The first advantage of hub and cluster networks is reducing costs. Second, it decreases the risks for new CCS projects. Third, it removes the interdependency between the size of individual emitters and their investment decisions. Nevertheless, a hub cluster network has also some disadvantages. More complexity and coordination are required for shared infrastructure. Therefore, for individual participants that want to scale up fast, a hub clustering network might be less attractive. Bellona Germany (2019) showed that a system where a barge transport CO2 from A to B provides flexibility in the first five or ten years. Also, Kreutzberger (2008) stated that a point-to-point network or a line network is mainly used in barge transport systems because in the ports the freight is already bundled. In Figure 22, the assumed network typology for the analysed CCS system is presented. In the blue box, the general value chain of

CCS is proposed as a hub-and-clustering network. While for the onshore transportation system of CCS, a centralised hub will be the receiving point for liquid CO2. However, the emitters will be directly connected to this hub, without intermediate hubs. Thus, if the scope is limited to the onshore transportation phase, the connections from the hub to the emitters can be considered point-to-point. This is depicted in the green box.

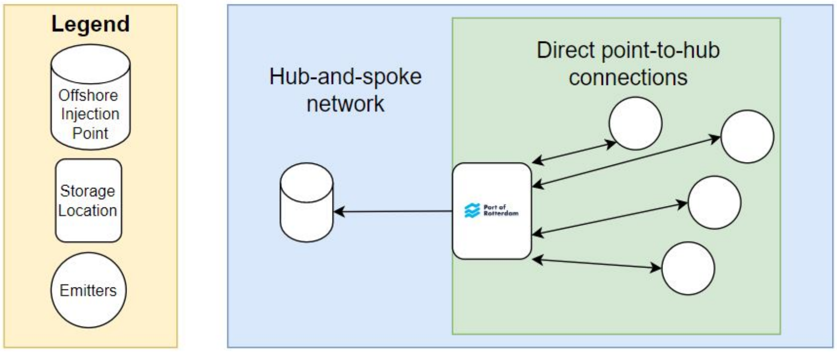


Figure 22: Proposed Network Typology in a Dutch CCS system
Note. Own Figure

4.3 Potential Storage Capacity and Supply

The capacity to store CO2 offshore in depleted gas fields is estimated at 17 Giga ton CO2 (Ministry of Economic Affairs and Climate Policy, 2021). Aramis expects to supply 5 Mton CO2 on annual basis in the first phase of the project (2026). Although the exact amount of supplied CO2 after 2026 is not certain, it is expected that towards 2030 an increase to 10 Mton will be annually supplied. In this phase, the supply from other origins, in particular abroad, will be considered. Towards 2035 Aramis expects a wider implementation of the transport and storage network with an annual supply of 20 Mton (Ministry of Economic Affairs and Climate Policy, 2021). A possible design of this CO2 supply is illustrated in Figure 23. As a result of the increased CO2 supply, extra ship movements, pipelines and storage locations are expected. Aramis tends to use a combination of the Porthos pipeline and the use of inland ships from other parts of the Netherlands to supply the CO2.

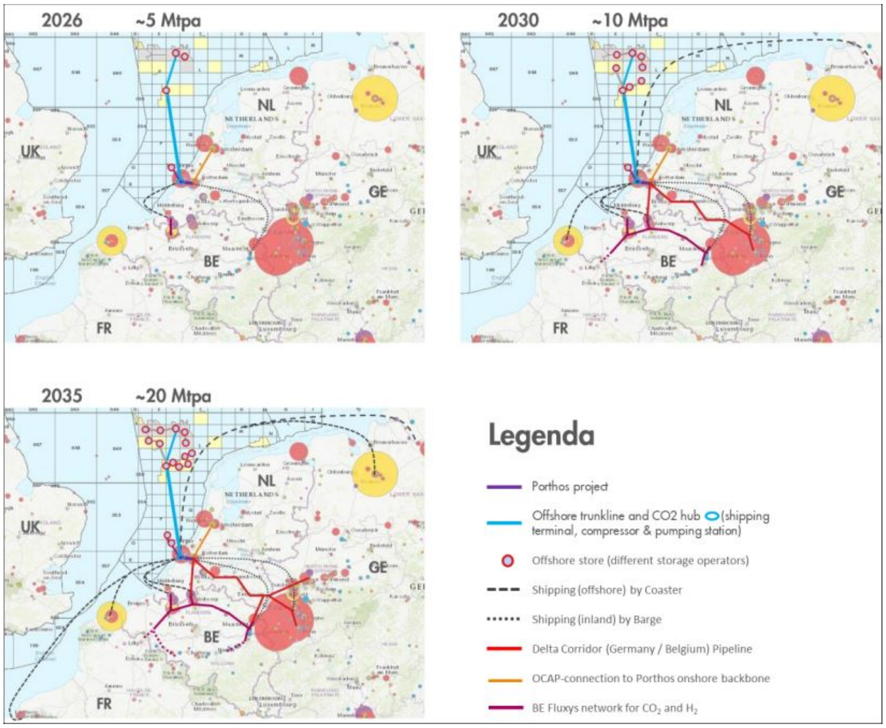
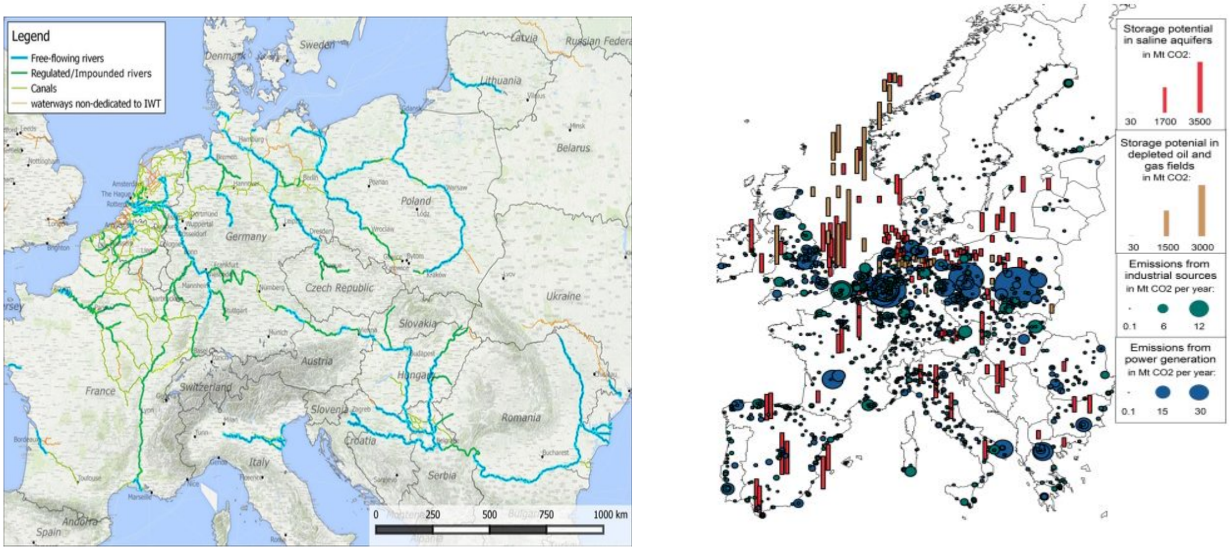


Figure 23: Possible design of CO2 supply
Note. From Ministry of Economic Affairs and Climate Policy (2021)

A new terminal should be established to collect and supply the CO2 by ship. This will be realised by CO2next. The new terminal should allow the loading of the liquefied CO2 supplied by ships. Furthermore, the terminal should be able to store the liquefied CO2 in tanks and thereafter pressurize the CO2. Pressurization is required to transport the CO2 to the depleted gas fields. Next to that, the terminal is also supposed to allow the export of liquefied CO2 for CCU purposes. The location to assign to the terminal is under investigation. A possibility is to extend the Yukonhaven in Rotterdam, which is in use to tranship LNG currently. CO2next expects a liquefied CO2 supply between 3.5 to 7.0 MTPA in the first phase of the Aramis project. For the later phases, no expectations are made by CO2next, because because of uncertainties in how the CCS market will develop (Ministry of Economic Affairs and Climate Policy, 2021).

4.4 Potential Capture Area Emitters

ZEP and CCSA (2022), identified that large amounts of CO2 has the possibility to be transported by barges. This is because the emission and storage cites are closely located near the major European waterways. Below in Figure 24, a map of the major European waterways and a map of the major European emissions sites and potential storage cites are depicted.



(a) Map of the major European Waterways

Note. From ZEP and CCSA (2022)

(b) Map of major European emission sites and potential storage sites

Note. From ZEP and CCSA (2022)

Figure 24: Emission and storage cites are near the waterways

Figure 24b, illustrates the major emitters in Europe. A blue circle means an electricity generation source, while a green circle illustrates industrial sources. Red bars show potential aquifer stores and orange bars represent depleted gas and/or oil fields. The conclusion that can be made which is important for this research is that the emission sources are not equally distributed throughout the North Sea Region. In the Rhine area are the largest emission sources located. Because the Rhine area is connected to the Dutch waterway system, it is interesting to further analyse to potential in this area. An industry expert of the Bellona Group in Germany stated that it is interesting to connect the North Rhine Westphalia (NRW) to the ongoing CCS project in surrounding countries. Instead of using internal German CO2 storage or a highly expensive CO2 pipeline, the EU waterways offer a great opportunity in facilitating flexible CO2 transport. He presented an example of a CO2 route, whereby the CO2 is transported from a source within the NRW region to a facility in Duisburg. The facility operates as a transhipment port or temporary storage. Thereafter, the CO2 can be transported by barges to the storage facility in Rotterdam (Bellona Germany, 2019). This opportunity is next to other opportunities for connection hubs visualised in Figure 25.

Figure 25: Connecting ongoing and potential projects
Note. From Bellona Germany (2019)

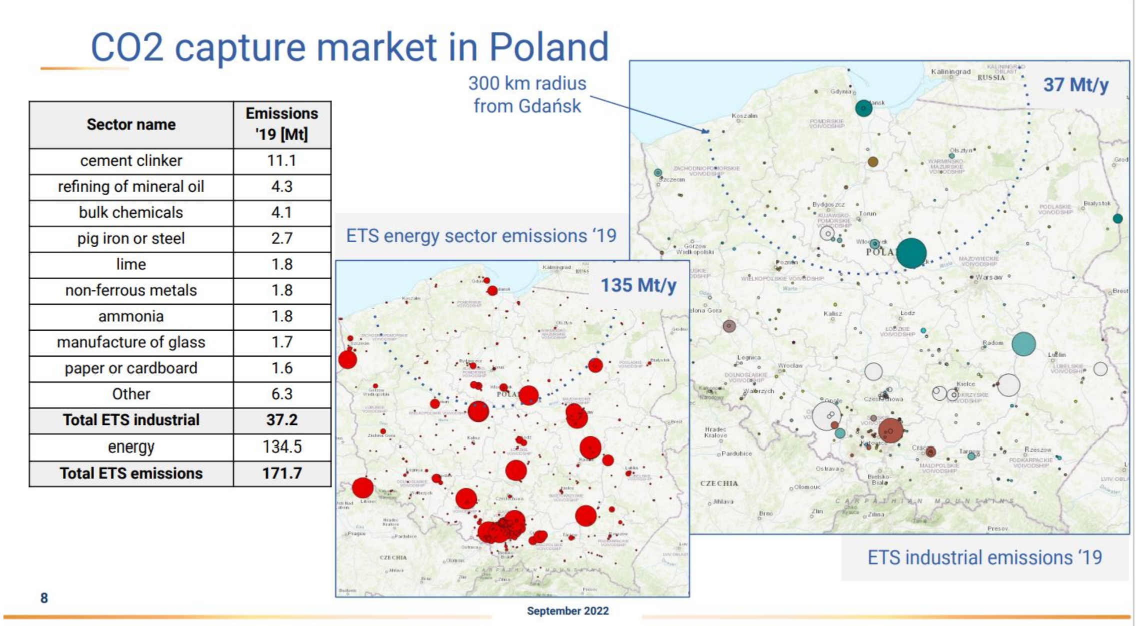
Next to the NRW region, also the Chemelot cluster might be connected to the Porthos project, as can be seen in Figure 25. In the strategy paper of Chemelot, it is stated that CO2 transport by barge is considered a temporary transport mode. Chemelot stated they need to invest in facilities to liquefy the CO2 for ship transport. A requisite from Chemelot is the transport of CO2 by barge counts within the ETS system (Chemelot, 2021). Next to that, a pipeline to transport the CO2 is preferred by Chemelot. In case of pipeline transport is not feasible for Chemelot it is required that barges will operate for the longer term because of the high investment costs, subsidy requisites and long-term contracts. The expected supply estimation of CO2 from Chemelot is depicted in Figure 26.

	2020	2025	>2028	2050
Chemelotsite	-	ca. 0,5 Mton[6]	ca. 0,8 Mton	p.m.

Figure 26: Estimation supply of CO2 by Chemelot
Note. From Chemelot (2021)

Besides the proposed hub for handling liquified CO2 in Rotterdam, also plans exist for building an extra CO2 hub in Eemshaven in the Netherlands and CO2 hubs in other countries within Europe.

In the UK, The Port of Immingham is assigned to a development plan for a new CO2 terminal (Mandra, 2022). In Germany, a terminal for the import and export of CO2 is planned to be built. The terminal will be located in Wilhelmshaven (Hanke, 2022). A similar terminal is expected in Gdansk, Poland (Air Liquide Poland, 2022). As can be seen from Figure 27, also in Poland a huge potential for a network typology that is similar to the Porthos network exists.



CO2 capture market in Poland

Sector name	Emissions '19 [Mt]
cement clinker	11.1
refining of mineral oil	4.3
bulk chemicals	4.1
pig iron or steel	2.7
lime	1.8
non-ferrous metals	1.8
ammonia	1.8
manufacture of glass	1.7
paper or cardboard	1.6
Other	6.3
Total ETS industrial	**37.2**
energy	134.5
Total ETS emissions	**171.7**

300 km radius from Gdańsk

ETS energy sector emissions '19

135 Mt/y

37 Mt/y

ETS industrial emissions '19

8

September 2022

Figure 27: Potential CCS market in Poland connected to Hub Gdansk

Note. From Air Liquide Poland (2022)

4.5 Other Purposes for Captured CO2

In this research, storage of carbon is the most often referred solution to perform with the captured CO2. However, other solutions to use the captured CO2 are also available. These solutions will be discussed below.

A solution with high potential is to put the captured CO2 in depleted oil and gas fields to recover oil and gas from fields that are nearly depleted (Global CCS Institute, nda). However, given the objective to decrease CO2 emissions, it is not desirable to use the captured CO2 for enhanced oil and gas recovery.

Another solution with medium potential is to use the captured CO2 in the food and beverage industry (Koytsoumpa et al., 2018), for instance in horticulture. The captured carbon can be supplied to greenhouses to stimulate the growth of crops. Several pilots in the Netherlands are running with carbon utilisation in horticulture currently. One of them is led by AVR, a Dutch

Waste to Energy company. The pilot started in 2019 and the first 7.500 tons of captured CO2 are supplied to different greenhouses in horticulture. The CO2 is used for the cultivation of different crops, such as flowers, vegetables and plants. Currently, the capture installation, established in Duiven, boasts a capacity of 1MPTA. The goal of AVR is to scale up and capture, reuse, and apply 8 MTPA (AVR, 2019). An interesting development is the capture module from Value Maritime. The capture module captures the CO2 from the exhaust of vessels, thereafter, it uses the CO2 to charge a CO2 battery. The CO2 batteries will be loaded and offloaded for re-use purposes in the horticulture (Prevljak, 2021). The process loop is depicted in Figure 28.

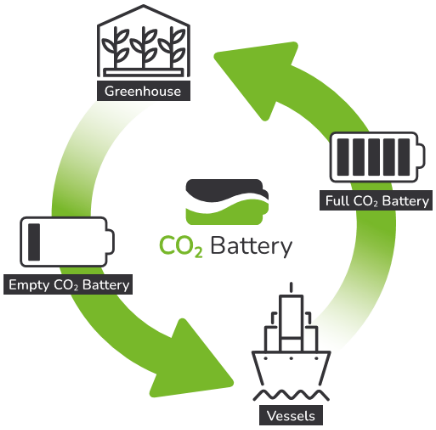


Figure 28: Value Maritime's CO2 solution
Note. From Prevljak (2021)

Furthermore, re-used CO2 has a medium potential in the mineralisation industry (Koytsoumpa et al., 2018). The FUNMIN project is an initiative by the University of Londen and aims to optimise the mineralisation of CO2. This is a process whereby CO2 is chemically reacted with magnesium- and/or calcium-containing minerals. The process is considered a potential CCUS solution to transform CO2 into valuable products for the cement and agricultural sectors. The application has a medium potential because the slow rate of mineral from the solution is challenging for speeding up CO2 utilisation via mineralization as a cost-effective CCUS technology (Di Tommaso, nd). In Figure 29, a visualisation of the possible carbon mineralisation applications is depicted.

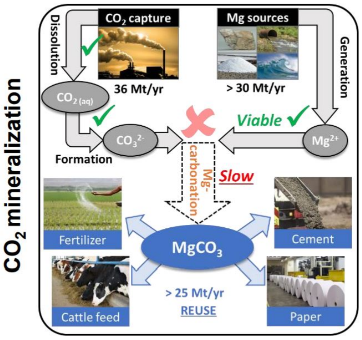
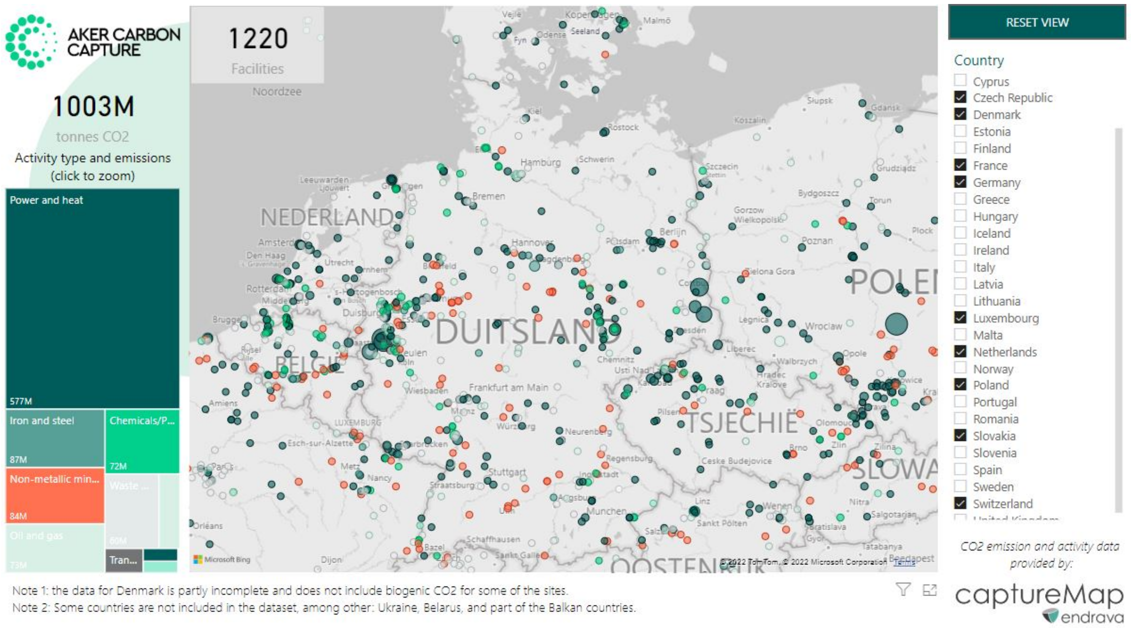


Figure 29: Cambridge Carbon Capture Ltd technology (CO2LC) to store CO2 in mineral form (MgCO3))
Note. From Di Tommaso (2019)

CO2next, the terminal for handling the liquid CO2 in the Port of Rotterdam, stated during interviews, that it is expected that utilisation of CO2 is not feasible in the short-term. The options mentioned above are interesting for a later stage of the implementation of CCS.

4.6 General overview emitters

As can be derived from this chapter, emitted CO2 can be captured for different purposes at different locations. Figure 30, is derived from the Aker Carbon Capture map to provide a general overview of the emission sites in the European region that are closely connected to potential hubs.



Country
☐ Cyprus
☑ Czech Republic
☑ Denmark
☐ Estonia
☐ Finland
☑ France
☑ Germany
☐ Greece
☐ Hungary
☐ Iceland
☐ Ireland
☐ Italy
☐ Latvia
☐ Lithuania
☑ Luxembourg
☐ Malta
☑ Netherlands
☐ Norway
☑ Poland
☐ Portugal
☐ Romania
☑ Slovakia
☐ Slovenia
☐ Spain
☐ Sweden
☑ Switzerland

Note 1: the data for Denmark is partly incomplete and does not include biogenic CO2 for some of the sites.
Note 2: Some countries are not included in the dataset, among other: Ukraine, Belarus, and part of the Balkan countries.

Figure 30: General overview emission sites
Note. From Aker Carbon Capture Map

4.7 Conclusion

In this chapter, the answers were found to the sub-questions 3(a) and 3(b).

3. *What is the current state of carbon capture (utilisation) and storage inland shipping chain?*

   (a) *What are the possible areas to transport liquefied CO2 from and to, and what are the corresponding volumes and time-span?*

   The capacity to store CO2 in depleted gas fields is estimated at 17 Giga ton (Ministry of Economic Affairs and Climate Policy, 2021). Although no full-scale infrastructure is available in the Netherlands, several projects are running to contribute to the upscaling of CCS. The Aramis project is founded to establish a new infrastructure for CO2 transport between emission sites to the collection point in the Port of Rotterdam. The expectation is that the supply of CO2 will increase gradually from 5 MTPA in 2026 to 10 MTPA in 2030 and 20 MTPA in 2035. CO2Next is developing a terminal for the liquid CO2 supply from the emission sites to the collection point in the Port of Rotterdam. While Porthos is making the pipeline infrastructure for the offshore transport phase of carbon, from the Port of Rotterdam to the depleted gas fields. In Norway, the Northern Lights project is a CCS project operational in the implementation phase, currently. The Dutch projects are not operational at this moment, because the infrastructure is not established yet. Regarding the capture area of CO2, it can be concluded that a large potential exists in the Northern European Region. Especially, the Rhine Area has a large potential. Because it is closely connected to the Netherlands by water and land, it is interesting to further analyse the potential of this area for the Dutch CCS system. Within the Netherlands, the Chemelot cluster might be connected to the Pothos project. Similarly, as the plan for construction of a hub in the Port of Rotterdam, also other construction plans for hubs elsewhere in Europe are developing, such as Eemshaven, the Port of Immingham, Wilhelmshaven and Gdansk.

   The captured CO2 could also be utilised in CCU projects, instead of storing purposes in CCS. CCU developments, such as in horticulture, can also increase the demand to transport services for CO2 by ship or pipe. Nevertheless, it is not expected that these applications will be intensively operational in the short-term.

   (b) *How can a CCS transportation network be modelled?*

   Hub-and-clustering networks are required for upscaling CCS networks. The advantages of hub-and-clustering networks can be summarised as reducing costs, decreasing risks for new CCS projects and removing interdependency between the size of individual emitters and their investment decisions. Therefore, for the whole value chain of CCS projects hub-and-clustering networks are expected. Regarding, the onshore transportation network a different typology is proposed in this research. Bellona Germany (2019) and Kreutzberger

(2008), stated that point-to-point network is more suitable for the onshore transportation phase. This is because a point-to-point network offers flexibility in the implementation phase and because the freight is already bundled in the ports. The proposed onshore transportation network is thus a centralised hub as origin, connected point-to-point to the destinations, without intermediate inland hubs.

(c) *In what way are stakeholders supporting or blocking certain objectives and requirements of carbon transport within CCS?*

5 Stakeholder Analysis

In this chapter, the stakeholder analysis will be performed. First, in Section 5.1, the type of problem will be outlined. Then, in Section 5.2, the important involved actors will be identified and described. This chapter ends with a formal chart in Section 5.3. The goal of this chapter is to provide an answer to sub-question 3c.

3. What is the current state of carbon capture (utilisation) and storage inland shipping chain?
    (a) What are the possible areas to transport liquefied CO2 from and to, and what are the corresponding volumes and time-span?
    (b) How can a CCS transportation network be modelled?
    (c) In what way are stakeholders supporting or blocking certain objectives and requirements of carbon transport within CCS?

5.1 Problem Typology

In Section 2.3, the role of the analyst was described. Derived from this identified role, the problem typology will be determined in this section. Dunn (2015), claims that the exploration of a problem situation and the definition of what a problem exactly is, is essential to generate solutions and recommendations. Therefore, in this paragraph, the problem typology will be explained using the problem categorisation of Graaf and van de Hoppe (1989).

Table 2: Typology of tamed and untamed problems *Note.* From (Graaf and van de Hoppe, 1989)

		Degree of technological uncertainty	
		Small	Large
Degree of social consensus	Large	Tamed problems	Untamed technical problems
	Small	Untamed political problems	Untamed problems

Graaf and van de Hoppe (1989), distinguished four types of problems categorised based on the degree of social consensus and the degree of technological uncertainty, see Table 2. The first problem typology is a tamed problem. Tamed problems consist of social consensus and widely available technological solutions. The second problem typology is an untamed technical problem. These types of problems consist of shared awareness of the problem between actors and the shared awareness of the responsibility to solve a problem. The technological solutions are lacking and therefore research is needed to retrieve solutions. The third problem typology is an untamed political problem where technical solutions are available. However, social conflicts exist regarding the application of technical solutions. The last problem typology is the untamed problem. An untamed problem consists of conflicting social interests and uncertainty about technical solutions.

In this research, the problem statement is orientated towards the suitability of electric ship transport within the onshore transport phase of CCS. A high degree of social consensus exists about the fact that the two main onshore transport modes of carbon are pipelines and conventional ships (Kjärstad et al., 2016; Roussanaly et al., 2013). In case, electric ship transport can replace conventional ship transport without any losses in features, it is assumed that the degree of social consensus is large. Noticed should be that this consensus will depend on the customers' needs. In respect of the degree of technological uncertainty, it can be expected that technological solutions are available. The E-Pusher is already implemented in other transport chains and technological steps to transport carbon by ship are also widely applied in other CCS systems. Therefore, it can be concluded that for the suitability of carbon transport by electric ships this problem is tamed.

Nevertheless, the onshore transport of carbon is only one phase of the CCS system. CCS as a solution on itself for reaching climate goals is not considered a tamed problem. Conflicting arguments exist about whether CCS is a good solution to meet the climate goals, or not. However, authorities and the International Energy Agency claim that it is not possible to reach the climate goals without CCS. Therefore, CCS will be implemented in many countries. In the Netherlands, three CCS projects were unsuccessful at an earlier stage. Technical, legal and policy uncertainties were the driving factors for the failed projects. Furthermore, social acceptance has proved to be the main barrier to CCS projects worldwide and in the Netherlands. However, for the Aramis project new financial instruments, increased government support and an improvement in social engagements are introduced (Akerboom et al., 2021). As a result, it can be concluded that the Aramis project receives a higher degree of social consensus than the previous CCS projects.

In short, there is social consensus and technical resources are available for onshore carbon transport. Therefore, it is a tamed problem. Despite this categorisation, it should be regarded that CCS in itself is not a widely supported solution.

5.2 Identification of Actors

In this paragraph, the main involved actors will be identified. The actors will be categorised into main groups for simplicity in further steps in the stakeholder analysis.

5.2.1 Governmental authorities

On the international level is the International Maritime Organization (IMO) the agency that is responsible for shipping safety and security, worldwide. IMO is a part of the United Nations. On the European level is the European Commission the governmental authority that adopted a series of legislative proposals on how to achieve climate neutrality in the EU by 2050. Furthermore, the European Commission determined the requirements for selecting CO2 storage sites in CCS projects (European Commission, nd). Besides, the EU formed the London Protocol and ETS, whereby the London Protocol is forming a barrier to the transboundary transport of CO2, currently. The purpose of the London Protocol is to protect the marine environment from the dumping of wastes (Bergesen et al., 2018). At this moment, the legislation turned out into a barrier to CO2 transport with storage purposes abroad. An amendment was made to the London Protocol to allow transborder movement of CO2 with purposes for offshore storage (Reyes et al., 2021). The amendment needs to enter into force that it will be adopted by two-thirds of the parties involved in the protocol. Currently, this has not been established. Despite, the amendment is not ratified at the moment, it is possible, since 2019, to transport CO2 abroad for storage purposes. Unilateral declarations and bilateral agreements are therefore necessary. The procedure is as follows: Countries that desire to transport CO2 abroad for storage must deposit a Unilateral Declaration to the Secretary-General of the IMO. Then, both the importing as well exporting countries must establish a bilateral agreement, which shall align with the London Protocol and include the confirmation and allocation of the permitting responsibilities between the corresponding countries. Another legislation formed by the European Commission is the EU Emissions Trading System (ETS). ETS has the purpose to reduce CO2 emissions within sectors. This is attempted by using a limit of total emissions per sector, which will gradually decline over the years. For companies, it is possible to buy and sell allowances within this limit. Consequently, companies are stimulated to reduce CO2 emissions and could be rewarded if CO2 emissions are reduced (Reyes et al., 2021). Currently, the shipping industry is not included in this system. If the shipping industry will be included, and each company has to pay for each ton of emitted CO2 or can yield money for each ton of CO2 avoided, it is expected that companies will invest in decarbonization. As a result, a business case could be formed for companies where in earlier CCS projects this was lacking (Buirma, 2020).

The Dutch Government is responsible for reducing the CO2 emissions in the Netherlands in the coming decades. Therefore, the Dutch Government, in particular, the Ministry of Economic Affairs and Climate Policy is contributing to the CCS projects by using several policy instruments. One of them is funding the projects by granting the SDE++ subsidy. The subsidy is meant to bridge the gap between the ETS price and the cost of a project. Furthermore, the Ministry of Economic Affairs and Climate Policy is authorised to grant permits for CO2 transport and storage. Companies should meet the requirements of the Mijnbouwwet (Mining Act) to receive permits (Rijksoverheid, nd). In particular, the exploration licence and long monitoring requirements required for depleted gas fields are covered in this legislation (Rijksoverheid, nd). Next to that, the government implemented a national carbon tax in 2021. The tax could be considered as a demand-pull purpose to create decarbonization incentives. The economic instrument has the purpose to result in an emission reduction of 14.3 MegaTonnes CO2 within the coming decennial.

Also decentralised authorities, such as municipalities and water authorities, are involved and have the advisory power in the process of granting permits for CCS projects (Schipper and Dieperink, 2020).

5.2.2 Emitters and CCS projects

Emitters are responsible to achieve the climate goals and therefore need to develop CCS projects. A Dutch partnership formed by the industry is Aramis, established by TotalEnergies, Shell Netherlands, Energie Beheer Nederland (EBN) and Gasunie. The goal of Aramis is to contribute to the reduction of CO2 emissions by providing CO2 transport to unlock storage capacities for varying industries, such as steel, chemicals and refineries (Energies, 2021). Another project is Porthos, which is established by the Port of Rotterdam, Gasunie and EBN. The three public shareholdings will contribute by collecting CO2 in the Port of Rotterdam and then transporting it to a depleted gas reservoir (Porthos, nd). Furthermore, CO2next is a collaboration developing a terminal with the purpose to receive and supply CO2. All three of the projects are collaborating.

5.2.3 Transport Service Providers

Transport Service Providers are involved because they will transport the captured CO2. The offshore pipeline transport service will be provided by Porthos. The onshore transport service can be either by ship or pipeline. Inland water transport can be further divided into shipping companies for low-volume transport and large-volume transport. Because CCS is not widely implemented in the Netherlands yet, the most suitable transport service provider should be determined later. Nevertheless, KOTUG is considered in this analysis because the research in this field is requested by KOTUG. KOTUG is a maritime service provider that introduced a zero-emission tugboat called the E-Pusher. KOTUG has the interest to deploy the E-Pusher in the inland transport stage of CCS

5.2.4 Research Institutions

Different organisations to assess the science related to climate change exist. The Intergovernmental Panel on Climate change (IPCC) is the United Nations Body that investigates the state of scientific, technical and socio-economic knowledge on climate change, and the corresponding impacts and future risks (IPPC, 2005). Another Agency cooperating with countries worldwide to shape energy policies for a secure and sustainable future is the International Energy Agency (IEA). IEA investigates how CCS can play a central role in the energy transition alongside other technical innovations (IEA, 2022). The Netherlands Environmental Assessment Agency is PBL. PBL is a national institute for researching policies in the fields of the environment, nature and spatial planning. PBL is requested by the Ministry of Economic Affairs and Climate Policy to advise about possible subsidy policies, also containing subsidy options for CCS (PBL, 2021).

5.2.5 Non-governmental Environmental Organizations

The Non-governmental Environmental Organizations (NGOs) are independent organisations to stimulate public awareness of environmental developments. In the past, CCS could count on significant resistance from NGOs. Nowadays, NGOs consider CCS as a solution but are still alert on how CCS projects will be implemented.

5.3 Formal Chart

In the previous paragraph, the involved actors are identified. The formal chart will be presented in this paragraph. The formal chart provides an overview of the formal relations of the actors to each other.

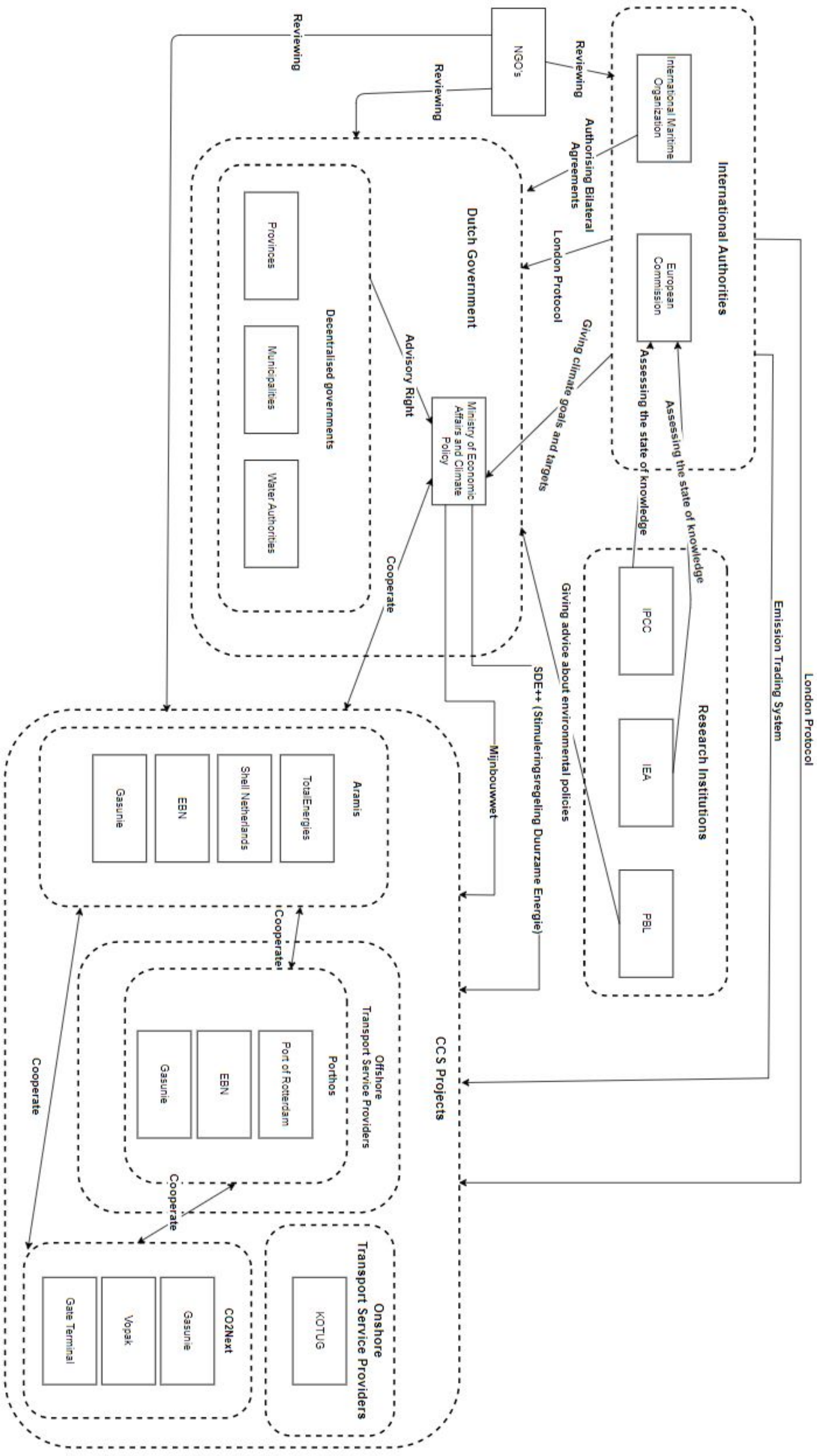


Figure 31: Formal Chart Dutch CCS System

5.4 Conclusion

In this chapter, the answer was found to sub-question 3(c).

3. What is the current state of carbon capture (utilisation) and storage inland shipping chain?
    (a) What are the possible areas to transport liquefied CO2 from and to, and what are the corresponding volumes and time-span?
    (b) How can a CCS transportation network be modelled?
    (c) In what way are stakeholders supporting or blocking certain objectives and requirements of carbon transport within CCS?

Earlier CCS projects were unsuccessful because of technical, legal and political factors. Stakeholders have to cooperate effectively in future CCS development plans to overcome the failure factors of previous failed projects. The stakeholder analysis revealed that most stakeholders are aware of the importance of CCS for reaching climate targets. Where in the past CCS was not widely supported, it can be concluded that currently, CCS deployment is perceived as inevitable, even by NGOs. However, some barriers exist concerning the implementation of CCS. The current Dutch CCS projects stated that they are willing to build infrastructure, but they need emitters that are willing to participate. Emitters need the infrastructure and also funding to bridge the gap between transportation and storage costs. On the other hand, the public authorities want to be sure that the infrastructure is available before providing funds. This dynamic can be categorised as a chicken-egg problem. Next to this problem, also the London Protocol is forming a barrier. It is not allowed to dump waste from one country to another country. Bilateral agreements have to be made between countries to allow transboundary transport of CO2 for storage purposes. Another legislation that plays an important role is ETS. ETS is expected to create an incentive for companies to participate in CCS systems, and thus extra support for upscaling CCS projects.

6 Operational Analysis - The E-Pusher and KOTUG

In this chapter, first, the profile and mission of KOTUG will be explained in Section 6.1. Second, a more detailed overview of the E-Pushers' constructional design will be outlined in Section 6.2. Third, the operational design of the E-Pusher will be highlighted in Section 6.3. Then, in Section 6.4, the proposed operational configuration of the E-Pusher in a CCS chain will be explained. Thereafter, the requirements from KOTUG for deploying the E-Pusher will be noticed in Section 6.5. Finally, Section 6.6, summarises and concludes this chapter by answering sub-question 4, which was formulated as follows:

4. *What are the technical-operational characteristics of the E-Pusher?*

6.1 Company Profile

This thesis is executed in cooperation with KOTUG, a towage company operating in the maritime industry on a global level. The headquarter is located in Rotterdam, the Netherlands. The main activities of the company are related to towage and related services, such as providing planning tools and consultancy training sessions. KOTUG aims to be the leading towage and maritime service provider on a global level. Associated with this goal is to commit to the principles and practices that contribute to the pursuit of sustainability goals. KOTUG describes sustainability as a safe and sound operation for the well-being of all involved while respecting the environment. Furthermore, it is pursued to provide an excellent level of training sessions. Apart from KOTUG's own sustainability goals, the towage company also attempts to help its clients reach their sustainability goals. This is done by inventions that not only contribute to the global energy transition but also support efficiency and safety during operational activities (KOTUG, nda). The E-Pusher is a specific example of an innovation in which KOTUG attempts to pursue its goals, as mentioned above. KOTUG contributes to the research activities in the field of sustainable design and operations in the maritime industry, by providing a use case with the E-Pusher.

6.2 Constructional Design of the E-Pusher

As mentioned in the previous subsection, the vessel that will be investigated in this research is the E-Pusher. The E-Pusher is a modular and scalable electric pusher tug that is powered by swappable energy containers. Therefore, the E-Pusher has an opportunity to operate more efficiently than traditional vessels (Prevljak, 2022). The E-Pusher is available in three sizes with varying lengths from 5.50 meters to 22 meters and a maximum depth of 0.45 meters to 1.35 meters, see Figure 32. In Appendix A, the characteristics of all the E-Pusher types are presented. Because of the depth, the E-Pusher is offered in a design that has a draft that is 30% less than conventional pusher tug designs. Next to that, the modular design of the E-Pusher allows a 50% faster delivery time (KOTUG, 2021). All components are standard container units and can be fabricated by different builders and delivered to a central assembly location. Therefore, a traditional shipyard is not needed, resulting in a competitive building in comparison with other vessels. The propulsion for all types of the E-Pusher is provided by electric azipods, which allows easy and quick changeable operations if an upgrade or downgrade of power is needed. A steel frame is used to support all horizontal push forces. The steel frame distributes the vertical weights to the various components on the deck. The hull contains Polyethyleen (PE), which provides buoyancy and resists water forces on the vessel during sailing (KOTUG, ndb). The power supply is provided by interchangeable containerized units, allowing multiple zero-emission transport options, such as battery packs, hydrogen fuel cells, and biogas generators. All vessels meet the requirements of the communautair certification, in particular the EU, CESNI, and ESTRIN certification, allowing transport between the EU member states. An overview of all the individual components the E-pusher is assembled on is depicted in Figure 33.

Figure 32: E-Pusher Series

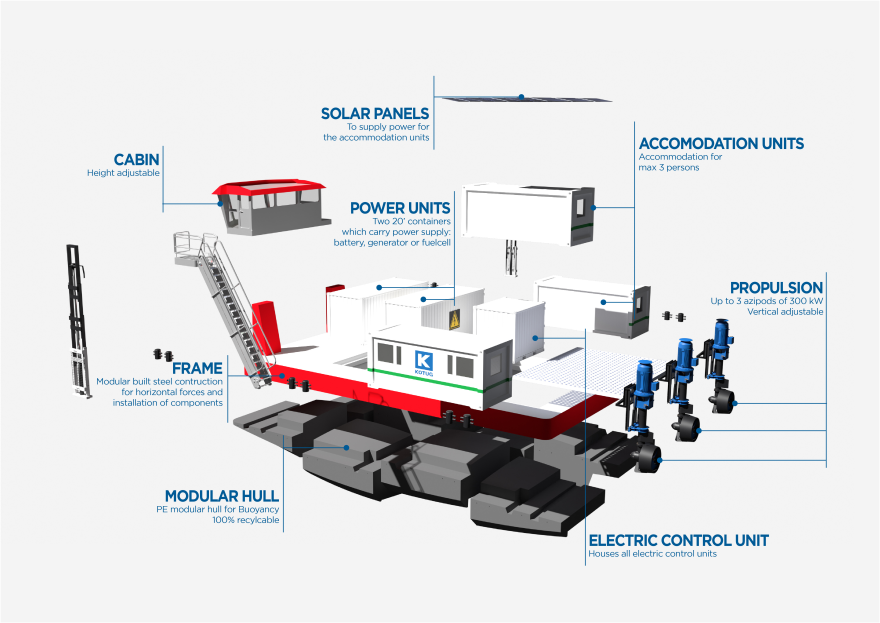


Figure 33: E-Pusher Component Overview

6.3 Operational Design of the E-Pusher

A conceptual design of a pusher boat connected to two standardised barges is represented in Figure 34. The E-Pusher is a pusher boat that will be connected to standardised barges. The pushers can be connected to the barges by cables. The power supply of the E-Pusher can be provided by several zero-emission options. However, in the Netherlands, the power will be supplied by swappable batteries. KOTUG cooperates with SHIFT to guarantee the power supply. SHIFT has an electricity network to provide an energy supply for the swappable containers. Electricity is generated during off-peak hours. Energy is supplied from wind farms or sun fields that are certified. The energy will be loaded in a battery pack. If the battery packs are loaded under this condition it can be considered green energy. The advantage of containerized energy storage is that it can be placed in any barge and easily be recharged or swapped. Next to that, using electric engines requires no engine room which allows more loading space than on comparable vessels of the same size. Swapping batteries has as advantage that the quality of the battery will not decrease very fast. Furthermore, swapping allows one to use a battery multiple times a day. Despite the mentioned advantages, the loading facility of SHIFT should be within the range of the E-Pusher during a voyage. In other words, significant is that a loading facility can be visited during a voyage of the E-Pusher. Currently, the loading infrastructure is not widely implemented. SHIFT is handling the up-scaling of this infrastructure. It is assumed that, depending on the cargo loads, each 45km facility will be guaranteed to swap or recharge the battery packs on a certain route. Some limitations are associated with this goal to extend the power supply network. For instance, some building and space restrictions will be encountered in the Rhine area in Germany.

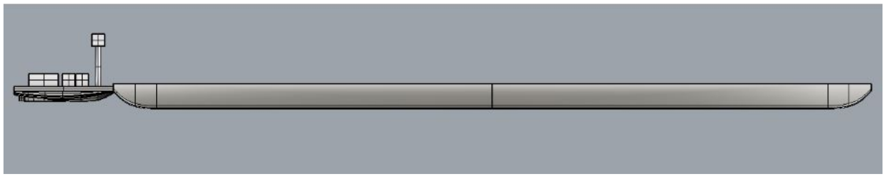


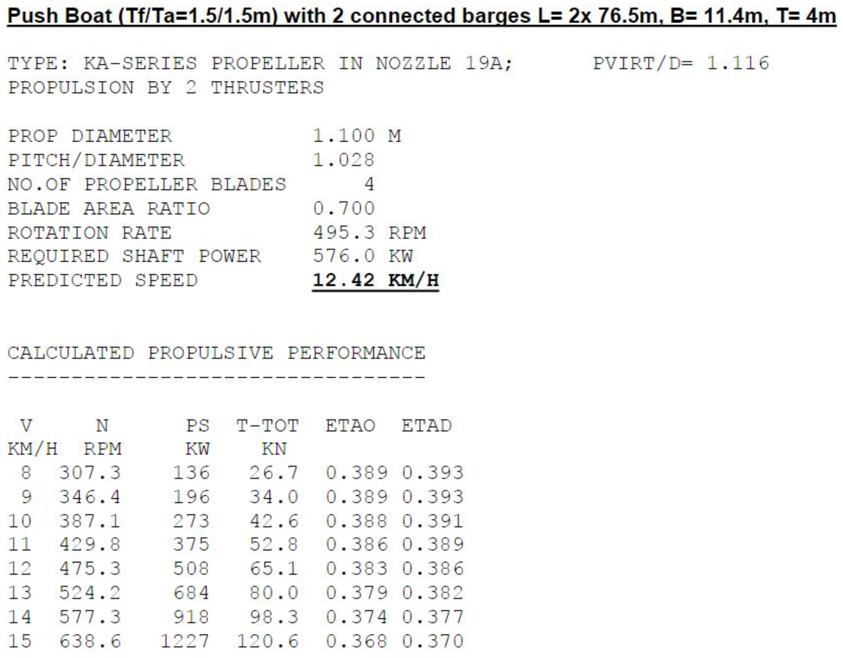
Figure 34: Pusher connected to barges
Note. From MARIN (2019)

6.4 Operational Specifications of the E-Pusher in a CCS Chain

A pusher corresponding with an E-Pusher class type L is connected to two Europe IIa barges. Each of the barges has a length of 76.5m and can carry approximately 2700 tons of load, see Table 3. The deadweight based on two standard barges in a long configuration is assumed to be 5500 tons. Given the installed power of 2 x 300 kW, the E-Pusher type L can reach speeds varying around 13 km/h, see Figure 35. The L-Type has two batteries with a capacity of 2.4 MW each. Thus in total, a battery capacity of 4.8 MW is available. The E-Pusher will operate during the day. The night will be used to charge the batteries. Assumed is that barges will sail under a speed of 12 km/h. As can be derived from the diagram in Figure 35, the required power under this speed is around 500 kW. This is under the condition that the push-boat combination encounters no current during the operations. The speed in the table can thus be defined as speed through water. In case, currents are present on the waterway, the speed should be defined as speed over ground speed over ground. Currents could be estimated at 1-5 km/h, depending on the waterway class type.

Table 3: Commonly used barge types
Note. From MARIN (2019)

CEMT class	**type barge**	**length**	**width**	**draught**	**loading capacity**
		[m]	**[m]**	**[m]**	**[tonnes]**
IV	Europe I	70	9.5	2.0	1450
Va	Europa II	76.5	11.4	3.5	2450
Va	Europe IIa	76.5	11.4	4.0	2780
Va	Europa IIa lengthened	90	11.4	4.0	3220



Push Boat (Tf/Ta=1.5/1.5m) with 2 connected barges L= 2x 76.5m, B= 11.4m, T= 4m

```
TYPE: KA-SERIES PROPELLER IN NOZZLE 19A;      PVIRT/D= 1.116
PROPULSION BY 2 THRUSTERS

PROP DIAMETER           1.100 M
PITCH/DIAMETER          1.028
NO.OF PROPELLER BLADES      4
BLADE AREA RATIO        0.700
ROTATION RATE           495.3 RPM
REQUIRED SHAFT POWER    576.0 KW
PREDICTED SPEED         12.42 KM/H


CALCULATED PROPULSIVE PERFORMANCE
---------------------------------

 V     N      PS  T-TOT  ETAO  ETAD
KM/H  RPM     KW    KN
 8  307.3    136   26.7  0.389 0.393
 9  346.4    196   34.0  0.389 0.393
10  387.1    273   42.6  0.388 0.391
11  429.8    375   52.8  0.386 0.389
12  475.3    508   65.1  0.383 0.386
13  524.2    684   80.0  0.379 0.382
14  577.3    918   98.3  0.374 0.377
15  638.6   1227  120.6  0.368 0.370
```

Figure 35: Speed Power Prediction

Note. From MARIN (2019)

6.5 KOTUG's Requirements

- Environmental requirement:
  The E-Pusher should have a significant sustainable impact regarding emissions during operations. In general, the TTW emission of CO2 is 2.6 kg/litre during combustion, if using a diesel-driven propulsion system. On average, a diesel-driven propulsion ship consumes 95-200 grams of CO2 per kW. Assumed is that each 5 kW corresponds with one-litre diesel. Thus, the usage of 5kW is associated with the emission rate of 2.6 kg CO2.

- Economical requirement:
  Mainly, innovations by companies are driven by economical objectives. In this case, it is desired to have an economically feasible business case. However, the main objective is to contribute to reaching climate agreements. KOTUG feels responsible for scaling-up zero-emission solutions. Therefore, KOTUG invests in these types of solutions. But next to own financial impulses also government funds are needed. So, it can be concluded that deploying an E-Pusher should be economically feasible, but the main target is not generating high revenues for providing services with the E-Pusher.

- Operational requirement:
  Safety is for KOTUG the main requirement. Maintenance of the different components of the E-Pusher requires special attention and procedures to guarantee safety. Furthermore, KOTUG prefers coordination in the voyages of vessels. In case, the intensity of transport in

inland waterways increases, it is also important to avoid collisions. Thus, coordination for the traffic flows is required, from KOTUG's perspective. Next to safety, also scaling up the power supply infrastructure is needed. As mentioned in Section 6.3, KOTUG cooperates with SHIFT. Currently, the power supply infrastructure is not widely implemented. Therefore, the facilities to deploy the E-Pusher should be scaled in case the E-Pusher will be used for longer transport distances.

6.6 Conclusion

In this chapter, the company's profile is explained and a thorough analysis of the technical and operational characteristics of the E-Pusher is performed. The goal of this chapter is to design a sketch of technical and operational characteristics for using an E-Pusher within CCS. The answer to the sub-question is as follows:

4. *What are the technical-operational characteristics of the E-Pusher?*
   The E-Pusher is a modular and scalable electric pusher-boat concept that is powered by swappable energy containers and operational during the day. The night is used for charging purposes. The electricity for charging the batteries is generated during off-peak hours, whereby energy is supplied from certified wind farms or sun fields. Therefore, the energy supplied is considered green energy. In this research, a configuration of the E-Pusher L-Type connected to two standardised barges is considered. The loading capacity of this combination is limited to 5500 tons. The installed power is 600 kW. In general, the expected sailing speed is 12 km/h. Given this sailing speed, the measured required shaft power is approximately 500 kW. The total battery capacity is 4.8 MW.

7 Model and Scenario Generation

The goal of this thesis is to explore the potential of electrified propelled barges within CCS, in particular for the E-Pusher. In the previous phases of the research, it is found how to asses a barge transport network, how a value chain of CCS can be designed and what the current status of CCS is. In this section, it is attempted to integrate all findings into a model. The model is designed to approach a realistic CCS value chain for the Netherlands, whereby it is possible to experiment with certain system variables. This allows exploring the impact of implementing the E-Pusher in a CCS value chain to the formulated KPIs of a barge network in Section 3.1. Thus, the purpose of the model is to simulate a real-world value chain for CCS. In the later stages of the research, the model will form the fundamental basis for experimentation. This chapter starts with defining the model requirements in Section 7.1. Followed by explaining the model terminology and design in Section 7.2. Thereafter, the reference case will be presented in Section 7.3. The modelling assumptions and formulas will be presented in Section 7.4. Finally, the scenarios will be generated and explained in Section 7.5.

7.1 Model Requirements

Before, building a model it is necessary to define all the requirements the model should meet. The types of requirements can be distinguished into system requirements and user requirements. First, the system requirements will be outlined. Second, the user requirements will be described.

System requirements are more dedicated to the model itself and contributes by validating a model. The system requirements defined by the author of this thesis are as follows:

- **Scenario building:** The model has to be able to allow experimenting with different scenarios. First, a base case should be formulated. Then, varying input parameters should lead to the generation of outcomes for multiple scenarios.
- **KPI Output:** The model has to be able to calculate and present the KPI output. The KPIs, corresponding indicators and values are expressed in Section 3.1.
- **Constraints:** The model has to be able to incorporate system constraints and evaluate whether scenarios are feasible or not.
- **Applicability:** The model has to be transparent, flexible and interpretable. Assumptions and corresponding sources should be present. Adaptations to the model have to be easy to make and the results (KPI Output) have to be easy to present.

User Requirements are requirements formed by the client. As mentioned in Section 6.1, this thesis is in cooperation with KOTUG. KOTUG has certain requirements that should be incorporated into a model. The following requirements from the user perspective should be respected:

- **Scenario-building:** The generated scenarios have to be relevant to KOTUG and the E-Pusher concerning technical and economical feasibility.
- **KPI Output:** The calculated values for the KPIs have to be insightful for KOTUG. In particular, the trade-off presented between the gains in emissions and the operational impact.
- **Constraints:** The constraints that will be modelled have to be clearly defined in a way that it is interpretable for KOTUG why a concept is feasible or not.
- **Applicability:** The operational characteristics of all types of transport modes have to be easy to interpret.

In Section 6.5, the requirements for the E-Pusher from KOTUG's perspective were formed. The economical and environmental requirements are captured in the general KPIs formed in Section 3.1. The requirement about guaranteeing safety is excluded in forming the model. This is because it is not possible to outline the safety at the moment. It is assumed that safety regarding technical issues will be guaranteed by severe requirements during manufacturing. While, the safety issues associated with sailing behaviour and handling cargo will be guaranteed by following well-formed regulations and procedures, formulated in Section 3.3.3.

7.2 Model Terminology and Design

In the model, three types of variables can be distinguished. The first type of variable is the input or **independent variables**. These variables will form the input of the system. It is possible to vary these variables to affect the outcome of an experiment. A further distinction can be made between parameters and constants. Input parameters can vary, while constant retain the same value. A parameter is for instance sailing speed, which can vary under different conditions. An example of a constant is the emission factor of a transport mode, which retains the same value. The second type of variable is the output variables or **dependent variables**. These variables represent the values for the output of a model. The outcomes could be changed by experimenting with the input variables. Lastly, the **intermediate variables** could be distinguished. Intermediate variables are internal variables that are calculated by the model. The internal variables will influence the output variables. A schematic representation of the dedicated model in this research with the mentioned terminology above is depicted in Figure 38. It should be noted that one of the KPIs in this research, the cycle time, influences intermediate variables because of a relation to the other KPIs. Therefore, a relation between KPI output and internal variables is illustrated.

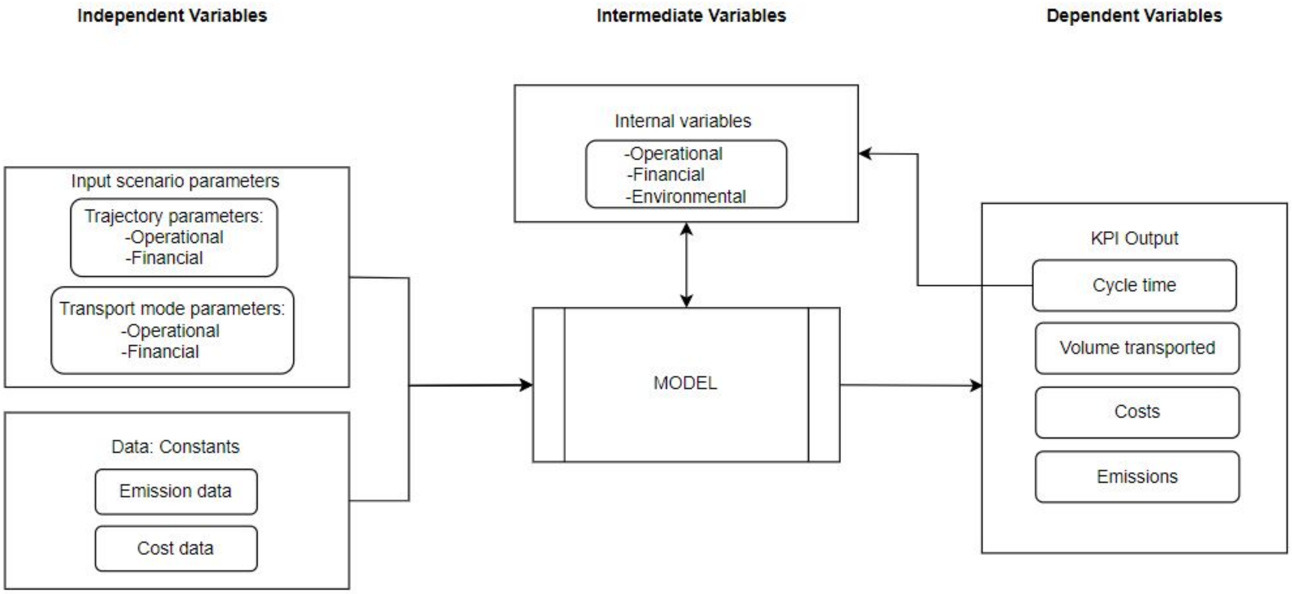


Figure 36: Relation Parameters, Model and KPIs

7.3 Reference Case

In Section 4.2, the proposed network model is explained. This typology will be used as the network in the model and scenarios. Because Rotterdam will be the port in the Netherlands where the carbon will be bundled this will be modelled as the origin location. Based on the locations of industrial emitters on the Aker Capture map, see Figure 30, some of these emitters closely connected to the Port of Rotterdam by waterway will be modelled as destinations. Different distances will be considered. Within the transport from emitters to the Port of Rotterdam, no intermediate stops or bundling locations are assumed. The model will be first developed for a barge transport network. Then, the model will be adjusted for each other transport mode in such a way, that is possible to analyse the transport of CO2 for the other modes within CCS. Based on the map from Aker Capture, industrial emitters with different distances will be modelled as destinations. For instance, this could be Rotterdam Botlek, Moerdijk, Arnhem, and Duisburg, respectively. Below, the modelled system is presented, including the adjustment that charging stations are needed for the E-Pusher, see Figure 37.

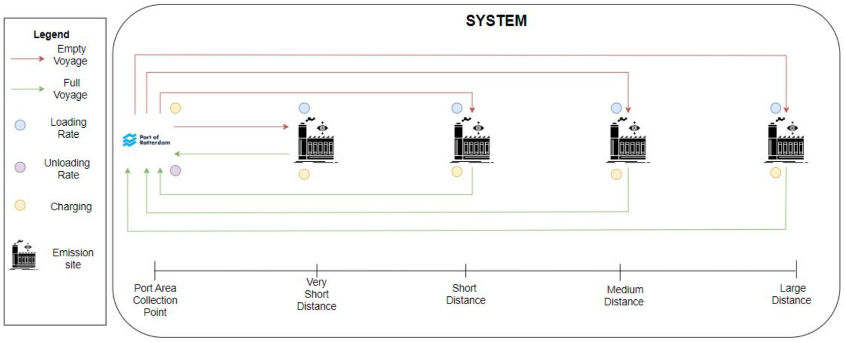
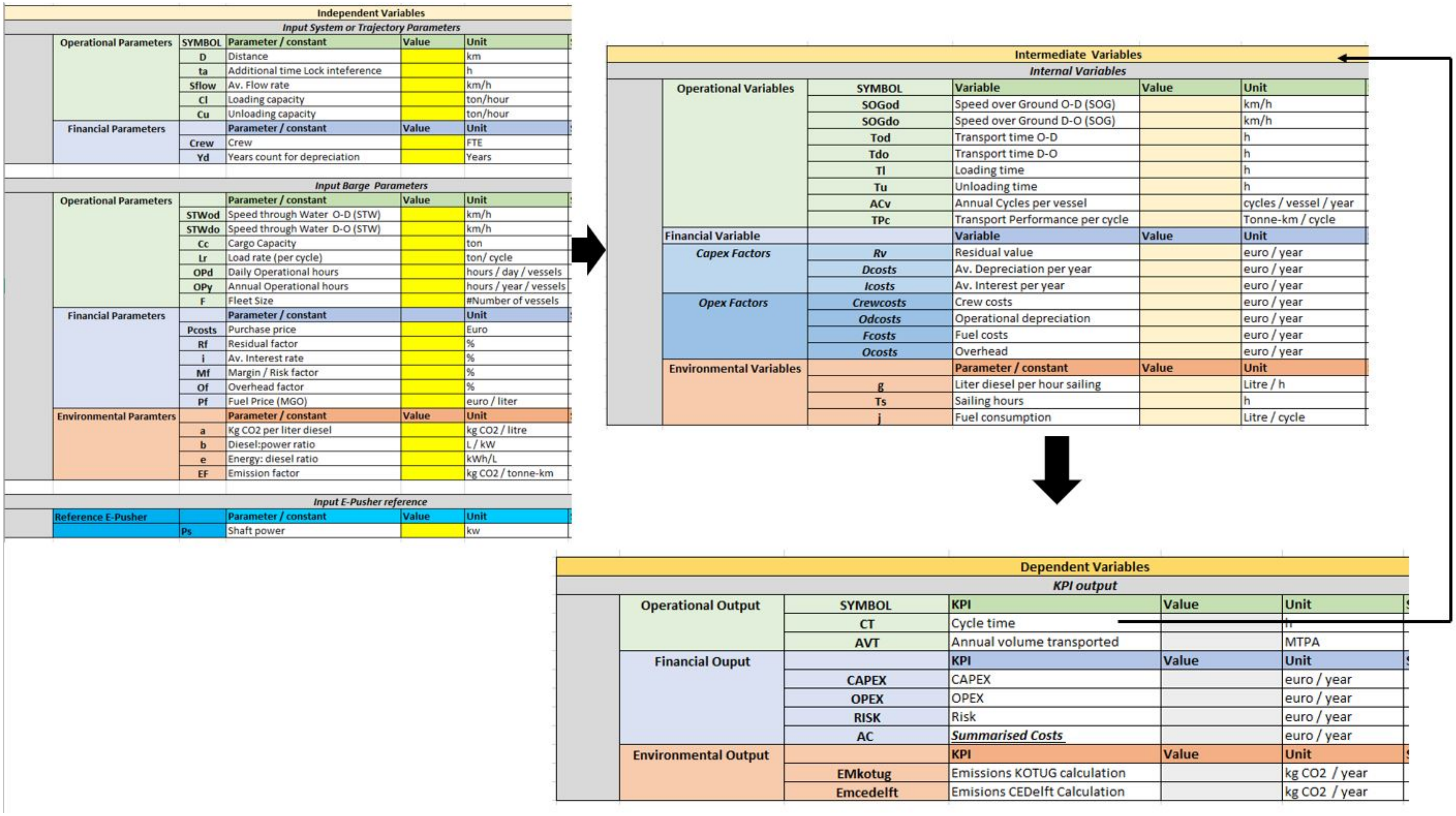


Figure 37: System Design

As can be seen, in Figure 37 different KPIs and parameters are present. A more detailed overview of the relation between the parameters, the system, and the KPIs is presented in Figure 38, on the next page.



Independent Variables

Input System or Trajectory Parameters

	SYMBOL	Parameter / constant	Value	Unit
Operational Parameters	**D**	Distance		km
	ta	Additional time Lock inteference		h
	Sflow	Av. Flow rate		km/h
	Cl	Loading capacity		ton/hour
	Cu	Unloading capacity		ton/hour
Financial Parameters		**Parameter / constant**	**Value**	**Unit**
	Crew	Crew		FTE
	Yd	Years count for depreciation		Years

Input Barge Parameters

		Parameter / constant	Value	Unit
Operational Parameters	**STWod**	Speed through Water O-D (STW)		km/h
	STWdo	Speed through Water D-O (STW)		km/h
	Cc	Cargo Capacity		ton
	Lr	Load rate (per cycle)		ton/ cycle
	OPd	Daily Operational hours		hours / day / vessels
	OPy	Annual Operational hours		hours / year / vessels
	F	Fleet Size		#Number of vessels
Financial Parameters		**Parameter / constant**		**Unit**
	Pcosts	Purchase price		Euro
	Rf	Residual factor		%
	i	Av. Interest rate		%
	Mf	Margin / Risk factor		%
	Of	Overhead factor		%
	Pf	Fuel Price (MGO)		euro / liter
Environmental Paramters		**Parameter / constant**	**Value**	**Unit**
	a	Kg CO2 per liter diesel		kg CO2 / litre
	b	Diesel:power ratio		L / kW
	e	Energy: diesel ratio		kWh/L
	EF	Emission factor		kg CO2 / tonne-km

Input E-Pusher reference

		Parameter / constant	Value	Unit
Reference E-Pusher	**Ps**	Shaft power		kw

Intermediate Variables

Internal Variables

	SYMBOL	Variable	Value	Unit
Operational Variables	**SOGod**	Speed over Ground O-D (SOG)		km/h
	SOGdo	Speed over Ground D-O (SOG)		km/h
	Tod	Transport time O-D		h
	Tdo	Transport time D-O		h
	Tl	Loading time		h
	Tu	Unloading time		h
	ACv	Annual Cycles per vessel		cycles / vessel / year
	TPc	Transport Performance per cycle		Tonne-km / cycle
Financial Variable		**Variable**	**Value**	**Unit**
Capex Factors	***Rv***	Residual value		euro / year
	Dcosts	Av. Depreciation per year		euro / year
	Icosts	Av. Interest per year		euro / year
Opex Factors	***Crewcosts***	Crew costs		euro / year
	Odcosts	Operational depreciation		euro / year
	Fcosts	Fuel costs		euro / year
	Ocosts	Overhead		euro / year
Environmental Variables		**Parameter / constant**	**Value**	**Unit**
	g	Liter diesel per hour sailing		Litre / h
	Ts	Sailing hours		h
	j	Fuel consumption		Litre / cycle

Dependent Variables

KPI output

	SYMBOL	KPI	Value	Unit
Operational Output	**CT**	Cycle time		h
	AVT	Annual volume transported		MTPA
Financial Ouput		**KPI**	**Value**	**Unit**
	CAPEX	CAPEX		euro / year
	OPEX	OPEX		euro / year
	RISK	Risk		euro / year
	AC	***Summarised Costs***		euro / year
Environmental Output		**KPI**	**Value**	**Unit**
	EMkotug	Emissions KOTUG calculation		kg CO2 / year
	Emcedelft	Emisions CEDelft Calculation		kg CO2 / year

Figure 38: Overview of variables, parameters and KPIs

7.4 Model Assumptions and Formulas

In this subsection, the model formulas will be presented. The symbols of the formulas can be found in Figure 38. Because the input parameters are self-explaining, only the formulas of the internal variables and the KPIs will be presented. The representation is for the general model of the barge. Required (mathematical) adjustments for the other transport modes will also be highlighted. In Appendix B, the model overviews in Excel for all transport modes are presented.

7.4.1 General Model

Intermediate variables: *Operational*

Yang et al. (2020), found in the literature that presenting the sailing time is uniformly calculated by the waterway distance divided by the sailing speed. However, a differentiation should be made between speed over water (STW) and speed over ground (SOG). Both concepts are explained in Section 3.1. For calculating the sailing time, it is required to use the speed over ground to estimate the actual sailing time. The input value for speed through water is given as 12 km/h. The flow rate is modelled based on the average flow rate in the Netherlands. This value is approximately 3 km/h (Geologie van Nederland, nd). For the E-Pusher also charging time is included, 0.5 hour per extra charging moment.

- Speed over Ground [km/h] = Speed through water [km/h] +- flow rate [km/h]

$$SOG = STW + -Sflow \tag{1}$$

- Transport time [h] = Distance [km] / speed over ground [km/h]

$$Tod = D/SOGod \tag{2}$$

The assumed cargo to load on a voyage for a general barge is estimated at 6000 tons, while for the E-Pusher this is 5500 tons. A full load is assumed during the transport from the emitter to the Port of Rotterdam. But an empty trip is performed from the Port of Rotterdam to the emitter. For truck transport, 20ft containers are used allowing cargo transport of 20 tons of liquid CO2. The operations for loading and unloading the cargo can handle vessels are 1000 and 1400 ton/h, respectively. For truck transport, the loading and unloading require one hour on average for each handling.

- (Un)Loading time [h] = Load rate [ton] / (un)loading capacity [ton/h]

$$Tl = Lr/Cl \tag{3}$$

The daily operational hours for the waterway transport are estimated at 16 hours, operating between 06:00 and 22:00. The vessels are sailing 6 days a week. For trucks it is estimated at 55h per week, operating 50 weeks within a year.

- Annual cycles per vessel [#Cycles] = Annual operational hours [h] / cycle time [h/cycle]

$$ACv = OPy/CT \tag{4}$$

- Transport performance per cycle [tonne-kilometre / cycle] = load per cycle [ton / cycle] * distance O-D [km]

$$TPc = Lr * D \tag{5}$$

Intermediate variables: *Financial*

The compression costs for transporting the CO2 are neglected in the calculations because expert consulting led to the assumption that for all considered transport modes the compression costs can be crossed out against each other.

- Residual Value [€] = Purchase price [€] * Residual factor [-]

$$Rv = Pcosts * Rf \tag{6}$$

- Av. Depreciation per year [€/year] = (Purchase price [€] - residual value [€]) / depreciation period [years]

$$Dcosts = (Pcosts - Rv)/Yd \tag{7}$$

- Av. interest per year [€/year] = (Purchase price [€] + (Purchase price [€] - residual value [€])) / (2 * interest rate) [1/year]

$$Icosts = (Pcosts + (Pcosts - Rv))/(2 * i) \tag{8}$$

- Crew costs [€]= FTE [-] * Crew costs [€]/ FTE [-]

$$Crewcosts = crew(Fixed) \tag{9}$$

- Operational depreciation [€/year] = Purchase Price [€] * factor average spend [1/year]

$$ODcosts = Pcosts * 0,04 \tag{10}$$

- Fuel costs [€/ year] = Fuel price [€/ Litre] * [Litre / cycle] * annual number of cycles [#Cycles / year]

$$Fcosts = Pf * j * ACv \tag{11}$$

- Overhead [€/year] = (Crew costs [€/ year] + Operational depreciation [€/ year] + Fuel costs [€/ year] + CAPEX [€/ year]) * overhead factor [-]

$$Ocosts = (Crewosts + ODcosts + Fcosts + CAPEX) * Of \tag{12}$$

Intermediate variables: *Environmental*
In the case of estimations for the ships' required propulsion, the speed through water should be used to obtain correct calculations of fuel consumption. Based on the TTW assumption, explained in 3.1, the value of 2.6 kg CO2 corresponds with one litre diesel. For 5 kW, one litre of diesel is required. Expert consulting led to the assumption that given an almost similar tonnage for the general barge and the E-Pusher, the power needed for both vessels can be considered as 1:1, under the same STW. The operational specifications of the E-Pusher in the configuration used in this research are presented in 6.4. The shaft power required corresponds with the operational profile provided by MARIN (2019). At all times, it is assumed that a diesel-propelled ship can achieve a SOG of 12 km/h. For the E-Pusher it is assumed that the speed cannot exceed an STW of 12 km/h, and thus also not a SOG higher than 12 km/h. For example, if the current is 3 km/h, the E-Pusher requires a shaft power corresponding to 12 km/h, but the resulting SOG is 9 km/h. A diesel-propelled ship can still reach a SOG of 12 km/h but requires a shaft power corresponding to 15 km/h. This will influence the range upstream and downstream for the E-Pusher. Another aspect incorporated is because of losses in energy of manoeuvring and charging. Therefore, an energy efficiency factor is added for the E-Pusher, which is 0.8. Similarly, as in the financial calculation, the compression energy is also neglected for the environmental variables. For all included transport modes the compression energy is crossed against each other.

- Litre diesel per hour sailing [L/h] = diesel:power ratio [L/kW] * shaft power per hour [kW/h]

$$g = b * Ps \tag{13}$$

- Sailing hours [h/cycle] = Transport time OD [h/cycle] + Transport time DO [h/cycle] (Not same as cycle time, because cycle time includes loading and unloading times)

$$Ts = Tod + Tdo \tag{14}$$

- Fuel Consumption [L/cycle] = Litre diesel per hour sailing [L/h] * sailing hours [h/cycle]

$$j = g * Ts \tag{15}$$

Output Variables: ***Operational***

- Cycle time [h] = Transport time O-D [h] + loading time [h] + transport time D-O [h] + Unloading time + 2 * Lock interference [h]

$$CT = Tod + Tl + Tdo + Tu + 2 * ta \tag{16}$$

- Annual volume transported [MTPA] = fleet size [#vessels] * annual cycles per vessels [#cycles / year / vessel] * load rate [ton/cycle] * 10^{-6}

$$AVT = F * ACv * Lr * 10^{-6} \tag{17}$$

Output Variables: ***Financial***
The financial data of the barge and the E-Pusher is based on internal data provided by KOTUG. The financial data for modelling truck transport is provided by a container trucking company. Risk is not included for truck transport. Determining the financial aspects of pipeline transport is by interpolation of the data from (Knoope et al., 2013; ZEP, nd). The interpolation is done for determining the costs for both CAPEX and OPEX of a pipeline per km. This way, it is possible to estimate costs for a certain trajectory by multiplying the euclidean distance with the interpolated value for costs per km. The interpolation data is estimations of a 2.5 MTPA pipeline and a 10 MTPA pipeline in Europe. Assumed is thus, that in case of a pipeline enough demand for the annual volume transported is available. As a result, the transport flow for pipeline is considered as continuous, whereby it for the waterway and roadway modes was considered as continuous.

- CAPEX [€/ year] = Av Depreciation per year [€/ year] + Av interest per year [€/ year]

$$CAPEX = Dcosts + Icosts \tag{18}$$

- OPEX [€/ year] = Crew costs [€/ year] + Operational depreciation [€/ year] + Fuel costs [€/ year] + overhead [€/ year]

$$OPEX = Crewcosts + ODcosts + Fcosts + Ocosts \tag{19}$$

- Risk [€/ year] = Risk factor [-] * (CAPEX [€/ year] + OPEX [€/ year])

$$RISK = Rf * (CAPEX + OPEX) \tag{20}$$

- Summarised Costs [€/ year] = CAPEX [€/ year] + OPEX [€/ year] + Risk [€/ year]

$$AC = RISK + CAPEX + OPEX \tag{21}$$

Output Variables: *Environmental*
Because a wide consensus on emissions calculations does not exist, two ways of calculating the emissions are used in this research to reflect the emissions from different methods. The first one is called the KOTUG Calculation, which is based on the fuel consumption given certain shaft powers. The second one is based on the calculation method of CE Delft (2021), whereby emission factors are used to multiply with the transport performance. Because it is expected that the E-Pusher has a higher cycle time because of charging batteries and a lower SOG, the annual volume transported is also expected to be lower. Furthermore, the fuel consumption would be different if an STW of 12 km/h is considered instead of a 15 km/h (STW). Therefore, a fair comparison should be made concerning the actual emissions savings of the E-Pusher. The emissions of the E-Pusher will be reported based on a barge that has a similar operational profile as the E-Pusher, thus not a general barge. This will be often mentioned as a barge based on the operational profile of the E-Pusher.

- Emissions KOTUG [kg CO2 / year] = Fleet size [vessel] * emission factor [kg CO2 / Litre] * vessel consumption cycle [Litre /cycle / vessel] * Annual cycles per vessel [cycles / vessel]

$$EMkotug = F * a * j * ACv \tag{22}$$

- Emissions CEDelft [kg CO2 / year] = Fleet size [vessel] * emission factor [kg CO2 / tonne-km] * Transport Performance [tonne-km / cycle / vessel] * Annual cycles per vessel [cycles / vessel]

$$EMCEdelft = F * EF * TPc * ACv \tag{23}$$

7.5 Scenario Generation

In this subsection of the research, the scenarios will be generated. The scenarios will be built based on different transport distances. The destinations are derived from the Aker Carbon Capture map to pursue realistic trajectories. Generally, the transported volume is considered an input variable or requirement to model trajectories in comparison studies between different transport modes. Aligning with Section 3.1, in this study it is modelled as output because it is a KPI. For each scenario, four configurations (transport modalities) will be modelled, namely, barge transport, truck transport, pipeline transport and E-Pusher transport. The barge transport will be modelled as the benchmark. The distance will be derived for each transport mode based on the trajectory characteristics of that transport mode. Thus, the waterway distance will be modelled for the barge and E-Pusher transport, the roadway distance for the truck transport and the euclidean distance for the pipeline transport. Noted should be that for pipeline transport the euclidean distance is an assumption. In practice, some restrictions could occur, resulting in a not fully euclidean distance. Different tools are used to determine the distance. For waterway distance, the calculator of *http://marineplan.com/* is used, for truck transport, the calculator of *https://impargo.de/en* is used and for pipeline transport, the calculator of *https://www.afstandmeten.nl/* is used. Another aspect that is depicted in the scenario configurations of the E-Pusher is the pictogram of the charging facilities. The model will incorporate the implementation of charging facilities between certain distances. But the pictograms are just indicative, so not the real number of facilities nor the exact location of the facilities is already modelled. Lastly, the black bar at the right side of the figures indicates the information retrieved by the Aker Carbon Capture map. Information includes CO2 emitted, the year of the provided data, and activities causing CO2 emissions. Below, each scenario and corresponding configurations are briefly explained.

Scenario 1 (Very short distance): Rotterdam Yangtzehaven - Rotterdam Botlek
As can be derived from Figure 39, the Yangtzehaven in the Port of Rotterdam is the considered as proposed terminal and thus the origin of the first scenario. The destination is in the Botlek area. For the waterway modes, configurations 1.1 and 1.4, the waterway distance is 25 km. For the truck mode, configuration 1.2, the roadway distance is 25 km. For the pipeline mode, configuration 1.3, the euclidean distance is used which is 20 km.

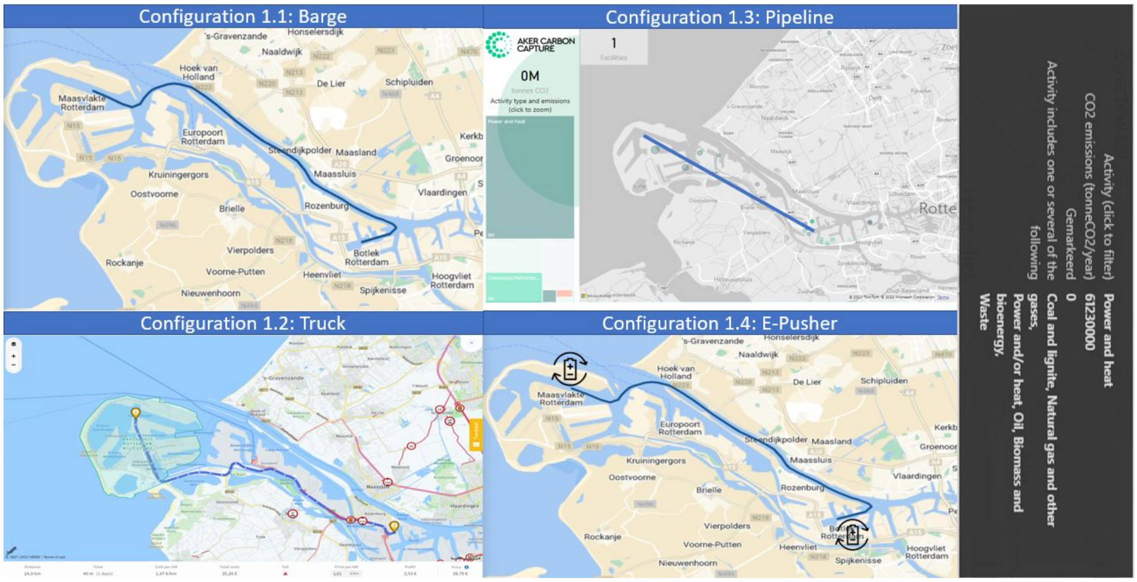


Figure 39: Scenario design 1 and configurations

Scenario 2 (Short distance): Rotterdam Yangtzehaven - Moerdijk

As can be derived from Figure 40, the Yangtzehaven in the Port of Rotterdam is the considered as proposed terminal and thus the origin of the first scenario. The destination is in the Moerdijk area. For the waterway modes, configurations 2.1 and 2.4, the waterway distance is 65 km. For the truck mode, configuration 2.2, the roadway distance is 85 km. For the pipeline mode, configuration 2.3, the euclidean distance is used which is 50 km.

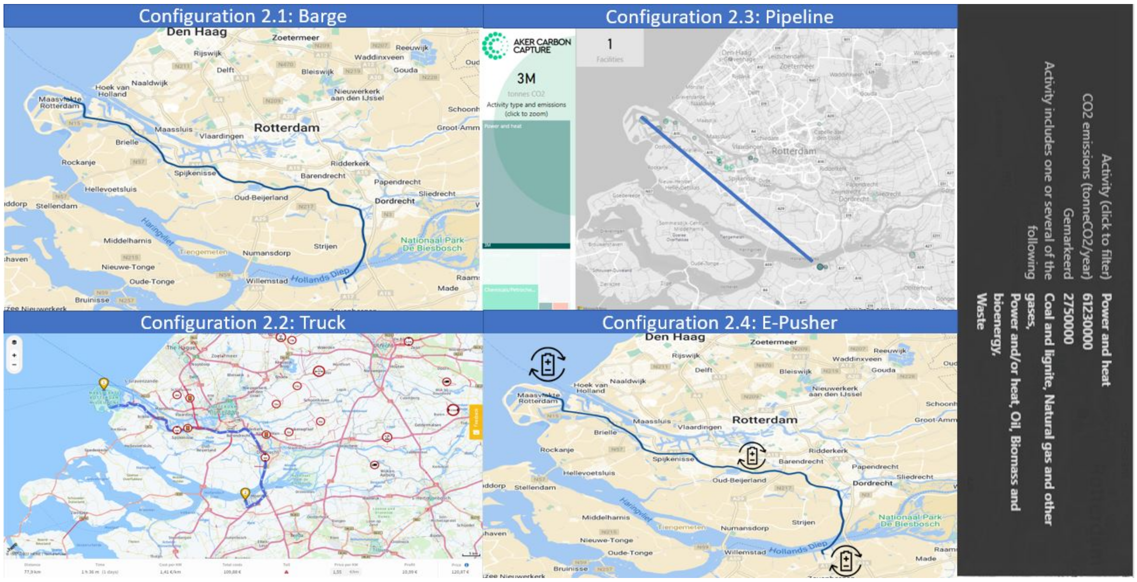


Figure 40: Scenario design 2 and configurations

Scenario 3 (Medium distance): Rotterdam Yangtzehaven - Arnhem

As can be derived from Figure 41, the Yangtzehaven in the Port of Rotterdam is the considered as proposed terminal and thus the origin of the first scenario. The destination is in Arnhem. For the waterway modes, configurations 3.1 and 3.4, the waterway distance is 175 km. For the truck mode, configuration 3.2, the roadway distance is 155 km. For the pipeline mode, configuration 3.3, the euclidean distance is used which is 135 km.

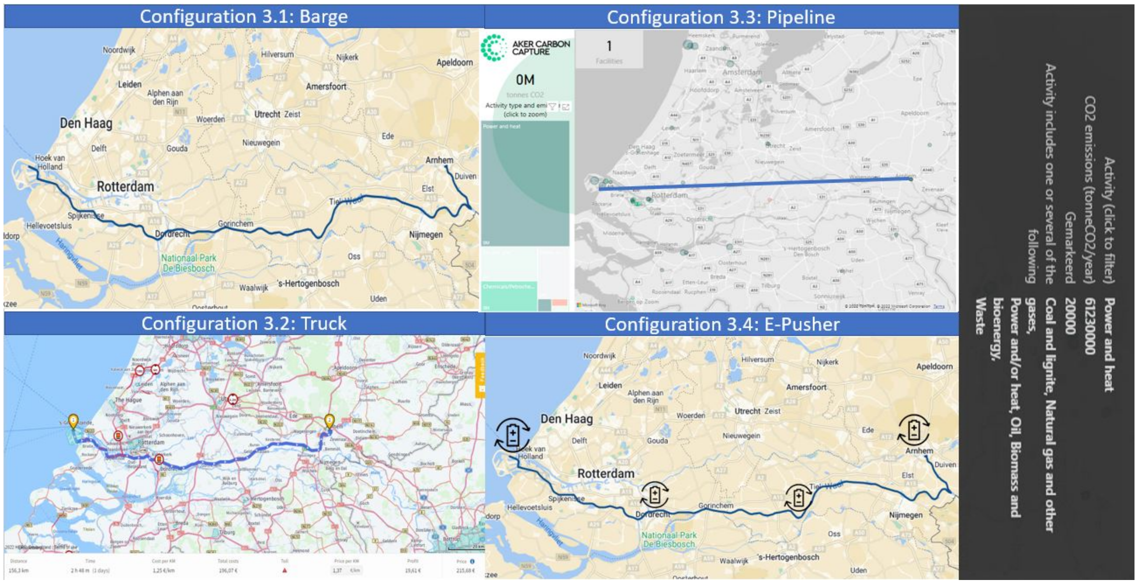


Figure 41: Scenario design 3 and configurations

Scenario 4 (Large distance): Rotterdam Yangtzehaven - Duisburg

As can be derived from Figure 42, the Yangtzehaven in the Port of Rotterdam is the considered as proposed terminal and thus the origin of the first scenario. The destination is in Arnhem. For the waterway modes, configurations 4.1 and 4.4, the waterway distance is 235 km. For the truck mode, configuration 4.2, the roadway distance is 245 km. For the pipeline mode, configuration 4.3, the euclidean distance is used which is 195 km.

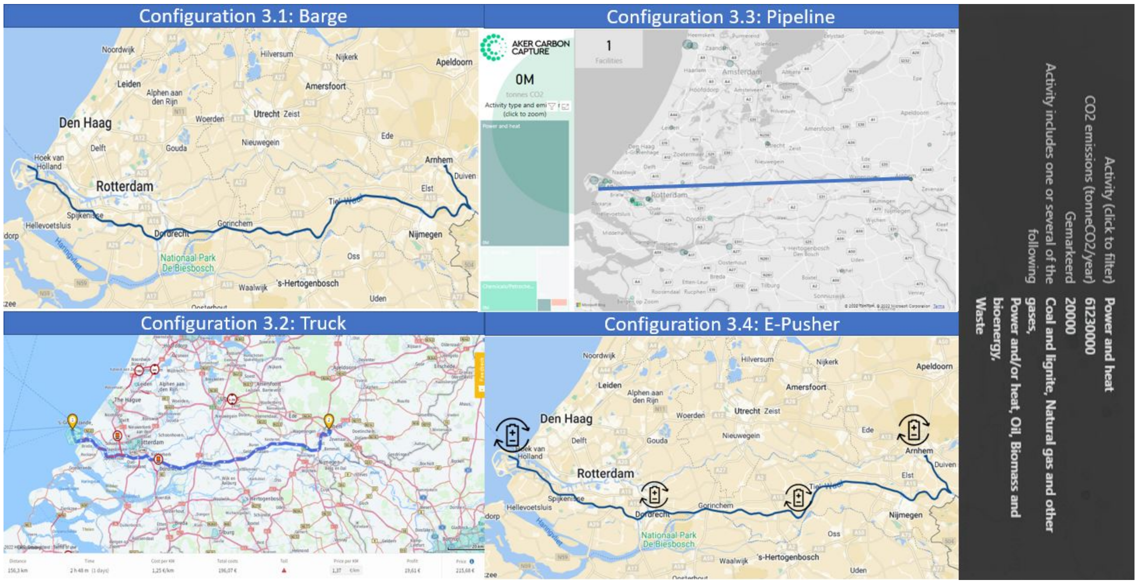


Figure 42: Scenario design 4 and configurations

Part IV

Integrate

8 Simulation and Results

In this section, the fifth sub-question will be answered by executing a simulation of the built model for all scenarios in Microsoft Excel. The model and the scenarios that are built are explained in Section 7. This section will illustrate and explain the results resulting from executing the model for each scenario. Consequently, it is attempted to approach the answer to the fifth sub-question, which was formulated as follows:

5. *What is the impact of deploying the E-Pusher in the transportation stage of CCS, to the outcomes of the KPIs and trade-off between the KPIs of other possible transport modes?*

8.1 Scenario 1: Rotterdam Yangtzehaven - Rotterdam Botlek

The first scenario is the trajectory with a very short distance, approximately 25 km. What can be observed from Table 4, is that the E-Pusher has an equal cycle time as the general barge. The difference in annual volume transported between the two transport modes by water is 0.14 MTPA. The costs per year for both waterway modes are of similar magnitude. The barge emissions and the emissions if a barge will be considered based on the E-Pushers' operational profile are also more or less the same. The emissions of a barge and a barge based on the operational profile of the E-Pusher are not very different within each separate calculation method for determining the emissions. In case, the emission outcomes of both calculation methods are compared to each other, it can be noticed that there is a relatively high difference in the outcomes for both the barge and a barge based on the E-Pushers' operational profile. The truck emissions are not very different for both calculations. The cycle time for a single truck and the corresponding costs are low in comparison with the waterway modes. However, also the annual volume transported is extremely low compared to the barge and the E-Pusher. The pipelines have a fixed amount of volume, the corresponding costs are two to four times higher than a single vessel's costs.

Table 4: KPI Table scenario 1

	CT [H]	AVT [MTPA]	AC [€/year]	EMkotug [kg CO2 / year]	EMcedelft [kg CO2 / year]
Barge	14	2.07	1,369,626	541000	878486
Truck	3	0.02	153,820	35501	30585
Pipe	N/A	2.5	3,546,235	N/A	N/A
Pipe	N/A	10	5,429,412	N/A	N/A
E-Pusher	14	1.93	1,340,598	* 540021	* 818833

* Emissions of the E-Pusher are noted if an barge that would operate under the operational profile of the E-Pusher

Noted should be that the values from Table 4 are not normalised and each transport mode is assumed to have one vessel, truck or pipe. Therefore, it is interesting to highlight the outcomes presented in Table 5, whereby some of the KPIs outcomes are divided into each other. Regarding the costs in euros per ton transported it can be observed that the pipe of 10 MTPA has the lowest value by the general barge and the E-Pusher with similar cost per ton for both waterway modes. The cost per ton for the pipe of 2.5 MTPA is two and a half times higher than for the 10 MTPA pipe. The truck has extremely high costs per ton compared to the other modes, a factor of 10-13 times higher than the waterway modes. The costs per ton transported for all transport modes are plotted in Figure 43. Concerning the emissions in the calculation provided by KOTUG, a barge and a barge based on the E-Pusher's operational profile emit 0.26 and 028 kg CO2 per ton transported, respectively. In the CE Delft method, this value is 0.43 kg CO2 per ton transported for both vessels. Where in the KOTUG calculation the emissions of a truck are approximately seven times higher than a vessel, it is in the CEDelft calculation slightly less than four times higher than a vessel's emissions, see Figure 44.

Table 5: Trade-off table for scenario 1

	AC / AVT [€/ ton]	EMkotug / AVT [kg CO2 / ton]	EMcedelft / AVT [kg CO2 / ton]	NettoCO2 KOTUG [%]	NettoCO2 CEDelft [%]
Barge	0.66	0.26	0.43	99.97	99.96
Truck	8.05	1.86	1.60	99.81	99.84
Pipe (2.5 MTPA)	1.42	N/A	N/A	N/A	N/A
Pipe (10 MTPA)	0.54	N/A	N/A	N/A	N/A
E-Pusher	0.70	* 0.28	* 0.43	* 99.97	*99.96

* Emissions of the E-Pusher are noted if an barge that would operate under the operational profile of the E-Pusher

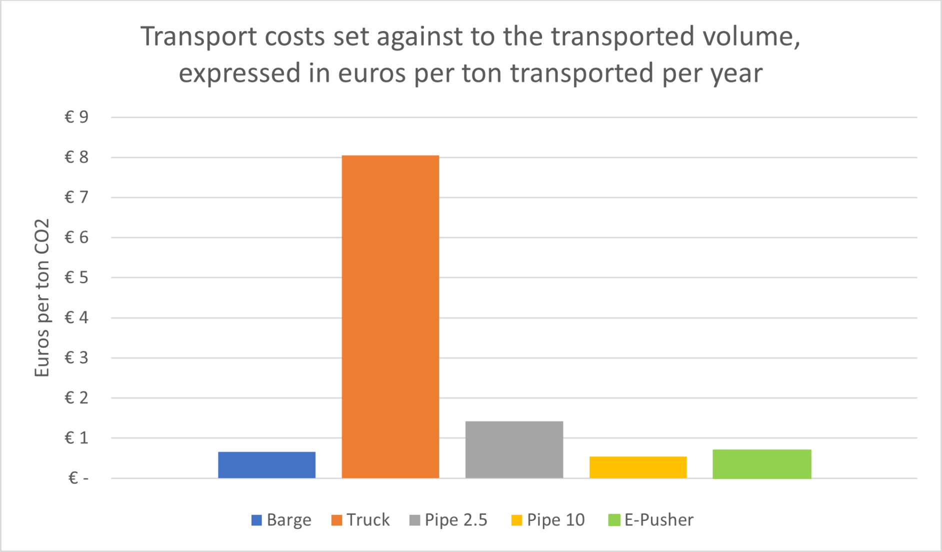


Figure 43: Plotted trade-off between costs and volume transported in scenario 1

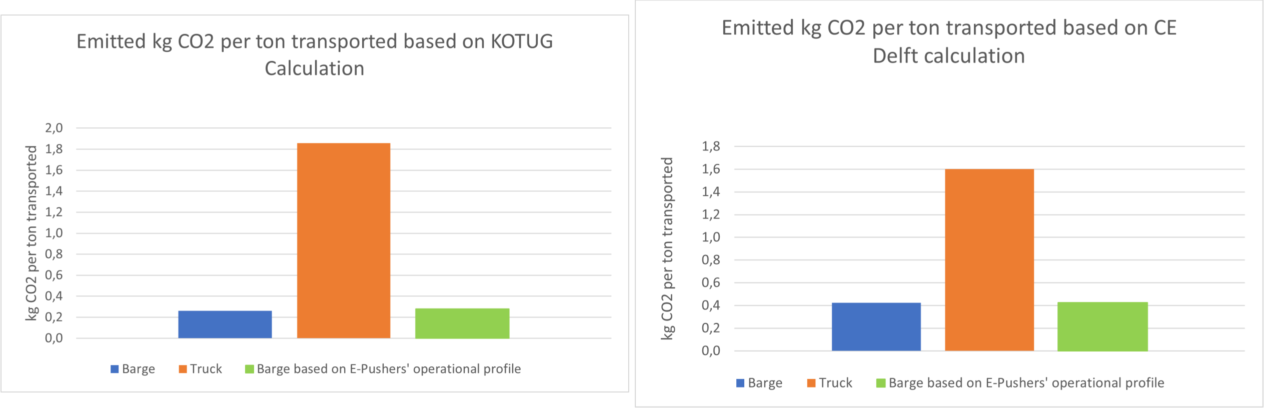


Figure 44: Plotted trade-offs for emissions to transported volume in scenario 1

8.2 Scenario 2: Rotterdam Yangtzehaven - Moerdijk

The second scenario is the trajectory with a short distance, approximately 65 km. What can be observed from Table 6, is that the E-Pusher has an extra hour cycle time than the general barge. The difference in annual volume transported between the two transport modes by water is 0.16 MTPA. The costs per year in these configurations vary by approximately ten percent, in the advantage of the E-Pusher. Similarly, as in scenario 1, the emissions per year for the barges are approximately one and a half times higher in the CE Delft calculation than in the KOTUG calculation. A difference for truck transport in this scenario compared to scenario 1, is that for the CEDelft emissions calculation the emissions per year are higher than for the KOTUG calculation. Likewise, in scenario 1, also in scenario 2, the cycle time, corresponding costs per year and the annual transported volume are low for truck transport in comparison with the waterway modes. The pipeline costs per year for the modelled configurations in this scenario are six to eight times higher than vessel costs per year.

Table 6: KPI Table scenario 2

	CT [H]	AVT [MTPA]	AC [€/year]	EMkotug [kg CO2 / year]	EMcedelft [kg CO2 / year]
Barge	21	1.41	1,564,667	958578	1556555
Truck	5	0.01	186,317	69702	60051
Pipe	N/A	2.5	8,865,588	N/A	N/A
Pipe	N/A	10	13,573,529	N/A	N/A
E-Pusher	22	1.25	1,414,135	*909189	* 1378601

* Emissions of the E-Pusher are noted if an barge that would operate under the operational profile of the E-Pusher

The barge costs per ton transported are the lowest, closely followed by the E-Pusher. Also, a pipeline of 10 MTPA would have low costs per ton transported in this scenario. A pipe of 2.5 MTPA would have three times the costs per year of a barge or an E-Pusher in this scenario. The truck has extremely high costs per ton. The emissions per year, derived from the KOTUG calculation, for a general barge and barge based on the E-Pushers' operational profile would be 0.68 and 0.73 kg CO2 per ton transported, respectively. Truck transport would emit almost ten times more. If the emissions per year would be calculated based on the CE Delft method, the truck emissions per year would be five times higher than the barge emissions per year in this scenario. The outcomes of the trade-offs in this scenario are presented in Figure 45 and Figure 46.

Table 7: Trade-off table for scenario 2

	AC / AVT [€/ ton]	EMkotug / AVT [kg CO2 / ton]	EMcedelft / AVT [kg CO2 / ton]	NettoCO2 KOTUG [%]	NettoCO2 CEDelft [%]
Barge	1.11	0.68	1.11	99.93	99.89
Truck	16.88	6.31	5.44	99.37	99.46
Pipe (2.5 MTPA)	3.55	N/A	N/A	N/A	N/A
Pipe (10 MTPA)	1.36	N/A	N/A	N/A	N/A
E-Pusher	1.13	*0.73	*1.11	* 99.93	* 99.89

* Emissions of the E-Pusher are noted if an barge that would operate under the operational profile of the E-Pusher

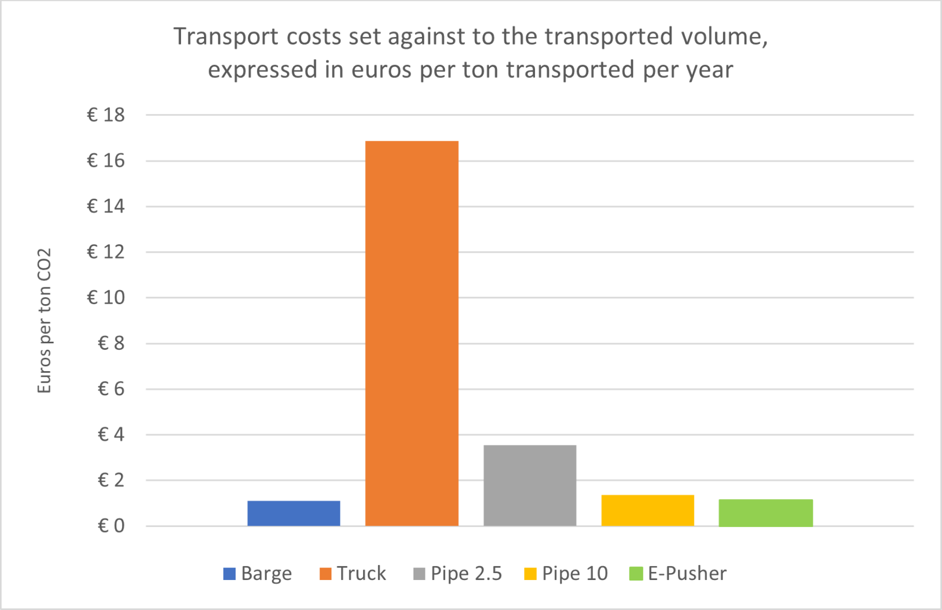


Figure 45: Plotted trade-off between costs and volume transported in scenario 2

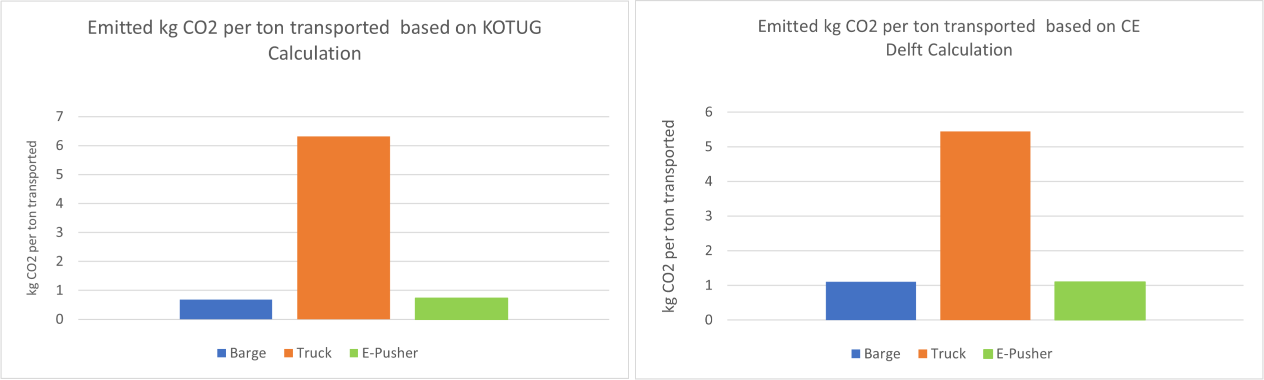


Figure 46: Plotted trade-offs for emissions to transported volume in scenario 2

8.3 Scenario 3: Rotterdam Yangtzehaven - Arnhem

The third scenario is the trajectory with a medium distance, approximately 175km. What can be observed from Table 8, is that the E-Pusher requires five extra hours for the cycle time compared to the general barge. The difference in MTPA between the two transport modes by water is 0.13 MTPA. The variation in costs per year for these configurations is similar to scenario 2 between both waterway modes. What is also similar to the previous scenarios, are the emissions per year for the barges that are approximately one and a half times higher in the CE Delft calculation than in the KOTUG calculation. The costs per year for implementing a pipeline of 2.5 MTPA and 10 MTPA are fourteen to twenty-one times higher than the costs of implementing the vessels.

Table 8: KPI Table scenario 3

	CT [H]	AVT [MTPA]	AC [€/year]	EMkotug [kg CO2 / year]	EMcedelft [kg CO2 / year]
Barge	39	0.75	1,759,517	1375747	2233963
Truck	7	0.01	200,982	85135	73347
Pipe	N/A	2.5	23,937,088	N/A	N/A
Pipe	N/A	10	36,648,529	N/A	N/A
E-Pusher	44	0.62	1,614,655	*1215059	* 1842392

* Emissions of the E-Pusher are noted if an barge that would operate under the operational profile of the E-Pusher

In this scenario, the barge costs per ton are the lowest. The E-Pusher's costs per ton are around ten percent higher than the barge costs per ton. A pipeline of 10 MTPA is followed with also relatively low costs per ton in comparison with the remaining modes. A pipeline of 2.5 MTPA has high costs per ton. Truck transport has more than ten times higher costs per year than the waterway modes in this scenario. Also, the truck transport emissions per year are ten times higher than that for barge transport, derived by the KOTUG calculation. The CE Delft calculation results in three times higher emissions per year for truck transport than that for barge transport. The outcomes of the trade-offs in this scenario are presented in Figure 47 and Figure 48.

Table 9: Trade-off table for scenario 3

	AC / AVT [€/ ton]	EMkotug / AVT [kg CO2 / ton]	EMcedelft / AVT [kg CO2 / ton]	NettoCO2 KOTUG [%]	NettoCO2 CEDelft [%]
Barge	2.34	1.83	2.98	99.93	99.89
Truck	27.18	11.51	9.92	99.37	99.46
Pipe (2.5 MTPA)	9.57	N/A	N/A	N/A	N/A
Pipe (10 MTPA)	3.66	N/A	N/A	N/A	N/A
E-Pusher	2.61	*1.96	*2.98	* 99.93	* 99.89

* Emissions of the E-Pusher are noted if an barge that would operate under the operational profile of the E-Pusher

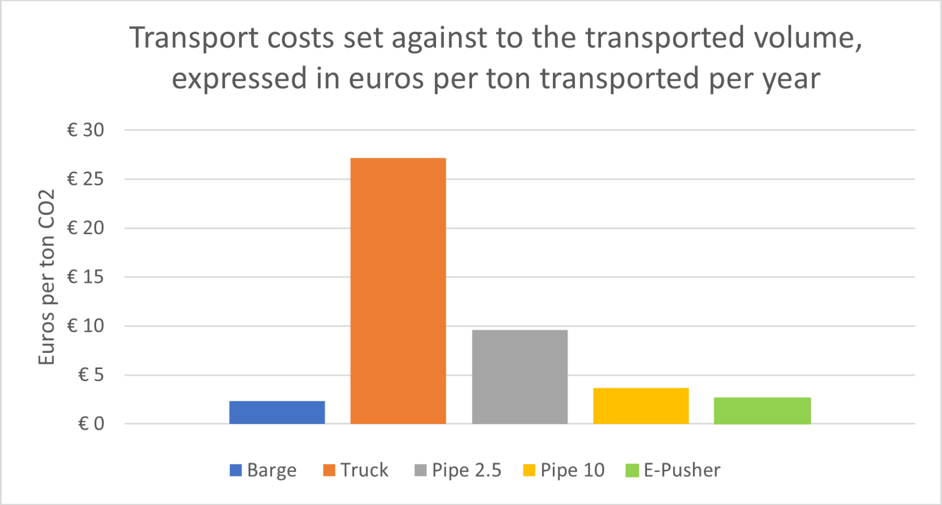


Figure 47: Plotted trade-off between costs and volume transported in scenario 3

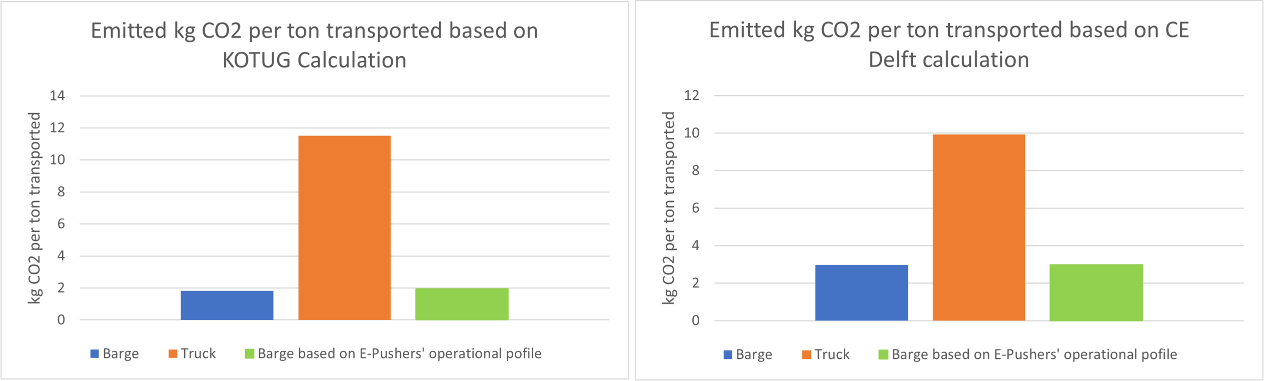


Figure 48: Plotted trade-offs for emissions to transported volume in scenario 3

8.4 Scenario 4: Rotterdam Yangtzehaven - Duisburg

The fourth scenario is the trajectory with a large distance, approximately 235 km. What should be noted is that the pipeline of 2.5 MTPA is excluded from the model for this scenario. In literature, no reliable interpolation values were available for this configuration and for such small volumes over long distances it is most likely not feasible to implement a pipeline (Knoope et al., 2015). Nevertheless, the other four transport possibilities were still analysed for this scenario. What can be observed from Table 10, is that the cycle time for the E-Pusher takes eight hours longer compared to a general barge. The difference in annual volume transported between the two transport modes by water is 0.11 MTPA. The variation in costs per year between both waterway modes is similar to the previous scenarios. Also, for the waterway modes, the differences in emission per year outcomes between the KOTUG calculation method and the CE Delft calculation method are from similar levels. The truck emissions per year are in the CE Delft calculation method around sixteen percent lower than in the KOTUG calculation method. The pipeline costs per year for the modelled configuration in this scenario are about twenty-five times higher than vessel costs per year.

Table 10: KPI Table scenario 4

	CT [H]	AVT [MTPA]	AC [€/year]	EMkotug [kg CO2 / year]	EMcedelft [kg CO2 / year]
Barge	49	0.6	1,804,673	1472424	2390948
Truck	11	0.01	209,847	94465	81385
Pipe	N/A	10	50,054,063	N/A	N/A
E-Pusher	57	0.49	1,617,746	*1281055	*1942462

* Emissions of the E-Pusher are noted if an barge that would operate under the operational profile of the E-Pusher

In this scenario, the barge costs per ton transported are the lowest, closely followed by the E-Pusher. The pipeline is around two-thirds higher in euros per ton than the barge transport. That is a factor of one and a half higher. The costs per ton for truck transport are thirteen times as high as for barge transport, regarding the costs per year. Derived from the KOTUG calculation method, the emissions per year, for a general barge and barge based on the E-Pushers' operational profile would be 2.46 and 2.63 kg CO2 per ton transported, respectively. Truck transport would emit around seven times more. If the emissions would be calculated based on the CE Delft method, the truck emissions would be four times higher than the barge emissions in this scenario. The outcomes of the trade-offs in this scenario are presented in Figure 49 and Figure 50.

Table 11: Trade-off table for scenario 4

	AC / AVT [€/ ton]	EMkotug / AVT [kg CO2 / ton]	EMcedelft / AVT [kg CO2 / ton]	NettoCO2 KOTUG [%]	NettoCO2 CEDelft [%]
Barge	3.02	2.46	4.00	99.75	99.60
Truck	40.43	18.20	15.68	98.18	98.43
Pipe (10 MTPA)	5.01	N/A	N/A	N/A	N/A
E-Pusher	3.33	*2.63	* 4.00	* 99.74	99.60

* Emissions of the E-Pusher are noted if an barge that would operate under the operational profile of the E-Pusher

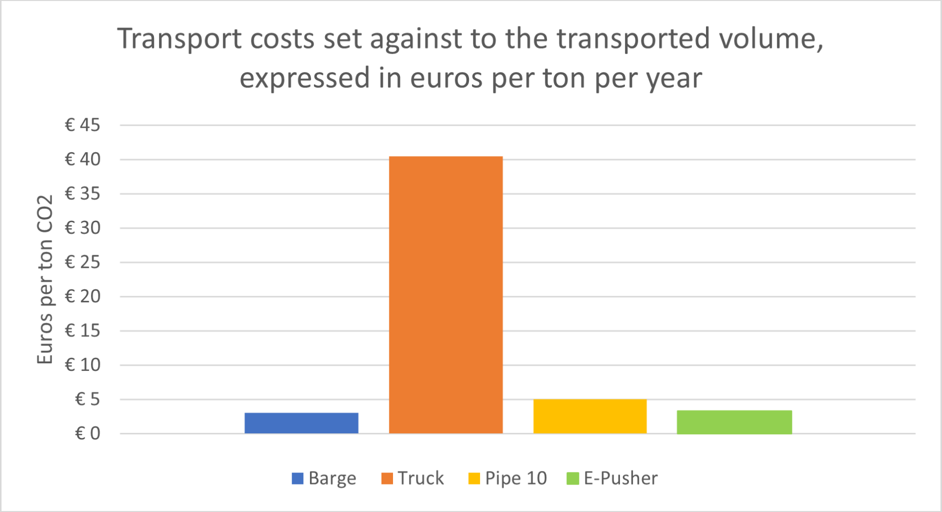


Figure 49: Plotted Trade-off between costs and volume transported in scenario 4

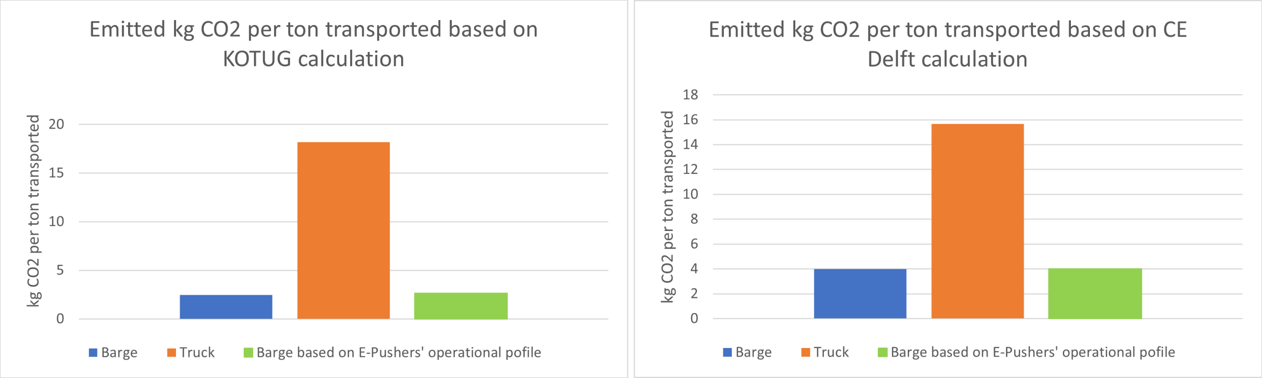


Figure 50: Plotted trade-offs for emissions to transported volume in scenario 4

8.5 Overall Results

In this subsection, the results of all scenarios will be incorporated and presented differently than in the previous sections. In the graphs below, the distance is displayed on the X-Axis, whereby the dots presented the distance points of the specific trajectory distances in the considered scenarios.

As be seen from Figure 51, for the first scenario, the truck costs are more than eight times higher than the waterway modes and the pipeline of 10 MTPA. This increases over further distances and is therefore even not visible on the graph anymore. Furthermore, can be derived from Figure 51, that a pipeline of 2.5 MTPA on short distance is concerning the costs per ton two times higher than the other remaining modes. If the distance increases, the difference in costs per ton will only further increase for the 2.5 MTPA pipe compared to the other modes, with lower costs per ton. Eventually, as stated in Section 8.4, is a pipeline of 2.5 MTPA not economically feasible from a large distance and therefore not modelled anymore. The general barge, E-Pusher and pipeline of 10 MTPA are for a very short distance similar in respect to the euros per ton transported. Approaching a short distance will lead to an increase in euros per ton for the pipeline in comparison with the waterway modes, which will in their turn remain similar to each other concerning the costs per ton. If the distance increases to medium distances, the difference in euros per ton transported for the pipeline of 10 MTPA will even become more than for the waterway modes. Thus a higher difference in costs per ton is observed at medium distances, for the 10 MTPA pipe compared to the waterway modes, than in short distances. This linear development will be more extreme if a large distance is encountered as a trajectory. In the medium distance, the first significant difference in costs between the general barge and the E-Pusher will occur, with lower costs in euros per ton for the general barge. Also, this difference will develop linear to large distances. Finally, for large distances, the general barge will be slightly lower in cost per ton than the E-Pusher, approximately 0.30 euros per ton, namely.

In Figure 52 it is highlighted that the emissions per ton curves over the different distances for the barge and the barge based on the E-Pusher's operational profile will develop linearly with similar outcomes at the different distance points. This behaviour could be observed both within the KOTUG calculation method and the CE Delft calculation method for emissions per ton. Also for the truck, the behaviour of the emissions develops similarly in both calculations. What should be noticed is that the behaviour of the curve between different modelled distances develops not similar. Within the first step from very short distance to a short distance, the curve is much steeper than in the successive step from short distance to the medium distance. For large distances, the truck emits seven times more CO2 per ton transported than barge transport, based on the KOTUG calculation. Regarding the CE Delft calculations, truck transport emits approximately four times more kg CO2 per ton transported.

In Figure 53, it can be seen that the net CO2 percentage is decreasing if the distance increase. This is both for the KOTUG as CE Delft calculation method. In the KOTUG calculation the net CO2 percentage decrease from very short to large distances with 0.22 %. For the CE Delft calculation, the net CO2 percentage decrease with 0.36 % from very short to large distances.

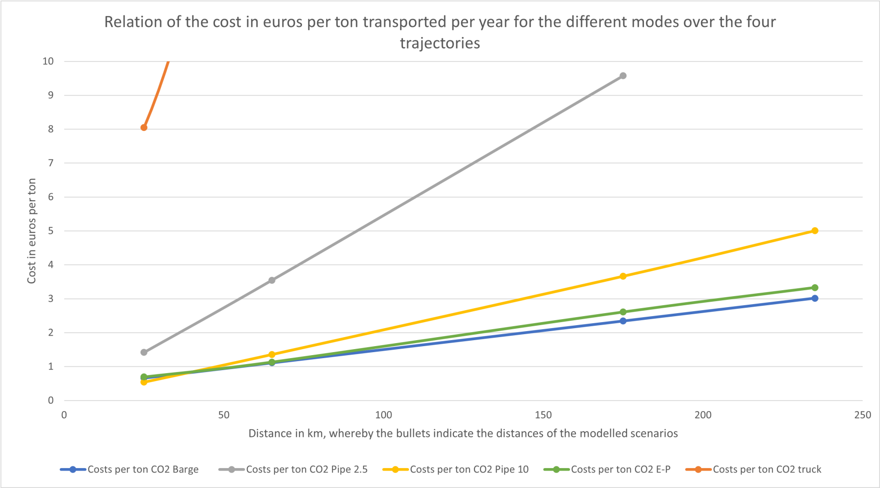


Figure 51: Relation of the cost per ton over the distances

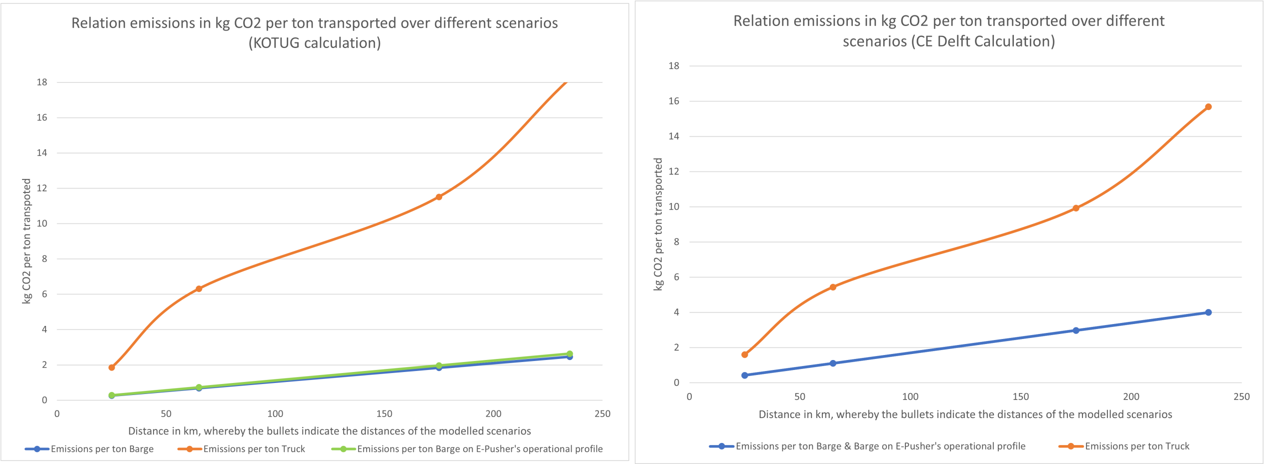


Figure 52: Relations of the emissions per ton over the different scenarios

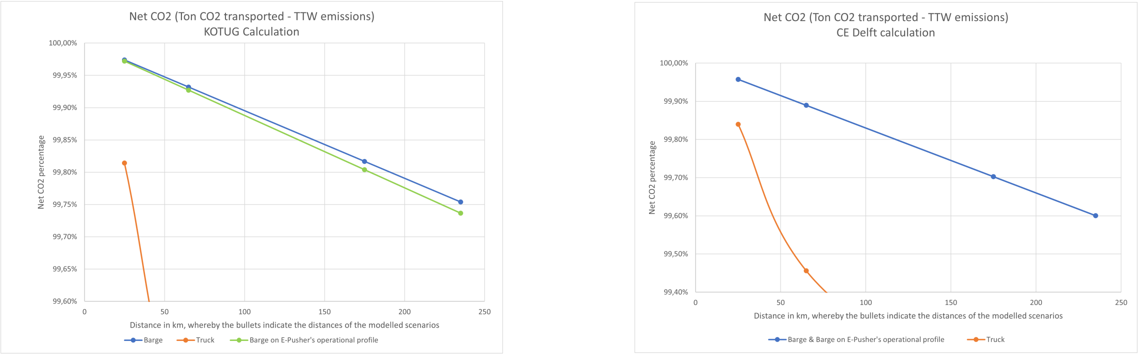


Figure 53: Relations of the net CO2 percentage over the different scenarios

8.6 Conclusion

This chapter has answered the following sub-question:

5. *What is the impact of deploying the E-Pusher in the transportation stage of CCS, to the outcomes of the KPIs and trade-off between the KPIs of other possible transport modes?*

From an economical point of view, the transport modes truck and the 2.5 MTPA pipeline are not very competitive. Furthermore, from an environmental point of view, the truck has high emissions per ton concerning the waterway modes. A pipeline of 10 MTPA has more potential in all scenarios than a truck and a pipeline of 2.5 MTPA, given a cost perspective. For very short distances, a pipeline of 10 MTPA has even the lowest costs per ton. The best performance concerning costs per ton in all the scenarios is for the waterway modes. As long the distance increases, the general barge would have the lowest costs per ton, given a range from 25 km to 235 km. The E-Pusher is very competitive, regarding costs per ton, till short distances. But, even for medium and large distances, the barge would not extremely outperform the E-Pusher in costs per ton. A critical note is that these results are calculated based on the values of the input parameters. Some values of the input parameters could be considered volatile. Therefore, it is interesting to highlight the impact of certain developments such as changed fuel or electricity prices, decreasing loading degrees because of waterway restrictions, and changed CAPEX for pipeline costs to the obtained results in this section.

Regarding the emissions, a barge and a barge based on the E-Pusher's operational profile perform similarly for all distances. Therefore, the results of those could be generalised. As explained in Section 6.3, the E-Pusher has zero TTW emissions, the direct savings of emissions at certain distances for deploying the E-Pusher could be derived from the graph. Following the results from the KOTUG Calculation, the emissions savings in kg CO2 per ton transported for the different distances are approximately 0.26 at 25 km, 0.68 at 65 km, 1.83 at 175 km, and 2.46 at 235 km. Remarkable is that the emissions per ton in the CE Delft calculation are slightly higher than one and a half times the emissions per ton in the KOTUG calculation. The difference can be declared by the fact that the KOTUG calculation considered the number of litres required for a cycle, and then it is multiplied by the emission ratio, 2.6 kg CO2 per litre. While, in the CE Delft calculation emissions are calculated by the transport performance, expressed in tonne-kilometre. The CE Delft method uses average emission factors for loaded and unloaded trips. The percentage net CO2 decreases from very short distances to large distances with 0.22 % for the KOTUG and 0.36 % for CE Delft calculation. The impact of deploying the E-Pusher on the emission savings would thus be higher at larger distances.

Part V

Evaluate

9 Discussion, Evaluation and Sensitivity

In this chapter, the way of modelling and the obtained results are evaluated. First, the assumptions made, are highlighted from a critical perspective in the discussion points. Then, the results will be evaluated by a sensitivity analysis to see how robust the findings are to potential developments. Lastly, the validation of assumptions and the scientific contribution of this thesis will be outlined. Following the mentioned sequence above leads to an answer to the last sub-question of this research, which will not be presented in this chapter but in the conclusion part in Section 10.1. The last sub-question was formulated as follows:

6. *Which potential developments have an impact related to the feasibility of deploying the E-Pusher in CCS?*

9.1 Discussion

- In this research, the CCS scope is orientated to the Netherlands and surrounding countries. The implementation of CCS projects is in the preliminary stage. The CCS implementation in itself will encounter several extra challenges not mentioned in this research. The most recent challenge is that the Porthos project is delayed because of restrictions for new construction plans (Porthos, 2022).

- KOTUG offered an interesting use case with the E-Pusher. The operational configuration analysed for the E-Pusher in this research provided interesting results. However, the uniqueness of the configuration limits the possibility to generalise the findings of the E-Pusher to other operational configurations. Also, it cannot be concluded what other emission-free vessels, with different operational configurations, have potential in onshore CCS chains.

- Several linear relations could be observed, for instance for cost per ton over distance. The number of transportation units is assumed to be irrelevant to the linear relation. It is only used as multiplying factor, and thus is considered that extra transportation units would have a similar cargo capacity. In practice, it could be that sharing infrastructure could lead to lower costs, or that the transportation units of certain transport modes can have different capacities. Also, certain relations for calculating the emissions are linearly modelled.

- Following the adapted framework led to calculating the KPIs based on the input and intermediate variables. So given the operational characteristics of the transport modes, the KPIs were calculated. But in practice, it might be the reverse. For instance, the annual volume transported could be a given requirement that has to be met. Given a fixed amount of volume that has to be transported, it should be calculated how many cycles are required, the corresponding costs and emissions. This could change the position of the transport modes, in respect of the lowest costs per ton.

- As can be observed from the results, the different calculation tools for the emissions led to different outcomes. No wide consensus exists about what is the best calculation tool for emissions in CCS chains. Regarding, the wide range of outcomes for the emissions, a critical perspective is required if saved emissions are announced or published.
- The estimations for the pipeline costs were based on interpolation and cost data found in literature about previous studies in Europe. Consulting an expert in pipeline modelling from TNO, also for CCS chains, led to the finding that it is a decent first estimate. However, a more detailed estimation tool is the one from Knoope et al. (2015). The OPEX of the pipeline is in this study considered as a function of the compression and corresponding pressure drop.
- Another aspect that is not incorporated while modelling pipeline transport in the different scenarios is that existing or building plans for pipelines are not considered in the model. An already established pipeline would save the CAPEX costs drastically.
- As derived from the literature review and expert consulting, a point-to-point network for onshore transport in CCS is considered in this research. Whereby, the origin is modelled as a hub for all destinations. The network typology might change over time if the implementation of CCS is in a more developed stage. Interesting could be what would be the effect on the potential of the E-Pusher, if another network typology is applicable. An example of a change in network typology is if inland hubs would be established, for collecting and distributing smaller quantities.
- Also, within a cycle of a waterway or roadway, it is assumed that one empty trip between the origin and destination is executed. Next to that, the transport flow can be considered for these modes as a discontinuous flow in discrete time steps. The assumption for pipeline mode was that given enough demand for volume, a continuous flow is applied. An important factor that is not considered in this research is the overall transport system efficiency if a certain transport mode is evaluated.
- As stated in the operational requirements from KOTUG in Section 6.5, the charging infrastructure is not widely implemented yet. In this research, it was assumed that enough charging facilities are available within the modelled trajectories. However, implementing charging infrastructure might be associated with a lot of challenges to overcome, such as safety risks, investment decisions and building restrictions.

9.2 Results Evaluation and Sensitivity

Several parameters are assigned to fixed values while in the practice these values might be volatile. Such parameters are for instance the fuel and electricity price, the CO2 opportunity factor, the loading degree and more. The impact of a 50% increase and decrease of these parameters on the results in the base case scenarios will be evaluated in this section. The full sensitivity analysis is performed in Appendix C. The most relevant results of this sensitivity analysis will be highlighted in this section.

An aspect, that also should be mentioned is that also a transition to electrifying trucks is ongoing nowadays. However, it is not chosen to analyse the impact of zero-emission trucks in the validation because the trucks are already highly outperformed, regarding the costs aspects. What is chosen to evaluate instead, is a halved and doubled CAPEX for the 10 MTPA pipeline mode. In section 9.1, it is mentioned that the pipeline costs can be much lower if an existing pipeline is used, or a pipeline is already under construction. Therefore, it is interesting to discover the impact of a halved CAPEX on the pipeline. Contrarily, it can be assumed that the CAPEX should be estimated as doubled in residential areas, areas with rivers or mountains. Consequently, it is chosen to experiment with an increase of 50% for the CAPEX of a pipeline. The truck mode and the pipe of 2.5 MTPA are excluded in this sensitivity analysis because the high differences in the outcomes of the base cases made them less interesting to further analyse.

Impact pricing developments

The impact of changes to prices such as fuel price, electricity price, CO2 opportunity factor and the CAPEX of a pipeline can be summarised as follows: Increasing fuel prices lead to higher costs per ton for the general barge, but the advantage for the E-Pusher is still minimal. In case, the electricity price will be halved, the E-Pusher will have similar costs per ton as the general barge. The E-Pushers' costs per ton is not very sensitive to an increase in the CO2 opportunity factor. The barge will still have the lowest costs per ton. A large impact can be observed if the CAPEX of the pipeline is halved. Remarkable is that the pipeline of 10 MTPA has the lowest costs per ton from very short to short distances. In the transition from short distances to medium distances, the barge will take over the lowest costs per ton position. The E-Pusher will have similar costs as the pipeline of 10 MTPA with a halved CAPEX for medium distances. Larger distances lead to a small advantage in costs per ton for the E-Pusher.

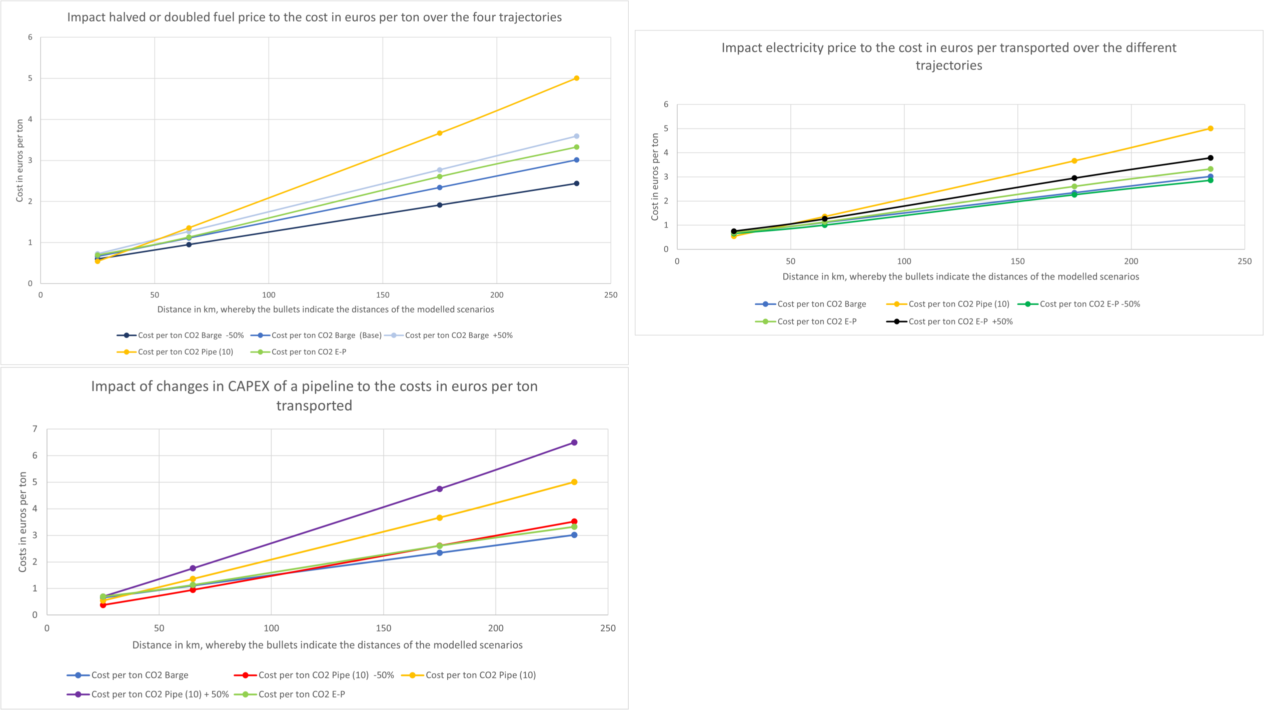


Figure 54: Sensitivity of cost per ton to pricing developments

Loading degree

The sensitivity of the results in the base cases to changes in the loading degree has only been experimented with for a decrease of 50% because a doubled loading degree requires other operational configurations. Fully loaded cargoes are assumed in the base case. A halved loading degree for the waterway modes leads to the lowest costs per ton for the pipeline of 10 MTPA over all distances considered. The emissions in kg CO2 per ton, in the KOTUG calculation, are doubled for both waterway modes, if half of the load is transported. It could be declared by the fact that the same amount of kg CO2 is emitted but the annual transport volume is halved. In the CE Delft calculation, the emissions were not sensitive to load changes. This could be declared by the way of modelling in the CE Delft method, namely, based on the transport performance in tonne-kilometre. A halved load rate, resulting in a halved tonne-kilometre per cycle is compensated by the halved annual volume transported.

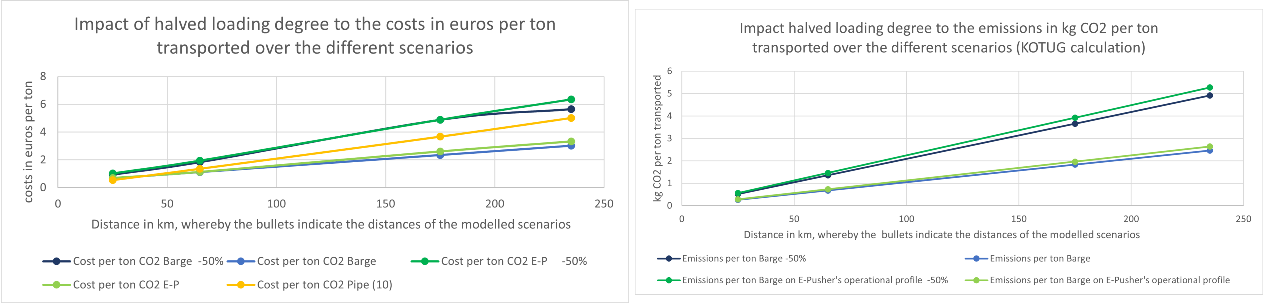


Figure 55: Sensitivity of cost per ton and emissions per ton to a halved load

Energy requirement

A halved energy requirement for the E-Pusher leads to the lowest costs per ton compared to the other modes, from short to large distances. A doubled energy requirement leads to a similar position as the base case for the E-Pusher. More specifically, higher costs per ton than the general barge but still lower costs per ton than the pipeline of 10 MTPA, from short to large distances.

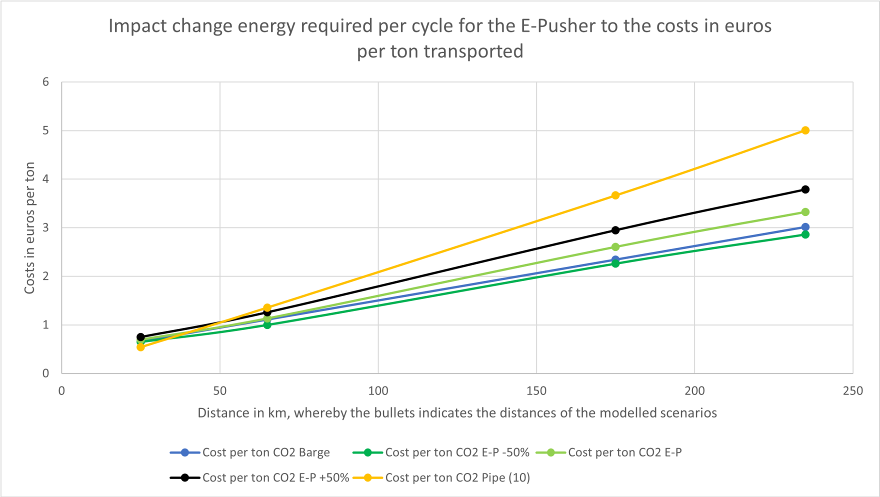


Figure 56: Sensitivity of costs per ton to change in energy requirements for the E-Pusher

Fuel consumption

The relation between fuel consumption to the costs per ton and the emissions per ton could be considered linear. A halved fuel consumption leads to halved costs per ton and halved emissions per ton. Similarly, this pattern could be observed for the impact of a 50% increase in fuel consumption to costs per ton and emissions per ton. Likewise, the emissions per ton in the CE Delft method are not sensitive to changes in loading degree, it is also not sensitive to changes in fuel consumption. Because emissions are calculated by tonne-kilometre.

Figure 57: Sensitivity of costs per ton and emissions per ton to changes in fuel consumption for the general barge

9.3 Validation and Scientific Contribution

Several parties and experts contributed to this research. First, KOTUG provided interesting insights into the E-Pusher from a commercial, technical, and operational point of view. An expert from SHIFT, the collaborating company with KOTUG for supplying battery packs, provided also operational details that had to be considered in developing a calculation model. MARIN, a maritime research institute provided the results of the simulation for the operational configuration, see Figure 35, that was analysed in this research. Also, industrial companies like TOTAL BV, Shell and a trucking company provided (expected) operational data of CCS transport for the model. Most of the information about CCS was found in the literature. However, the assumptions made for the developed model were also obtained and validated by meetings with Aramis, CO2Next and Gasunie. The industrial party VT Shipping and the maritime research institute STC-Nestra provided insights about liquid bulk transport and developments in sustainability for this type of transport. Meetings with Rijkswaterstaat, a part of the Dutch Ministry of Infrastructure and Water Management allowed the author of this thesis to validate the modelling assumptions for sailing with barges. An expert from TNO validated the way of modelling for pipeline transport. Also, some other, not mentioned, parties contributed to the validation of the model. The scientific contribution of this thesis can be formulated as follows:

This thesis contributed to the scientific literature by incorporating a sustainability factor into the framework of Konings (2009). The adapted model allowed to analyse a barge transport mode within a CCS chain from an academic perspective, while simultaneously meeting the desires of industrial maritime companies. Maritime companies would like to retrieve insights into the potential of emissions-free transport modes in CCS. This is not done before. The model has strengths that it outlines the important operational KPIs and added an environmental KPI to consider. Furthermore, the KPIs could be set off against each other. Consequently, new research topics to be explored are *found in this thesis, see Section 10.2.*

10 Conclusion and Recommendations

This section of the thesis provides the conclusion to the main answer and the recommendations for further research. The research started in collaboration with the TU Delft and KOTUG. KOTUG attempts to discover the possibilities for the E-Pusher in more transportation services, in particular the transportation network of CCS. From an academic perspective, it was not investigated what the role and the impact on the emissions might be for emission-free vessels in CCS chains. In this research, it is, therefore, attempted what the potential might be for the E-Pusher in the transportation network of CCS. The structure of this thesis follows the methodology of the SIMIE approach. First, in State the Problem, the problem statement, knowledge gap, research objective and research question were defined. Second, in Investigate Alternatives, the existing literature about modelling barge networks and requirements for CO2 transport by ship were identified. Third, in the Model the Current State, it was figured out how the network of CCS will be designed in the future by analysing the supply and demand, and the stakeholder dynamics behind CCS. Also, in this part, a more detailed analysis of the E-Pusher and the E-Pusher's configuration within CCS was performed. The last step in this part was to generate a model and scenarios for simulating realistic transportation trajectories of CCS. Following the mentioned steps, in the Integrate part, the simulation was performed to obtain the results. Finally, in the Evaluate part, the validation and sensitivity analysis were performed. The research ends with this chapter, providing the answer to the formulated main question by first answering all sub-questions in Section 10.1. Derived, from the conclusions several recommendations for further academic research and KOTUG are given in Section 10.2.

10.1 Conclusions

1. ***How are barge transport networks designed and what are the performance indicators to evaluate a barge transport network?***

   An adapted framework of Konings (2009), allowed to formulate KPIs to consider in this research from a network perspective, whereby both traditional KPIs from operators and shippers are considered as well as a sustainability KPI, which has significant importance nowadays. The KPIs considered are **Operational Impact** and **Sustainability**. The Operational Impact can be divided into operational capacity expressed in cycles per year, transported volume expressed in MTPA, and transportation costs in euros per year. Sustainability is defined by the CO2 emissions, expressed in kg CO2 per year.

2. ***What are the technical, operational and economical requirements for onshore transport of carbon dioxide by ship?***

   Transport of CO2 by ship can be in fixed tanks or containers. Furthermore, liquefaction of CO2 is required. Economically, transport conditions close to the triple point are desired, but it increases the safety risks, for instance, the formation of hydrates and dry ice. In literature, the most cost-effective liquefaction conditions, whereby safety risks are limited, are found at a pressure of 15 bar and a temperature of -27 degrees. Also, the ship size can influence shippers to determine the optimal transport conditions.

3. **What is the current state of carbon capture (utilisation) and storage inland shipping chain?**
   (a) **What are the possible areas to transport liquefied CO2 from and to, and what are the corresponding volumes and time-span?**

   Currently, the active CCS projects are contributing to the upscaling of CCS infrastructure in the Netherlands, which is not implemented yet. Aramis expects to supply CO2 with a gradual increase from 5 MTPA in 2026 to 10 MTPA in 2030 and 20 MTPA in 2035. Besides Aramis, also Porthos and CO2next are developing CCS infrastructure in the Port of Rotterdam. The capture area of CO2 has a large potential in the Northern European Region, in particular for the Rhine Area. Also, within the Netherlands, several clusters might be attractive, such as the Chemelot cluster. CCU projects are also expected to increase the demand for carbon transport but are not expected to be operational in the short-term. Likewise, the building of the infrastructure for the hub in the Port of Rotterdam, also other construction plans for hubs elsewhere in Europe exist, such as Eemshaven, Port of Immingham, Wilhelmshaven and Gdansk.

   (b) ***How can a CCS transportation network be modelled?***

   A hub-and-clustering network has several costs and risk advantages for upscaling the whole value chain of a CCS network. Therefore, a hub-and-clustering network is proposed for the whole value chain of CCS. Regarding, the onshore transportation network it is proposed that the destinations are point-to-point connected to a centralised hub. No intermediate inland hubs are proposed, this is because freight is already bundled in the ports acting as the hub and the point-to-point connections offer flexibility in the implementation phase of a CCS project.

   (c) ***In what way are stakeholders supporting or blocking certain objectives and requirements of carbon transport within CCS?***

   Where in the past CCS was often criticised by several parties, nowadays, a wide consensus among the different stakeholders exists about the significant role of CCS in reaching climate goals. However, certain issues should be overcome to guarantee that CCS projects will succeed this time. First of all, a chicken-egg problem could be observed. CCS projects want to build the infrastructure but need participators, participators need the infrastructure and funding from public authorities, while the public authorities need guarantees for building the infrastructure before granting funds. Furthermore, the London Protocol is forming a barrier for the transboundary transport of CO2. Bilateral agreements between countries could overcome this issue. Another potential driver for CCS projects might be the ETS. ETS is expected to support the upscaling of CCS projects by creating incentives for companies to participate.

4. ***What are the technical-operational characteristics of the E-Pusher?***

   The E-Pusher is a zero-emission push-boat concept powered by swappable containers and operational during the day. Two standardised barges can be connected to the E-Pusher L-Type. Given this configuration, the loading capacity is limited to 5500 tons and the installed power is 600 kW. The required shaft power is around 500 kW under a sailing speed of 12 km/h. The total battery capacity is 4.8 MW.

5. ***What is the impact of deploying the E-Pusher in the transportation stage of CCS, to the outcomes of the KPIs and trade-off between the KPIs of other possible transport modes?***

   For very short distances a pipeline of 10 MTPA will provide the lowest costs per ton transported. However, increasing the distances will lead to higher costs per ton compared to the waterway modes. Till short distances, the E-Pusher is very competitive concerning costs per ton transported compared to the transport mode with the lowest costs per ton, the general barge. Increasing the distances from short to medium and large distances lead to higher differences in costs per ton between the E-Pusher and the general barge, but the E-Pusher is not extremely outperformed compared to the other transport modes, such as the truck, a pipe of 2.5 MTPA and a pipe of 10 MTPA. Regarding the emissions per ton in the KOTUG calculation, the E-Pusher could save for distances of 25 km, 65 km, 175 km, and 245 km, approximately 0.26, 0.68, 1.83, and 2.46 kg CO2 per ton transported, respectively. In case the CE Delft calculation is used, the values will be slightly more than one and a half times higher, compared to the KOTUG calculation. The percentage net CO2 decreases from very short distances to large distances with 0.22 % for the KOTUG and 0.36 % for CE Delft calculation. The impact of deploying the E-Pusher on the emission savings would thus be higher at larger distances.

6. ***Which potential developments have an impact related to the feasibility of deploying the E-Pusher in CCS?***

   First of all, some barriers exist to the feasibility of the CCS implementation, for instance, construction restrictions for building CCS infrastructure. Second, in this research it is assumed that the pipeline should be built from the beginning, in practice, it might be that an already implemented pipeline could be used. The sensitivity analysis for a halved CAPEX of a 10 MTPA pipeline illustrated the change in position for the lowest costs per ton. The E-Pusher set against to the pipeline of 10 MTPA has under this development higher costs per ton for very short to short distances, even costs per ton for medium distances and large distances lower costs per ton. Another pricing development such as increased fuel prices leads to a minimal advantage for the E-Pusher compared to the general barge, over all the distances. Halved electricity costs lead to similar costs per ton for both waterway modes over all distances. No sensitive behaviour is observed for E-Pusher's costs per ton compared to the other competitive modes if the CO2 opportunity factor is changed with a factor of 50%. If the E-Pusher requires half of the energy, it becomes the transport mode with the lowest costs per ton. A halved fuel consumption for the general barge leads to halved costs per ton for the general barge. Similarly, given the KOTUG calculation, the emissions per ton will be halved for the general barge. The calculated emissions per ton in the CE Delft method are not sensitive to this change, because the emissions are calculated by the transport performance in tonne-kilometre. Also, if the loading degree is halved, the emissions per ton in the CE Delft method are not sensitive because of the way of modelling. What is very sensitive if the load is halved, is the costs per ton of the waterway modes. In that case, the pipeline of 10 MTPA becomes the transport mode with the lowest costs per ton over all the distances.

Main Research Question

Following from the answers to the sub-questions, the answer to main research question, ***"Which requirements and conditions determine to what extent the E-Pusher could be a suitable inland transport mode for liquid carbon within the transport stage of a CCS chain, and what are the emission effects to the CCS chain if the E-Pusher is deployed?"***, can be summarized as follows:

The answer to the main question can be divided into three sub-answers. The first answer is given from a higher scope, regarding the general barriers and drivers for the implementation barriers and drivers of CCS projects. The second sub-answer is more orientated to the position of the E-Pusher in a potential CCS transport network. The last sub-answer is focussing on the emission savings if the E-Pusher would be deployed.

1. This research presented that enough storage capacity, supply and demand of CO2 transport can be observed in the future. However, for the implementation of CCS, several barriers exist, and thus also for the potential role of the E-Pusher within CCS. First, the following chicken-egg problem can be observed. CCS initiatives are willing to build the infrastructure but need participators, participators need the infrastructure and funding from public authorities, and the public authorities in their turn need guarantees of building infrastructure before granting funds. Also, the London Protocol prohibit transboundary transport of CO2 for storage purposes. This issue is assumed to be solved if CCS will be implemented. Furthermore, a driver could be the ETS, whereby incentives a created to attract participators for CCS projects, and thus for the upscaling of CCS projects.
2. Regarding the potential of the E-Pusher in the proposed transportation network if CCS is implemented the following answer can be given. Mainly, the barge would perform the best

in costs per ton over all the distances. The E-Pusher's performance is in general better than a truck and a pipeline of 2.5 MTPA. For very short distances, a pipeline of 10 MTPA would result in the lowest costs per ton. But if the distances increase the E-Pusher would have lower costs per ton than the pipeline of 10 MTPA. Till short distances, the E-Pusher is very competitive to the general barge and if the distances increase to large distances the E-Pusher is not very outperformed by the general barge. The developments that can directly influence the competitiveness of the E-Pusher negatively are a halved CAPEX for the 10 MTPA pipeline and a halved loading degree for the waterway modes. A halved CAPEX for a pipeline is realistic when an already established pipeline will be used or a pipeline is already planned to be built. Halved loading degrees are also a realistic development for large distances because of waterway restrictions on the Rhine. On the other hand, increased fuel prices or halved electricity prices can give the E-Pusher a slightly more advantageous position compared to the other modes.

3. Given the proposed network typology and trajectories it is found that deploying the E-Pusher could lead to direct TTW emissions savings. Based on the KOTUG calculation, whereby the fuel consumption of a general barge is considered, the direct savings are 0.26 kg CO2 per ton for very short distances of 25 km, increasing to 2.46 kg CO2 per ton for large distances of 245 km. The TTW savings derived from the CE Delft calculation, whereby the transport performance is considered, would be approximate, in each trajectory, one and half times than in the KOTUG calculation. These results, confirm the findings from (Weihs et al., 2014) stated in Section 1.1.1. Weihs et al. (2014) stated that longer shipping distances lead to increasing CO2 emissions from fuel combustion and boil-off, and thus to a decreased real amount of CO2 injected and avoided. Also, in this research, the emissions from barge transport increase if the shipping distances increase. The percentage net CO2 decreases from very short distances to large distances with 0.22 % for the KOTUG and 0.36 % for CE Delft calculation. The E-Pusher would thus save more emissions under larger distances.

10.2 Recommendations

This research provided the first insights into the potential to deploy a zero-emission vessel into a CCS transport network. Because, both the CCS transport network and the deployment of zero-emissions vessels are not in a very developed stage, it is important to investigate and validate new research aspects. First, the general research recommendations will be given. Then, the specific recommendation for the commissioner of this report, KOTUG will be provided.

Recommendations for Further Academic Research

- The analysis to assess the KPIs for all considered transport modes in all the modelled scenarios is performed from a network perspective. To validate the impact of the E-Pusher in a certain trajectory, the execution of a more in-depth analysis for each scenario is recommended. Especially for the E-Pusher and a conventional barge, certain operational trajectory characteristics can have a significant impact on the KPIs. Examples of these trajectory characteristics are stronger currents, low water levels in the rivers, poor weather, losses of energy because of manoeuvring and much more. Also, for modelling pipeline transport at a certain distance, building restrictions might be encountered. The assumed Euclidean distance might not be realistic in all trajectories, for instance, rivers or residential can be present in the trajectories.

- Also, another aspect of modelling the pipeline transport of CO2 should be reconsidered. The estimated costs of the pipeline are determined in this research by interpolation based on different studies for pipeline building plans in Europe. Expert consulting revealed that it is a decent first estimate tool. However, Knoope et al. (2015) provided a more accurate estimation tool to calculate the pipeline costs and corresponding energy consumption based on more relevant parameters, such as diameter outlet, pressure drop, heat ratio, the universal gas constant and more. It was chosen, to consider the rough estimates by interpolation because of the time pressure for executing this research and the lack of information for all the included values of the parameters in the modelled scenarios. For further research, it is recommended to use the more accurate calculation tool of Knoope et al. (2015) and obtain all the values for the specific parameters.
- Next to that, expert consulting led to the assumption that the compression costs can be neglected in this explorative phase of determining the CO2 transportation costs. This is because the costs are assumed to be crossed out against each other for the different transport modes. Similarly, this is assumption is made for the energy consumption of compressing the CO2. In further research stages, incorporating the compression costs and energy requirements for transporting the CO2 can widen the scope of this research and provide the results concerning the costs and energy consumption with more reliability.
- A certain network typology is chosen in this research. In later implementation stages of CCS, also other network typologies might have potential. For instance, a more detailed hub-and-spoke network in the inland transport chain. The impact of more intermediate hubs and the corresponding bundling of loads to the outcomes of this proposed network typology is interesting to outline. Further research could focus on how efficient the proposed transport systems are or how to make the proposed transport systems more efficient.
- Reporting the emissions from transportation is performed by two different methods. The first one is by using the KOTUG Calculation based on fuel consumption and the second one is by using the CEDelft calculation based on the transport performance in tonne-kilometre. The results of both methods are different to each other. From an academic perspective, it is interesting to determine what type of calculation method is most valid. Also, other methods

for calculating emissions could be considered. Furthermore, other aspects concerning emissions could be considered in further research. In this research, only the TTW emissions are considered it might be interesting to calculate the emissions of a certain mode from the manufacturing processes of the different components to the end-of-life state. But, also regarding the TTW emissions further research might be interesting. In this research, the sailing behaviour of captains, which might have an impact on TTW emissions, is neglected.

Recommendations for KOTUG

Next to the academic recommendations, also for the commissioner of this research more practical recommendations can be given. As mentioned, KOTUG is a company ahead in maritime excellence. In line with the ambitions of KOTUG to contribute to the global climate transition by scaling-up zero-emissions solutions, this research outlined what the potential is for the E-Pusher in future CCS projects. Below, the recommendations are given within the reach of KOTUG, to retrieve more insight into the potential role of the E-Pusher in CCS.

- First, a more thorough analysis of the operational configuration of the E-Pusher considered in this thesis is recommended. The operational configuration in this research was based on the simulation results of MARIN. Interesting for KOTUG is to retrieve insights into the feasibility of this operational design, regardless of CCS projects. Retrieving findings of the operational features in practice enables one to determine the operational impact based on facts, instead of only assumptions. Also, in this comprehensive analysis, it could be tested how robust the proposed configuration of the E-Pusher in this research is to trajectory conditions, such as strong currents resulting in more energy requirement and waterway restrictions resulting in lower cargo loads.

- Second, it is recommended to perform a more detailed commercial analysis when the development of CCS projects is in a further stage. From a network perspective, this research provided some explorative commercial results in terms of cost prices per ton transported. However, because the projects are in developing stages and no current CCS transports are active in both the Netherlands as well as the surrounding countries, it was not possible to determine how valuable offering a CO2 transport service is. Another aspect, that is recommended in this commercial analysis is to investigate the possibilities and corresponding added value for KOTUG to collaborate with other potential allies in a CCS transport network. On the supply side, a large developing demand by the industrial emitters for liquefied carbon transport is observed. Also, the parties for handling the received liquefied CO2 are developing their projects, such as Porthos and CO2Next. Pursuing an active and engaged role opens possibilities for a first-mover advantage in CCS shipping chains.

- Third, a recommendation is to obtain more insight into how a potential charging infrastructure for electric vessels in CCS chains could be designed and evaluated. Examples of design factors that could be considered are how many charging points are required, the distance between charging points, and implementing fixed or mobile charging solutions. This recommendation has relevance for both KOTUG and the general academic research field.

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Part VI

APPENDICES

A E-Pusher Types

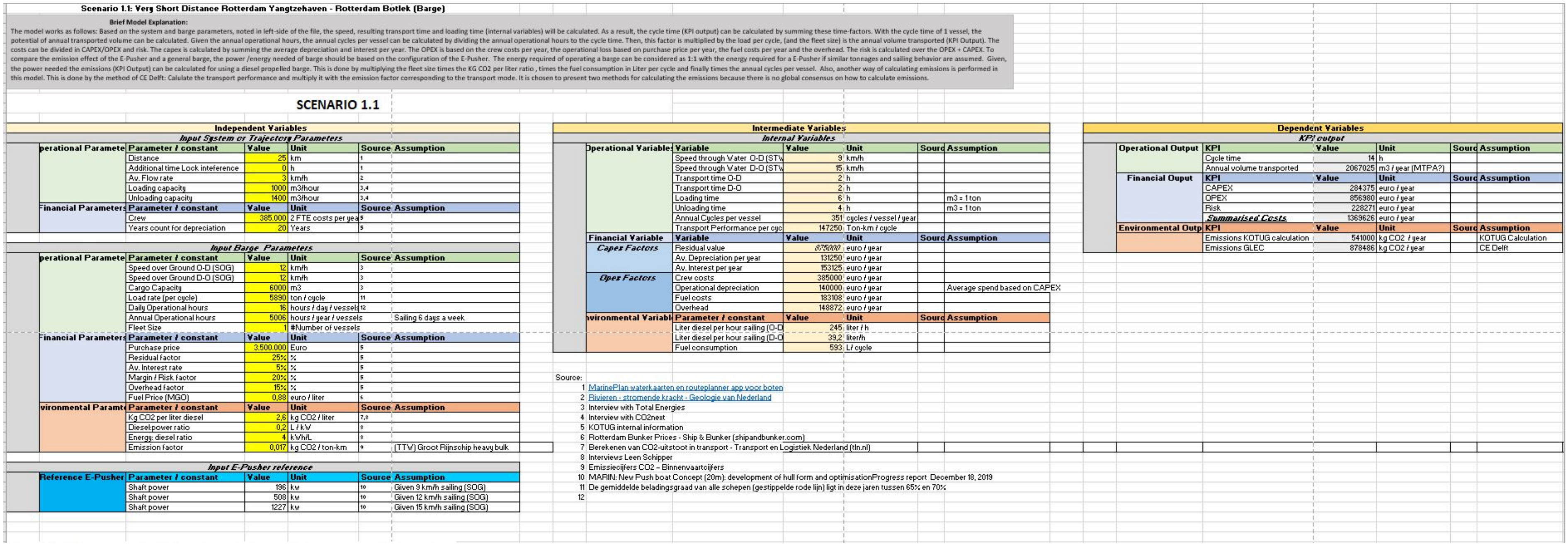
In Table 12, the characteristics of all E-Pusher types are presented.

Table 12: E-Pusher Vessels' Specifications

E-Pusher Type Characteristics	**S**	**S+**	**M**	**L**
Type of transportation	Inner cities	Inner cities and Larger waterways	Short distances	Larger waterways
Dimensions				
Length over all	5.7 m	9 m	16 m	20.5 m
Width	2.38 m	3.5 m	7.4 m	9.5 m
Max. draught	0.5 m	0.85 m	1.35 m	1.35 m
Minimum airdraft	0.9 m	1.80 m	4.30 m	5 m
Max. eye height		2.80 m	9 m	11 m
Propulsion				
Electric azipods	2 * 15 KW	1 * 140 KW	2 * 300 KW	3 * 300 KW
Accomodation				
Standard TEU Units			2	3
Certification				
Communautair	+/- 6000 m3	+/- 3500 m3	+/- 200 m3	

B Formula List and Model Overviews

B.1 Overviews of the Models in Excel



Scenario 1.1: Very Short Distance Rotterdam Yangtzehaven - Rotterdam Botlek (Barge)

Brief Model Explanation:

The model works as follows: Based on the system and barge parameters, noted in left-side of the file, the speed, resulting transport time and loading time (internal variables) will be calculated. As a result, the cycle time (KPI output) can be calculated by summing these time-factors. With the cycle time of 1 vessel, the potential of annual transported volume can be calculated. Given the annual operational hours, the annual cycles per vessel can be calculated by dividing the annual operational hours to the cycle time. Then, this factor is multiplied by the load per cycle, (and the fleet size) is the annual volume transported (KPI Output). The costs can be divided in CAPEX/OPEX and risk. The capex is calculated by summing the average depreciation and interest per year. The OPEX is based on the crew costs per year, the operational loss based on purchase price per year, the fuel costs per year and the overhead. The risk is calculated over the OPEX + CAPEX. To compare the emission effect of the E-Pusher and a general barge, the power /energy needed of barge should be based on the configuration of the E-Pusher. The energy required of operating a barge can be considered as 1:1 with the energy required for a E-Pusher if similar tonnages and sailing behavior are assumed. Given, the power needed the emissions (KPI Output) can be calculated for using a diesel propelled barge. This is done by multiplying the fleet size times the KG CO2 per liter ratio , times the fuel consumption in Liter per cycle and finally times the annual cycles per vessel. Also, another way of calculating emissions is performed in this model. This is done by the method of CE Delft: Calulate the transport performance and multiply it with the emission factor corresponding to the transport mode. It is chosen to present two methods for calculating the emissions because there is no global consensus on how to calculate emissions.

SCENARIO 1.1

Independent Variables

Input System or Trajectory Parameters

perational Paramete	Parameter / constant	Value	Unit	Source	Assumption
	Distance	25	km	1	
	Additional time Lock inteference	0	h	1	
	Av. Flow rate	3	km/h	2	
	Loading capacity	1000	m3/hour	3,4	
	Unloading capacity	1400	m3/hour	3,4	
Financial Parameters	**Parameter / constant**	**Value**	**Unit**	**Source**	**Assumption**
	Crew	385.000	2 FTE costs per yea	5	
	Years count for depreciation	20	Years	5	

Input Barge Parameters

perational Paramete	Parameter / constant	Value	Unit	Source	Assumption
	Speed over Ground O-D (SOG)	12	km/h	3	
	Speed over Ground D-O (SOG)	12	km/h	3	
	Cargo Capacity	6000	m3	3	
	Load rate (per cycle)	5890	ton / cycle	11	
	Daily Operational hours	16	hours / day / vessels	12	
	Annual Operational hours	5006	hours / year / vessels		Sailing 6 days a week
	Fleet Size	1	#Number of vessels		
Financial Parameters	**Parameter / constant**	**Value**	**Unit**	**Source**	**Assumption**
	Purchase price	3.500.000	Euro	5	
	Residual factor	25%	%	5	
	Av. Interest rate	5%	%	5	
	Margin / Risk factor	20%	%	5	
	Overhead factor	15%	%	5	
	Fuel Price (MGO)	0,88	euro / liter	6	
vironmental Paramte	**Parameter / constant**	**Value**	**Unit**	**Source**	**Assumption**
	Kg CO2 per liter diesel	2,6	kg CO2 / liter	7,8	
	Diesel:power ratio	0,2	L / kW	8	
	Energy: diesel ratio	4	kWh/L	8	
	Emission factor	0,017	kg CO2 / ton-km	9	(TTW) Groot Rijnschip heavy bulk

Input E-Pusher reference

Reference E-Pusher	Parameter / constant	Value	Unit	Source	Assumption
	Shaft power	196	kw	10	Given 9 km/h sailing (SOG)
	Shaft power	508	kw	10	Given 12 km/h sailing (SOG)
	Shaft power	1227	kw	10	Given 15 km/h sailing (SOG)

Intermediate Variables

Internal Variables

Operational Variables	Variable	Value	Unit	Sourc	Assumption
	Speed through Water O-D (STW	9	km/h		
	Speed through Water D-O (STW	15	km/h		
	Transport time O-D	2	h		
	Transport time D-O	2	h		
	Loading time	6	h		m3 = 1 ton
	Unloading time	4	h		m3 = 1 ton
	Annual Cycles per vessel	351	cycles / vessel / year		
	Transport Performance per cyc	147250	Ton-km / cycle		
Financial Variable	**Variable**	**Value**	**Unit**	**Sourc**	**Assumption**
Capex Factors	Residual value	875000	euro / year		
	Av. Depreciation per year	131250	euro / year		
	Av. Interest per year	153125	euro / year		
Opex Factors	Crew costs	385000	euro / year		
	Operational depreciation	140000	euro / year		Average spend based on CAPEX
	Fuel costs	183108	euro / year		
	Overhead	148872	euro / year		
nvironmental Variabl	**Parameter / constant**	**Value**	**Unit**	**Sourc**	**Assumption**
	Liter diesel per hour sailing (O-D	245	liter / h		
	Liter diesel per hour sailing (D-O	39,2	liter/h		
	Fuel consumption	593	L/ cycle		

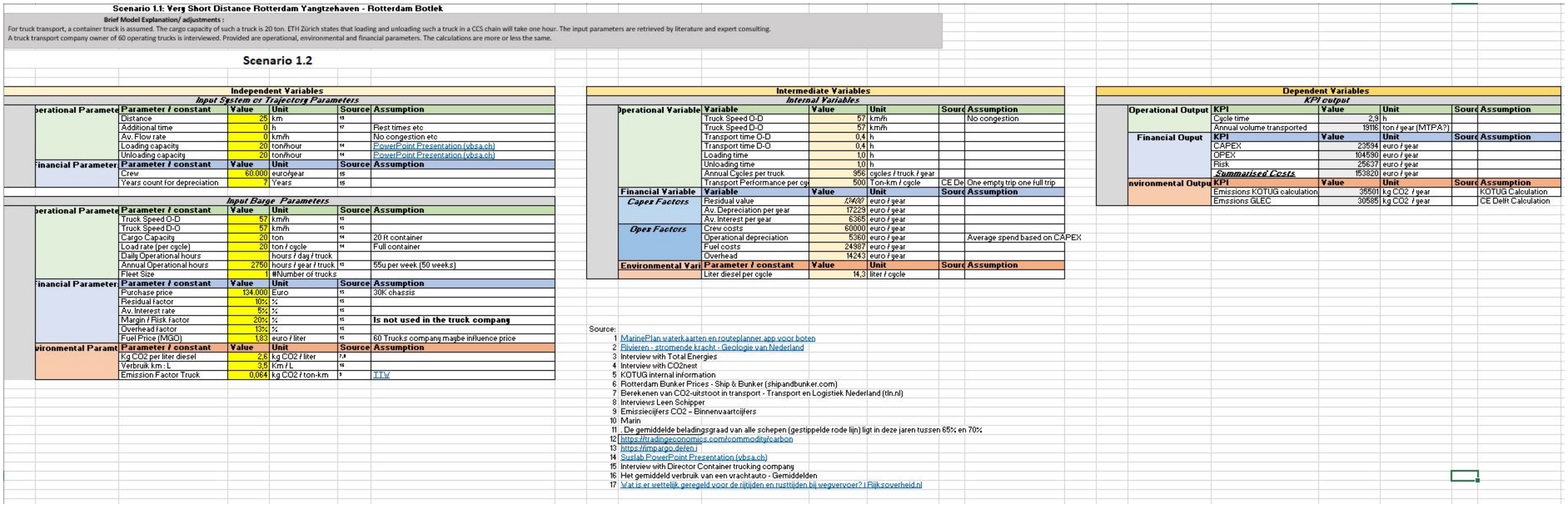
Source:
1 MarinePlan waterkaarten en routeplanner app voor boten
2 Rivieren - stromende kracht - Geologie van Nederland
3 Interview with Total Energies
4 Interview with CO2next
5 KOTUG internal information
6 Rotterdam Bunker Prices - Ship & Bunker (shipandbunker.com)
7 Berekenen van CO2-uitstoot in transport - Transport en Logistiek Nederland (tln.nl)
8 Interviews Leen Schipper
9 Emissiecijfers CO2 – Binnenvaartcijfers
10 MARIN: New Push boat Concept (20m): development of hull form and optimisationProgress report December 18, 2019
11 De gemiddelde beladingsgraad van alle schepen (gestippelde rode lijn) ligt in deze jaren tussen 65% en 70%
12

Dependent Variables

KPI output

Operational Output	KPI	Value	Unit	Sourc	Assumption
	Cycle time	14	h		
	Annual volume transported	2067025	m3 / year (MTPA?)		
Financial Ouput	**KPI**	**Value**	**Unit**	**Sourc**	**Assumption**
	CAPEX	284375	euro / year		
	OPEX	856980	euro / year		
	Risk	228271	euro / year		
	Summarised Costs	1369626	euro / year		
Environmental Outp	**KPI**	**Value**	**Unit**	**Sourc**	**Assumption**
	Emissions KOTUG calculation	541000	kg CO2 / year		KOTUG Calculation
	Emissions GLEC	878486	kg CO2 / year		CE Delft

Figure 58: Barge model



Scenario 1.1: Very Short Distance Rotterdam Yangtzehaven - Rotterdam Botlek

Brief Model Explanation/ adjustments :

For truck transport, a container truck is assumed. The cargo capacity of such a truck is 20 ton. ETH Zürich states that loading and unloading such a truck in a CCS chain will take one hour. The input parameters are retrieved by literature and expert consulting.
A truck transport company owner of 60 operating trucks is interviewed. Provided are operational, environmental and financial parameters. The calculations are more or less the same.

Scenario 1.2

Independent Variables

Input System or Trajectory Parameters

	Parameter / constant	Value	Unit	Source	Assumption
perational Paramete	Distance	25	km	13	
	Additional time	0	h	17	Rest times etc
	Av. Flow rate	0	km/h		No congestion etc
	Loading capacity	20	ton/hour	14	PowerPoint Presentation (vbsa.ch)
	Unloading capacity	20	ton/hour	14	PowerPoint Presentation (vbsa.ch)
inancial Parameter	**Parameter / constant**	**Value**	**Unit**	**Source**	**Assumption**
	Crew	60.000	euro/year	15	
	Years count for depreciation	7	Years	15	

Input Barge Parameters

	Parameter / constant	Value	Unit	Source	Assumption
perational Paramete	Truck Speed O-D	57	km/h	15	
	Truck Speed D-O	57	km/h	15	
	Cargo Capacity	20	ton	14	20 ft container
	Load rate (per cycle)	20	ton / cycle	14	Full container
	Daily Operational hours		hours / day / truck		
	Annual Operational hours	2750	hours / year / truck	15	55u per week (50 weeks)
	Fleet Size	1	#Number of trucks		
inancial Parameter	**Parameter / constant**	**Value**	**Unit**	**Source**	**Assumption**
	Purchase price	134.000	Euro	15	30K chassis
	Residual factor	10%	%	15	
	Av. Interest rate	5%	%	15	
	Margin / Risk factor	20%	%	15	**Is not used in the truck company**
	Overhead factor	13%	%	15	
	Fuel Price (MGO)	1,83	euro / liter	15	60 Trucks company maybe influence price
vironmental Paramt	**Parameter / constant**	**Value**	**Unit**	**Source**	**Assumption**
	Kg CO2 per liter diesel	2,6	kg CO2 / liter	7,8	
	Verbruik km : L	3,5	Km / L	16	
	Emission Factor Truck	0,064	kg CO2 / ton-km	9	TTW

Intermediate Variables

Internal Variables

	Variable	Value	Unit	Sourc	Assumption
Operational Variable	Truck Speed O-D	57	km/h		No congestion
	Truck Speed D-O	57	km/h		
	Transport time O-D	0,4	h		
	Transport time D-O	0,4	h		
	Loading time	1,0	h		
	Unloading time	1,0	h		
	Annual Cycles per truck	956	cycles / truck / year		
	Transport Performance per cy	500	Ton-km / cycle	CE De	One empty trip one full trip
Financial Variable	**Variable**	**Value**	**Unit**	**Sourc**	**Assumption**
Capex Factors	Residual value	13400	euro / year		
	Av. Depreciation per year	17229	euro / year		
	Av. Interest per year	6365	euro / year		
Opex Factors	Crew costs	60000	euro / year		
	Operational depreciation	5360	euro / year		Average spend based on CAPEX
	Fuel costs	24987	euro / year		
	Overhead	14243	euro / year		
Environmental Vari	**Parameter / constant**	**Value**	**Unit**	**Sourc**	**Assumption**
	Liter diesel per cycle	14,3	liter / cycle		

Dependent Variables

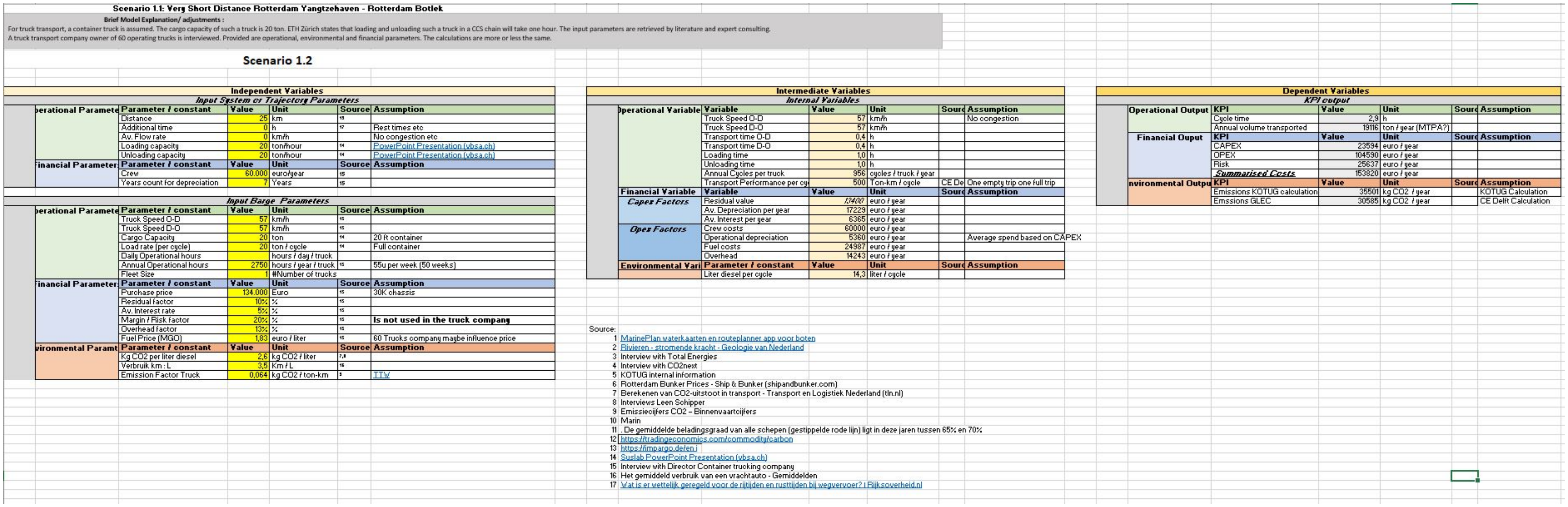
KPI output

	KPI	Value	Unit	Sourc	Assumption
Operational Output	Cycle time	2,9	h		
	Annual volume transported	19116	ton / year (MTPA?)		
Financial Ouput	**KPI**	**Value**	**Unit**	**Sourc**	**Assumption**
	CAPEX	23594	euro / year		
	OPEX	104590	euro / year		
	Risk	25637	euro / year		
	Summarised Costs	153820	euro / year		
nvironmental Outpu	**KPI**	**Value**	**Unit**	**Sourc**	**Assumption**
	Emissions KOTUG calculation	35501	kg CO2 / year		KOTUG Calculation
	Emssions GLEC	30585	kg CO2 / year		CE Delft Calculation

Source:

1 MarinePlan waterkaarten en routeplanner app voor boten
2 Rivieren - stromende kracht - Geologie van Nederland
3 Interview with Total Energies
4 Interview with CO2next
5 KOTUG internal information
6 Rotterdam Bunker Prices - Ship & Bunker (shipandbunker.com)
7 Berekenen van CO2-uitstoot in transport - Transport en Logistiek Nederland (tln.nl)
8 Interviews Leen Schipper
9 Emissiecijfers CO2 – Binnenvaartcijfers
10 Marin
11 . De gemiddelde beladingsgraad van alle schepen (gestippelde rode lijn) ligt in deze jaren tussen 65% en 70%
12 https://tradingeconomics.com/commodity/carbon
13 https://impargo.de/en i
14 Suslab PowerPoint Presentation (vbsa.ch)
15 Interview with Director Container trucking company
16 Het gemiddeld verbruik van een vrachtauto - Gemiddelden
17 Wat is er wettelijk geregeld voor de rijtijden en rusttijden bij wegvervoer? | Rijksoverheid.nl

Figure 59: Truck model



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For truck transport, a container truck is assumed. The cargo capacity of such a truck is 20 ton. ETH Zürich states that loading and unloading such a truck in a CCS chain will take one hour. The input parameters are retrieved by literature and expert consulting.
A truck transport company owner of 60 operating trucks is interviewed. Provided are operational, environmental and financial parameters. The calculations are more or less the same.

Scenario 1.2

Independent Variables

Input System or Trajectory Parameters

	Parameter / constant	Value	Unit	Source	Assumption
perational Paramete	Distance	25	km	15	
	Additional time	0	h	17	Rest times etc
	Av. Flow rate	0	km/h		No congestion etc
	Loading capacity	20	ton/hour	14	PowerPoint Presentation (vbsa.ch)
	Unloading capacity	20	ton/hour	14	PowerPoint Presentation (vbsa.ch)
inancial Parameter	**Parameter / constant**	**Value**	**Unit**	**Source**	**Assumption**
	Crew	60.000	euro/year	15	
	Years count for depreciation	7	Years	15	

Input Barge Parameters

	Parameter / constant	Value	Unit	Source	Assumption
perational Paramete	Truck Speed O-D	57	km/h	15	
	Truck Speed D-O	57	km/h	15	
	Cargo Capacity	20	ton	14	20 ft container
	Load rate (per cycle)	20	ton / cycle	14	Full container
	Daily Operational hours		hours / day / truck		
	Annual Operational hours	2750	hours / year / truck	15	55u per week (50 weeks)
	Fleet Size	1	#Number of trucks		
inancial Parameter	**Parameter / constant**	**Value**	**Unit**	**Source**	**Assumption**
	Purchase price	134.000	Euro	15	30K chassis
	Residual factor	10%	%	15	
	Av. Interest rate	5%	%	15	
	Margin / Risk factor	20%	%	15	**Is not used in the truck company**
	Overhead factor	13%	%	15	
	Fuel Price (MGO)	1,83	euro / liter	15	60 Trucks company maybe influence price
vironmental Paramt	**Parameter / constant**	**Value**	**Unit**	**Source**	**Assumption**
	Kg CO2 per liter diesel	2,6	kg CO2 / liter	7,8	
	Verbruik km : L	3,5	Km / L	16	
	Emission Factor Truck	0,064	kg CO2 / ton-km	9	TTW

Intermediate Variables

Internal Variables

	Variable	Value	Unit	Sourc	Assumption
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	Truck Speed D-O	57	km/h		
	Transport time O-D	0,4	h		
	Transport time D-O	0,4	h		
	Loading time	1,0	h		
	Unloading time	1,0	h		
	Annual Cycles per truck	956	cycles / truck / year		
	Transport Performance per cy	500	Ton-km / cycle	CE De	One empty trip one full trip
Financial Variable	**Variable**	**Value**	**Unit**	**Sourc**	**Assumption**
Capex Factors	Residual value	*13400*	euro / year		
	Av. Depreciation per year	17229	euro / year		
	Av. Interest per year	6365	euro / year		
Opex Factors	Crew costs	60000	euro / year		
	Operational depreciation	5360	euro / year		Average spend based on CAPEX
	Fuel costs	24987	euro / year		
	Overhead	14243	euro / year		
Environmental Vari	**Parameter / constant**	**Value**	**Unit**	**Sourc**	**Assumption**
	Liter diesel per cycle	14,3	liter / cycle		

Dependent Variables

KPI output

	KPI	Value	Unit	Sourc	Assumption
Operational Output	Cycle time	2,9	h		
	Annual volume transported	19116	ton / year (MTPA?)		
Financial Ouput	**KPI**	**Value**	**Unit**	**Sourc**	**Assumption**
	CAPEX	23594	euro / year		
	OPEX	104590	euro / year		
	Risk	25637	euro / year		
	Summarised Costs	153820	euro / year		
nvironmental Outpu	**KPI**	**Value**	**Unit**	**Sourc**	**Assumption**
	Emissions KOTUG calculation	35501	kg CO2 / year		KOTUG Calculation
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Source:

1 MarinePlan waterkaarten en routeplanner app voor boten
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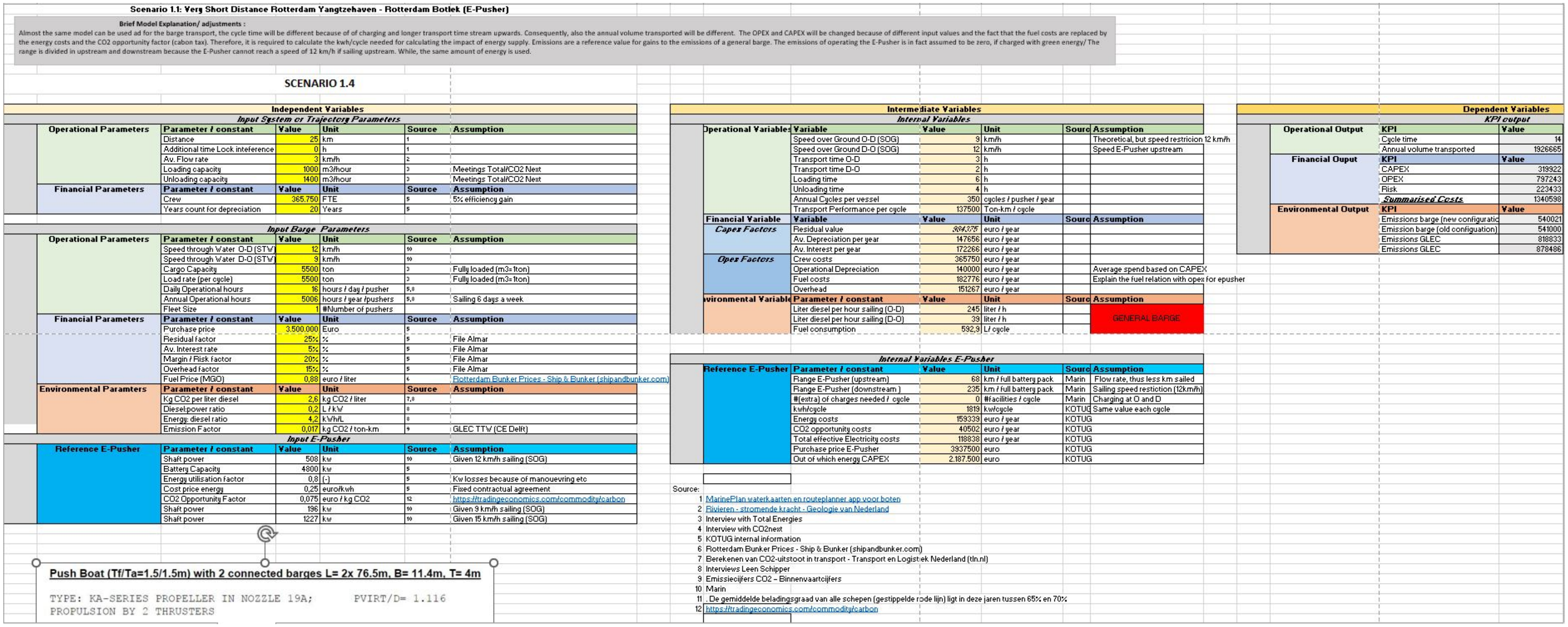
16 Het gemiddeld verbruik van een vrachtauto - Gemiddelden
17 Wat is er wettelijk geregeld voor de rijtijden en rusttijden bij wegvervoer? | Rijksoverheid.nl

Figure 60: Pipeline model



Scenario 1.1: Very Short Distance Rotterdam Yangtzehaven - Rotterdam Botlek (E-Pusher)

Brief Model Explanation/ adjustments :

Almost the same model can be used ad for the barge transport, the cycle time will be different because of of charging and longer transport time stream upwards. Consequently, also the annual volume transported will be different. The OPEX and CAPEX will be changed because of different input values and the fact that the fuel costs are replaced by the energy costs and the CO2 opportunity factor (cabon tax). Therefore, it is required to calculate the kwh/cycle needed for calculating the impact of energy supply. Emissions are a reference value for gains to the emissions of a general barge. The emissions of operating the E-Pusher is in fact assumed to be zero, if charged with green energy/ The range is divided in upstream and downstream because the E-Pusher cannot reach a speed of 12 km/h if sailing upstream. While, the same amount of energy is used.

SCENARIO 1.4

Independent Variables

Input System or Trajectory Parameters

Operational Parameters	**Parameter / constant**	**Value**	**Unit**	**Source**	**Assumption**
	Distance	25	km	1	
	Additional time Lock inteference	0	h	1	
	Av. Flow rate	3	km/h	2	
	Loading capacity	1000	m3/hour	3	Meetings Total/CO2 Next
	Unloading capacity	1400	m3/hour	3	Meetings Total/CO2 Next
Financial Parameters	**Parameter / constant**	**Value**	**Unit**	**Source**	**Assumption**
	Crew	365.750	FTE	5	5% efficiency gain
	Years count for depreciation	20	Years	5	

Input Barge Parameters

Operational Parameters	**Parameter / constant**	**Value**	**Unit**	**Source**	**Assumption**
	Speed through Water O-D (STW)	12	km/h	10	
	Speed through Water D-O (STW)	9	km/h	10	
	Cargo Capacity	5500	ton	3	Fully loaded (m3=1ton)
	Load rate (per cycle)	5500	ton	3	Fully loaded (m3=1ton)
	Daily Operational hours	16	hours / day / pusher	5,8	
	Annual Operational hours	5006	hours / year /pushers	5,8	Sailing 6 days a week
	Fleet Size	1	#Number of pushers		
Financial Parameters	**Parameter / constant**	**Value**	**Unit**	**Source**	**Assumption**
	Purchase price	3.500.000	Euro	5	
	Residual factor	25%	%	5	File Almar
	Av. Interest rate	5%	%	5	File Almar
	Margin / Risk factor	20%	%	5	File Almar
	Overhead factor	15%	%	5	File Almar
	Fuel Price (MGO)	0,88	euro / liter	6	Rotterdam Bunker Prices - Ship & Bunker (shipandbunker.com)
Environmental Paramters	**Parameter / constant**	**Value**	**Unit**	**Source**	**Assumption**
	Kg CO2 per liter diesel	2,6	kg CO2 / liter	7,8	
	Diesel:power ratio	0,2	L / kW	8	
	Energy: diesel ratio	4,2	kWh/L	8	
	Emission Factor	0,017	kg CO2 / ton-km	9	GLEC TTW (CE Delft)

Input E-Pusher

Reference E-Pusher	**Parameter / constant**	**Value**	**Unit**	**Source**	**Assumption**
	Shaft power	508	kw	10	Given 12 km/h sailing (SOG)
	Battery Capacity	4800	kw	5	
	Energy utilisation factor	0,8	(-)	5	Kw losses because of manouevring etc
	Cost price energy	0,25	euro/kwh	5	Fixed contractual agreement
	CO2 Opportunity Factor	0,075	euro / kg CO2	12	https://tradingeconomics.com/commodity/carbon
	Shaft power	196	kw	10	Given 9 km/h sailing (SOG)
	Shaft power	1227	kw	10	Given 15 km/h sailing (SOG)

Push Boat (Tf/Ta=1.5/1.5m) with 2 connected barges L= 2x 76.5m, B= 11.4m, T= 4m

TYPE: KA-SERIES PROPELLER IN NOZZLE 19A; PVIRT/D= 1.116
PROPULSION BY 2 THRUSTERS

Intermediate Variables

Internal Variables

Operational Variables	**Variable**	**Value**	**Unit**	**Sourc**	**Assumption**
	Speed over Ground O-D (SOG)	9	km/h		Theoretical, but speed restricion 12 km/h
	Speed over Ground D-O (SOG)	12	km/h		Speed E-Pusher upstream
	Transport time O-D	3	h		
	Transport time D-O	2	h		
	Loading time	6	h		
	Unloading time	4	h		
	Annual Cycles per vessel	350	cycles / pusher / year		
	Transport Performance per cycle	137500	Ton-km / cycle		
Financial Variable	**Variable**	**Value**	**Unit**	**Sourc**	**Assumption**
Capex Factors	Residual value	*384.375*	euro / year		
	Av. Depreciation per year	147656	euro / year		
	Av. Interest per year	172266	euro / year		
Opex Factors	Crew costs	365750	euro / year		
	Operational Depreciation	140000	euro / year		Average spend based on CAPEX
	Fuel costs	182776	euro / year		Explain the fuel relation with opex for epusher
	Overhead	151267	euro / year		
vironmental Variable	**Parameter / constant**	**Value**	**Unit**	**Sourc**	**Assumption**
	Liter diesel per hour sailing (O-D)	245	liter / h		GENERAL BARGE
	Liter diesel per hour sailing (D-O)	39	liter / h		
	Fuel consumption	592,9	L/ cycle		

Internal Variables E-Pusher

Reference E-Pusher	**Parameter / constant**	**Value**	**Unit**	**Sourc**	**Assumption**
	Range E-Pusher (upstream)	68	km / full battery pack	Marin	Flow rate, thus less km sailed
	Range E-Pusher (downstream)	235	km / full battery pack	Marin	Sailing speed restiction (12km/h)
	#(extra) of charges needed / cycle	0	#facilities / cycle	Marin	Charging at O and D
	kwh/cycle	1819	kw/cycle	KOTUG	Same value each cycle
	Energy costs	159339	euro / year	KOTUG	
	CO2 opportunity costs	40502	euro / year	KOTUG	
	Total effective Electricity costs	118838	euro / year	KOTUG	
	Purchase price E-Pusher	3937500	euro	KOTUG	
	Out of which energy CAPEX	2.187.500	euro	KOTUG	

Source:

1 MarinePlan waterkaarten en routeplanner app voor boten
2 Rivieren - stromende kracht - Geologie van Nederland
3 Interview with Total Energies
4 Interview with CO2next
5 KOTUG internal information
6 Rotterdam Bunker Prices - Ship & Bunker (shipandbunker.com)
7 Berekenen van CO2-uitstoot in transport - Transport en Logistiek Nederland (tln.nl)
8 Interviews Leen Schipper
9 Emissiecijfers CO2 – Binnenvaartcijfers
10 Marin
11 . De gemiddelde beladingsgraad van alle schepen (gestippelde rode lijn) ligt in deze jaren tussen 65% en 70%
12 https://tradingeconomics.com/commodity/carbon

Dependent Variables

KPI output

Operational Output	**KPI**	**Value**
	Cycle time	14
	Annual volume transported	1926665
Financial Ouput	**KPI**	**Value**
	CAPEX	319922
	OPEX	797243
	Risk	223433
	Summarised Costs	1340598
Environmental Output	**KPI**	**Value**
	Emissions barge (new configuratic	540021
	Emission barge (old configuation)	541000
	Emissions GLEC	818833
	Emissions GLEC	878486

Figure 61: E-Pusher model

C Sensitivity Analysis

C.1 Pricing developments

Fuel price impact:

In this analysis, the impact to the trade-off costs per ton transported if fuel prices changes for the barge will be presented. What can be observed from Figure 62, is that if the fuel prices decrease with 50 percent the Barge has only more and more advantage. If the fuel prices increase with 50 percent, the E-Pusher has a small advantage regarding the costs, in comparison with the barge.

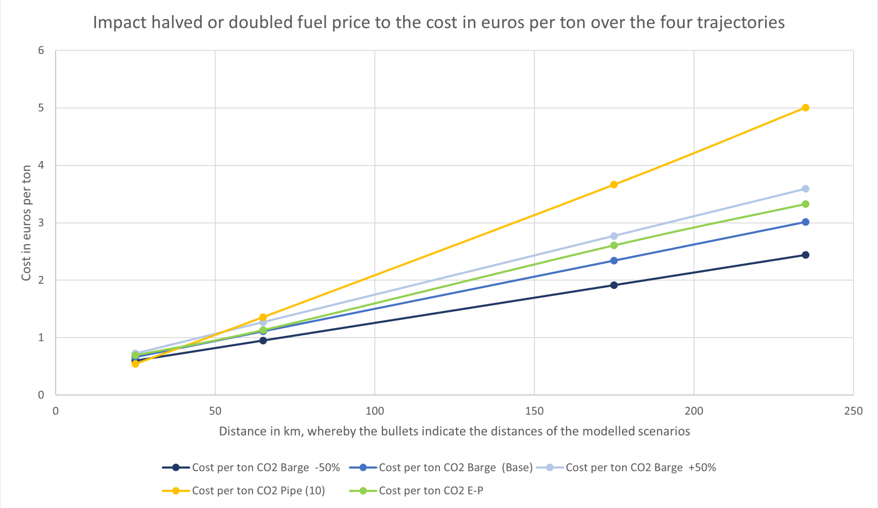


Figure 62: Sensitivity of the transport costs to changes in fuel price, expressed in euro per ton transported.

Electricity Price impact:

In this analysis, it will be presented how changes in electricity prices could impact the trade-off between costs and volume transported. What can be observed from Figure 63, is that if the electricity prices decrease with 50 percent the E-Pusher will have similar costs as a general barge, over very large distances the E-Pusher even has a small advantage in costs, compared to the general barge. An increase in electricity costs will have a contrarily impact, the E-Pushers' costs will only be further away to the costs of the general barge.

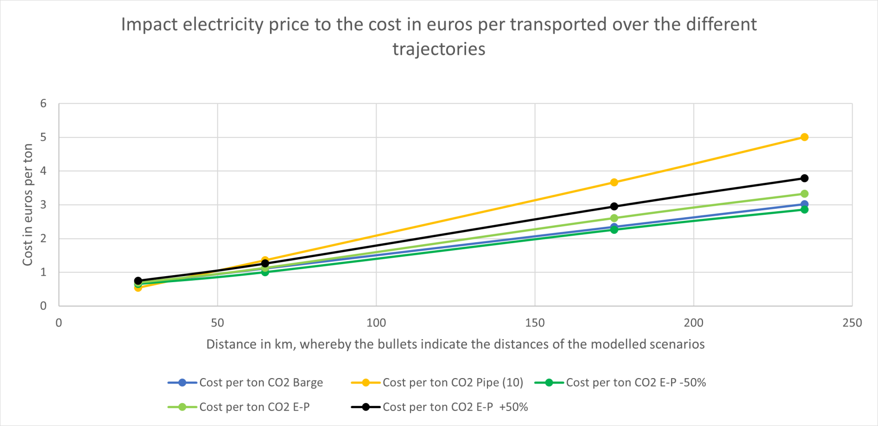


Figure 63: Sensitivity of the transport costs to changes in electricity price, expressed in euro per ton transported.

CO2 Tax Impact:

In this analysis, it will be presented how an increase or decrease of the CO2 opportunity factor would influence the costs per ton for the E-Pusher. As can be derived from Figure 64, a halved CO2 opportunity factor leads to higher costs per ton for the E-Pusher. An increase of 50 percent to the CO2 opportunity factor leads to lower costs for the E-Pusher. But the general barge will still have the lowest costs per ton.

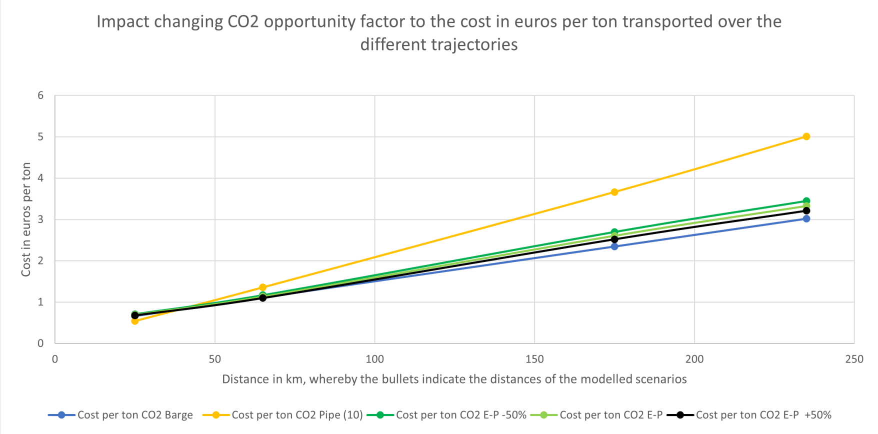


Figure 64: Sensitivity of the transport costs to changes in CO2 factor, expressed in euro per ton transported.

CAPEX Pipeline:

In this analysis, it will be presented how an increase or decrease of the pipelines' CAPEX will change the trade-off costs for the pipeline. As can be derived from Figure 65, a halved pipeline CAPEX will give the lowest costs for very short and short distances. The barge will be again the transport mode with the lowest costs if medium distances are selected. This pattern could also be observed for large distances. The E-Pusher will have similar costs per ton as a Pipeline with halved CAPEX for medium distances, for large distances the E-Pusher will have slightly lower costs per ton. The costs pipeline with a 50 percent increased CAPEX will higher in comparison with the waterway modes, the behavior of this curve is similar as to the base case pipeline curve.

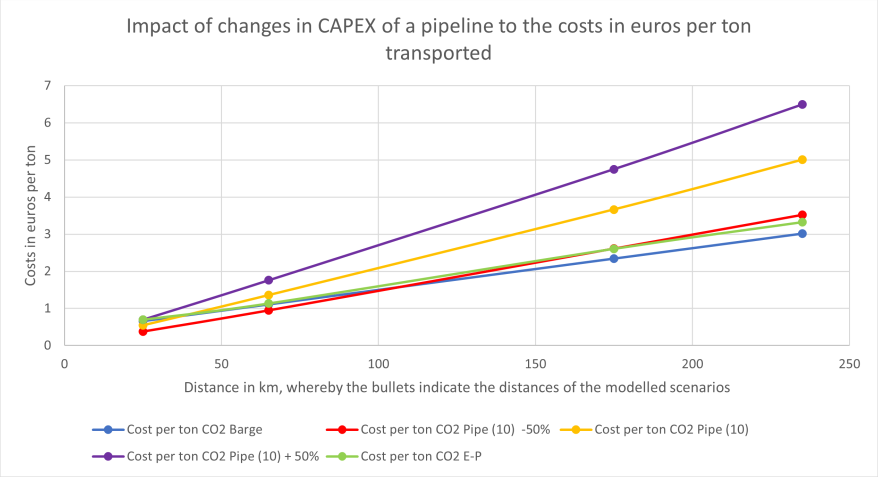


Figure 65: Sensitivity of the transport costs to changes in the CAPEX of a pipeline, expressed in euro per ton transported.

C.2 Loading impact and energy requirement

Loading degree:

In this analysis, it will be presented how a decrease of the load of the waterway modes will impact the costs per ton and the emissions per ton. An increase is not considered because both configurations are already assumed as fully loaded. As can be observed from Figure 66 and 67, will the pipeline have lower costs from short distances to large distances if the loading degree is halved for the vessels. Regarding the emissions based on KOTUG calculation, it can be observed that the emissions will be doubled for each vessel within each trajectory. This can be declared by the fact that the load is multiplying factor in the KOTUG calculation. A load factor of 0.5 will have a direct impact to the the annual volume transported, which will be the halved on similar basis. The emitted KG CO2 is not related to the load factor in this calculation, thus the direct impact is logical. The same amount of CO2 emitted will be divided by a halved annual transport volume, resulting in doubled kg CO2 per ton transported. The CE Delft calculation is not presented, this emissions in this calculation were not sensitive to the load changes. This can also be declared by the way of modelling the emissions. The emissions are calculated based on the transport performance in tonne-kilometre. A halved load rate, resulting in a halved tonne-kilometre per cycle is compensated by the halved annual volume transported. Thus, no effect.

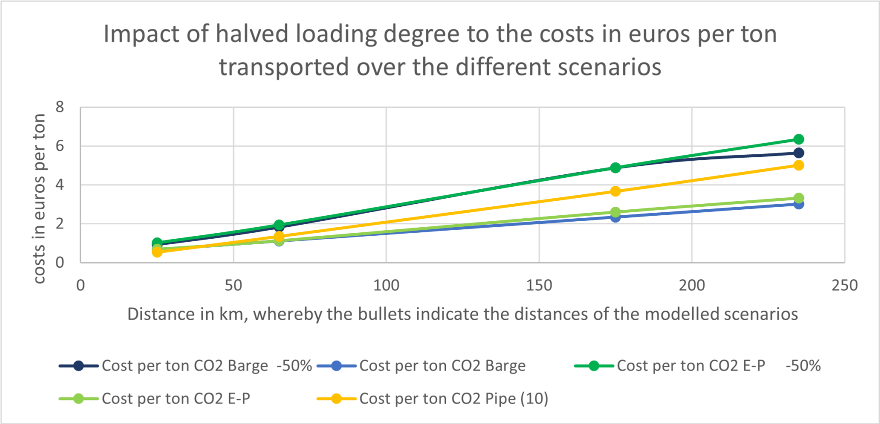


Figure 66: Sensitivity of a halved load degree for the waterway modes to the the transport costs per ton

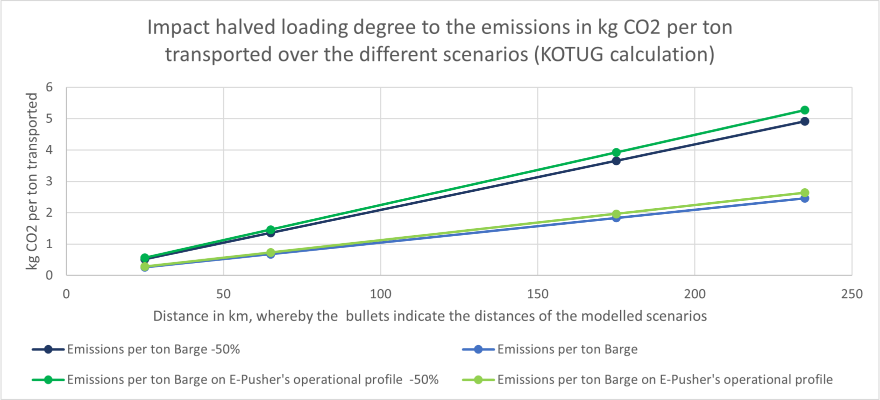


Figure 67: Sensitivity of a halved load degree for the waterway modes to the the transport costs per ton, KOTUG Calculation

Energy Requirement E-Pusher

In this analysis, it will be presented how a changes in energy required per cycle for the E-Pusher influence the trade-offs. As can be observed from Figure 68, a halved amount of energy required results in the lowest costs per ton for the E-Pusher in comparison with all transport modes, from short distances to large distances. A doubled amount of energy required per cycle leads to similar costs per ton as for the pipeline, in medium distances. No observations could be made about the impact of this change to the general barges' emissions per ton. This, is because the emissions are linearly modelled based on the number of litre required per cycle, for a barge. Thus, therefore this aspects needs to be modelled to determine the impact to the emissions.

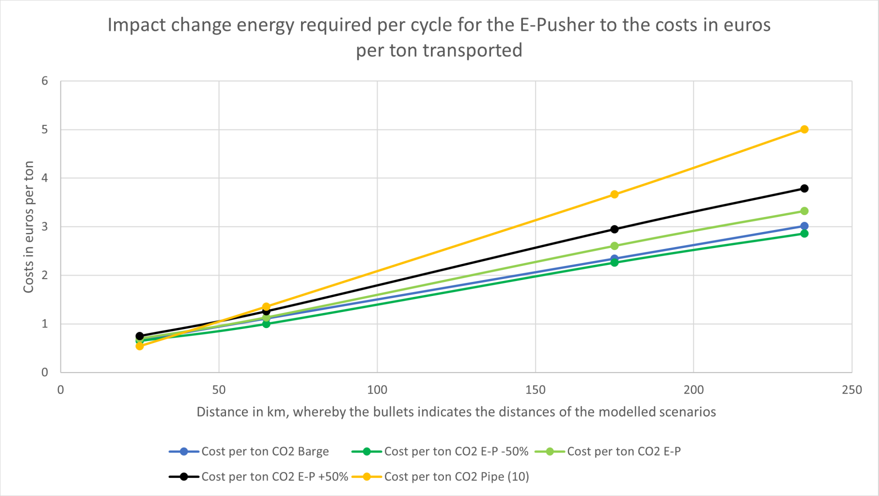


Figure 68: Sensitivity of energy requirements for the E-Pusher to the trade-offs

Fuel consumption general barge

In this analysis, the fuel consumption for a general barge is increased or decreased with 50 percent, for all scenarios. What can be observed, from Figures 69 and 70 is that both the costs per ton and emissions per ton in the KOTUG calculation have a linear relation to the fuel consumption. Logically, a halved fuel consumption for a barge leads to lower costs per ton for the barge, which has already in the base case the lowest costs per ton. An increase of 50 percent for the fuel consumption, results in higher costs per ton from short distances to large distances, for the barge compared to the E-Pusher. Regarding the emissions, the emitted CO2 per kg will also doubled or halved if the fuel consumption is increased or decreased by 50 percent. The CE Delft calculation method will result in similar values if the fuel consumption is changed. This is because the fuel consumption is not considered in this method. The emissions are calculated by tonne-kilometre.

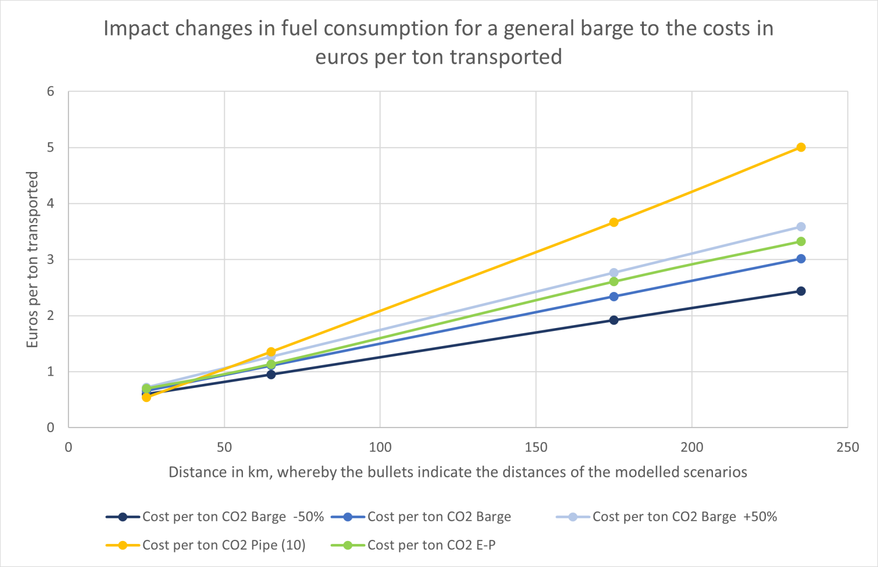


Figure 69: Sensitivity of fuel consumption general barge to costs per tons

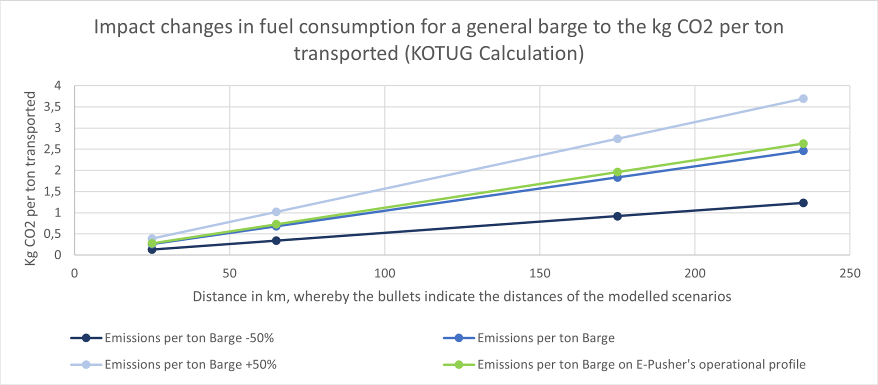


Figure 70: Sensitivity of fuel consumption general barge to emissions in kg CO2 per tons

Potential of the E-Pusher as Transport Mode in the Dutch Carbon Capture and Storage System

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Abstract – **Carbon Capture and Storage (CCS) is considered an essential solution to reaching climate goals. The two main identified transport modes in CCS, pipelines and ships, are widely compared to each other in the literature. This research contributes to the literature about the evaluation of transportation modes in CCS chains, by determining to what extent electrified ships can play a role in CCS. This is not studied before. This research is executed by following the Systems Engineering approach, in particular the SIMIE process. In a proposed point-to-point network for onshore transportation, mainly general diesel-propelled barges would perform with the lowest costs per ton, whereby the distance ranges from 25 km up to 250 km. As longer the distances, more Tank-to-Wheel (TTW) emissions savings could be obtained if barge transport is electrified. Identifying the most accurate emissions reporting method and performing operational validation for modelling the transport modes and trajectories could provide the obtained results with more scientific and practical robustness.**

Keywords: *Carbon Capture and Storage, TTW Emissions, Systems Engineering, Transportation, Electrification*

Part I

State of the Problem

1 Introduction

Globally, companies and governmental authorities are identifying possibilities to contribute to reaching climate goals. Carbon Capture and Storage is considered a temporary solution to decrease CO2 emissions. On the global level, the contribution of CCS to decreasing CO2 emissions is expected at 30%. Therefore, CCS is considered an essential solution to reach the climate goals, also, in the Netherlands (Rijksoverheid, 2021). In this research, the potential of a new transport innovation is evaluated as a transport mode within a CCS chain. This new transport mode is an electrified pusher tug, called the E-Pusher. The innovation is introduced by KOTUG and is a modular and scalable electric pusher tug that is powered by swappable energy containers.

Commonly, a CCS value chain is organised as follows: First, CO2 is captured at the emission site. Second, the CO2 is transported from the emission site to a collection point. Then, from the collection point, the CO2 will be transported to an offshore location. Finally, the CO2 will be injected under the seabed at the offshore location. The scope of this research is bounded by the onshore transportation from the emissions sites to the collection points, see Figure 1. Furthermore, the geographical scope is mostly bounded by the North-Western European Region closely connected to empty (gas) fields under the seabed, with the main focus on the industrial clusters connected to the Port of Rotterdam in the Netherlands.

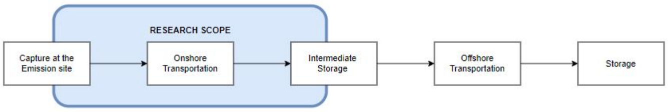


Figure 1: Visual depiction of the scope of this research

Currently, the CCS transportation infrastructure is not established and implemented. The development of infrastructure and transport services is of high importance to achieve full-scale CCS deployment. Therefore, efficient and reliable solutions are required in the value chain (Størset et al., 2018). The most viable transport solutions are pipelines and ships. In literature, pipelines are found to be suitable for short distances and large emissions capacities. While ships offer higher flexibility for short-term solutions, are more cost-effective for longer distances and for lower emission capacities (Kjärstad et al., 2016; Roussanaly et al., 2013). The flexibility of ships is expected to contribute to the scale-up stages of CCS projects. However, a disadvantage of ships is that for longer distances the actual amount of CO2 emissions saved is reduced because of fuel combustion and boil-off (Weihs et al., 2014). An aspect that is not researched yet is the impact of electrified ships on the CO2 emissions resulting from the transport in CCS chains. Also, it is not investigated yet how feasible electrified ships are in CCS transportation chains. Therefore, the effect of using electrified ships as a transport mode in CCS on the decrease in CO2 emissions is formulated as knowledge gap.

1.1 Research Objective

Scientific research into the feasibility of electrified ship transport in CCS chains has not been executed yet. Fulfilling the main goal of this research contributes to the scientific literature. The main goal of this thesis is to determine to what extent electrified ship transport can play a role and what the emissions impact is if electrified ship transport would be deployed, in the transportation stage of CCS chains. To achieve the main goal, this research attempts to provide an answer to the main question, which is formulated as follows: *"Which requirements and conditions determine to what extent the E-Pusher could be a suitable inland transport mode for liquid carbon within the transport stage of a CCS chain, and what are the emission effects to the CCS transportation chain if the E-Pusher is deployed?"*.

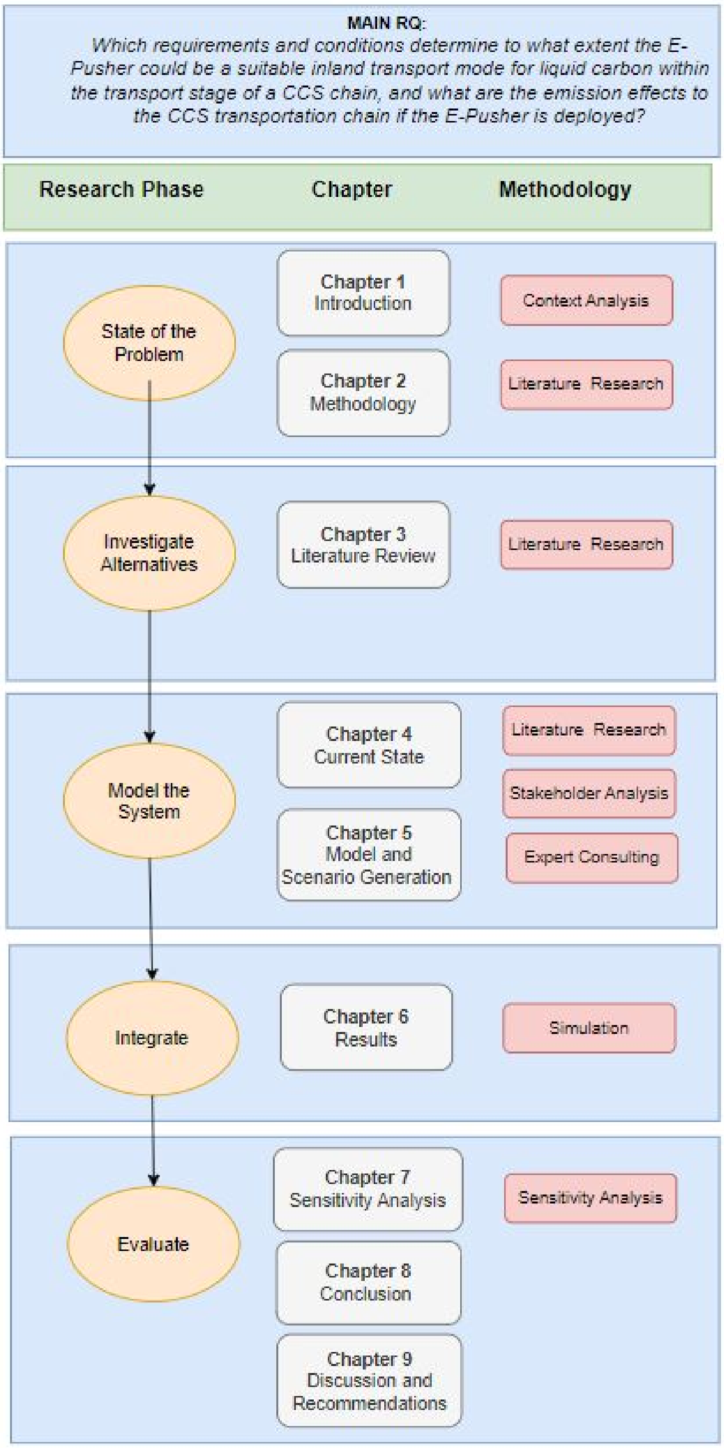
1.2 Research Structure

First, the methodology for executing this research will be explained. Second, the remaining literature review will be performed. Third, the current state of CCS in the Netherlands and surrounding countries will be determined. Then, the model and built scenarios to perform the analysis will be explained. Thereafter, the results following from simulating the model and scenarios will be presented. Subsequently, the results will be evaluated by a sensitivity analysis. Summarising the findings will lead to an answer to the main question that is given in the conclusion. Finally, in the discussion part, the recommendations derived from this research will be given.

2 Methodology

Systems Engineering is an approach based on system thinking. Not only the considerations of the whole system but also the considerations of subsystems are incorporated. Because this research also has multiple system levels, such as a CCS chain at a higher level and transportation mode systems at lower levels, Systems Engineering is forming a reliable fundamental structure of this research. Within Systems Engineering multiple types of approaches exist. This research followed an adapted form of the SIMILAR process. Each sign of SIMILAR indicates a step in the whole process (INCOSE, 2014). For the SIMILAR process, the sequence of steps is **S**tate the problem, **I**nvestigate, **M**odel the System, **I**ntegrate, **L**aunch the system, **A**ssess performance, and **R**e-evaluate. The last three steps are combined because Launch the System and Asses Performance is not possible given the explorative nature and limitations for the execution time of this research. The abbreviated form of the SIMILAR approach results in the SIMIE approach. The steps and corresponding relevance of SIMIE to this research are explained in this section and presented in Figure 2.

- **State of the Problem:**
  Create a clear definition of the Problem and the Scope.
- **Investigate the Alternatives:**
  Perform remaining literature research. Define the transportation requirements.
- **Model the System:**
  Determine the current state. Generate the model and scenarios.
- **Integrate:**
  Obtain the results by simulation of the model and scenarios.
- **Evaluate:**
  Validate the assumptions and outcomes. Provide the conclusions and recommendations.



MAIN RQ:
Which requirements and conditions determine to what extent the E-Pusher could be a suitable inland transport mode for liquid carbon within the transport stage of a CCS chain, and what are the emission effects to the CCS transportation chain if the E-Pusher is deployed?

Figure 2: SIMIE approach in this research

Part II

Investigate Alternatives

3 Literature Review

3.1 Framework and KPIs

Because the E-Pusher is a waterway mode, the main focus of all the considered CCS transportation modes is orientated to the barge mode. Barge transport is recognised as an important transportation mode of freight in countries with a large transport capacity and high-quality of waterways. Most of the transport is moved between the seaports and the hinterland (Wiegmans and Konings, 2007). Konings (2009), developed a framework to design and assess an intermodal barge transport network from both operator's and shipper's perspectives. The framework of Konings (2009), is suitable to use in this research because the whole CCS network can be considered as an intermodal transport network. Inland transport operations can be performed by pipeline, barge, truck or rail, while offshore transport can be pipeline or ship only. Therefore, this framework is used as starting point. However, the framework has also some limitations for this research. In this research, not the operator's or shipper's perspectives but a network perspective is considered. Furthermore, the KPIs are only dedicated to operational and financial factors. At the time the framework was developed, sustainability was not of high significance in designing and assessing transportation networks. An extra layer indicating a network perspective and an extra KPI *Sustainability* are added to overcome the mentioned limitations. The adapted version of the framework is visible in Figure 3.

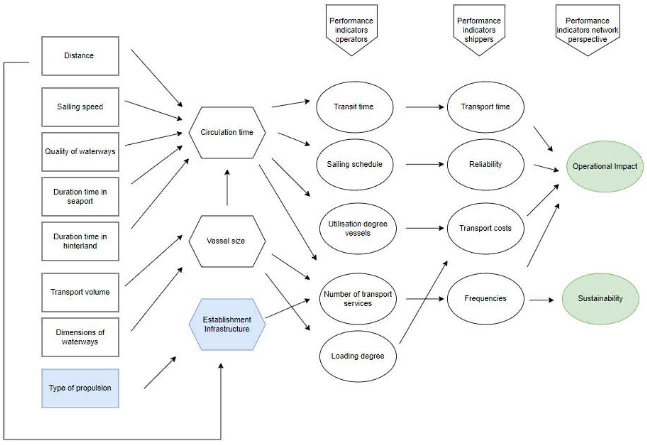


Figure 3: Adapted framework for barge network design
Note. Figure made by the Author, adapted from Konings 2009

The KPIs considered in assessing the performance of a barge network are derived from the adapted framework. In this research, the operational impact and sustainability are determined to be the KPIs to assess. In Table 1, the KPIs are presented with corresponding units. It is chosen to combine the frequency and transport time in the operational capacity of a vessel. This KPI will be expressed in cycles per year. Associated with the number of cycles per year it is also important to express the amount of volume transported. The KPI will be thus, transported volume expressed in tons per year, or in a more common unit that is used in CCS chains, namely Mega Ton per Annum (MTPA). The costs' KPI will be divided into Operational Expenditures (OPEX) and Capital Expenditures (CAPEX). Both will be expressed in euros per year. The sustainability KPI, emissions, will be expressed in kg CO2 emitted per year. Reliability expresses how reliable a system is. This KPI will not be calculated quantitatively. The reliability aspects for each transport mode will be covered in literature research and thus it will not be considered in a model later in the research. In the validation phase, reliability aspects can be considered during the evaluation of the results.

Table 1: KPIs to asses the E-Pushers' potential

KPI	**Indicator**		**Unit**
Operational Impact	*Operational capacity*		Cycles/year
	Transported volume		MTPA
	Costs	*OPEX*	Euros / year
		CAPEX	Euros / year
Sustainability	*Emissions CO2*		kg CO2 / year

3.2 Transport Conditions

Several transport requirements apply for moving the captured CO2 by barge. The CO2 is required to be liquefied. Different temperatures and pressures exist to transport liquefied CO2. Economically, it is desired to obtain transport conditions close to the triple point of CO2 (Xu et al., 2018). However, transport conditions close to the triple point increase the risks of safety issues, such as the formation of hydrates and dry ice (Equinor, 2019). Seo et al. (2016) found given a cost-effective perspective whereby safety risks are limited, optimal transport conditions are at 15 bar under a temperature of -27 degrees. For a barge mode, the liquefied CO2 can be transported either in fixed tanks or containers.

Part III

Model the System

4 Current State

In the previous section, the KPIs to asses a network design are determined. In this section, a transportation network suitable for evaluation will be proposed and the motives for selecting this design will be explained.

4.1 Proposed network typology

Currently, the CCS transportation infrastructure is not (widely) implemented yet. Hub-and-clustering networks are required for upscaling CCS networks. The advantages of hub-and-clustering networks can be summarised as reducing costs, decreasing risks for new CCS projects and removing interdependency between the size of individual emitters and their investment decisions (Global CCS Institute, 2016). Therefore, for the whole value chain of

CCS projects hub-and-clustering networks are expected. Regarding, the onshore transportation network a different typology is proposed in this research. Kreutzberger (2008), stated that for an inland barge network freight is already bundled in the ports, therefore, it is not necessary to establish intermediate hubs. Moreover, Bellona Germany (2019 found that a point-to-point network offers more flexibility in the implementation phase of CCS chains, which is the current phase of CCS. Thus, if the scope is limited to the onshore transportation phase, the connections from the hub to the emitters can be considered point-to-point. This is depicted in the green box in Figure 4.

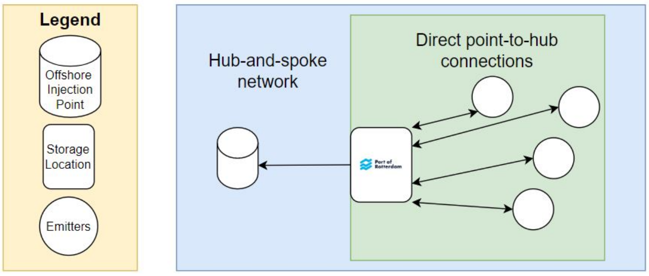


Figure 4: Proposed network typology in a Dutch CCS system
Note. Figure made by the Author

4.2 Potential Transportation Routes and Infrastructure

In the Netherlands, several CCS projects are contributing to the upscaling of infrastructure for CO2 transport, which is not implemented till now. Aramis, a project for upscaling the infrastructure between emissions sites and the collection point in the Port of Rotterdam, expects a gradual increase from 5 MTPA in 2026 to 10 MTPA in 2030 and 20 MTPA in 2035. Besides Aramis, also Porthos and CO2next are developing CCS infrastructure in the Port of Rotterdam. CO2next is establishing the terminal to collect and supply CO2 by ship, in the Port of Rotterdam. CO2next expects a supply between 2.5 to 7.0 MTPA for liquefied CO2 by ship, in the first stage of the Aramis project (Ministry of Economic Affairs and Climate Policy, 2021). The development of this supply can be driven by different industrial clusters, such as the Chemelot cluster and the North Rhine Westphalia cluster. This is because these clusters are closely connected to the Dutch waterway system (Bellona Germany, 2019). The transport services of CO2 can also be driven by Carbon Capture and Utilisation (CCU) projects, but it is not expected that this is feasible in the short-term.

Similarly, as the building plans for the hub in the Port of Rotterdam, also construction plans for hubs elsewhere in Europe are developing. Examples of other potential hubs are Eemshaven, the Port of Immingham, Wilhelmshaven and Gdansk. Figure 5, presents an overview of connecting ongoing and potential CCS projects.

Figure 5: Connecting ongoing and potential projects
Note. From Bellona Germany, (2019)

4.3 CCS Stakeholder Dynamics

CCS on itself is not a new solution. In the past, several projects were running to implement CCS on a wider scale, both in the Netherlands and worldwide. However, earlier CCS projects were unsuccessful because of technical, legal and political factors (Akerboom et al., 2021). Stakeholders have to cooperate effectively in future CCS development plans to overcome the failure factors of previous failed projects. A circumstance that is different nowadays, compared to the periods of previous CCS projects is that CCS is more widely supported as a solution to reach climate goals. CCS deployment is perceived as inevitable, even by NGOs. However, some barriers exist concerning the implementation of CCS. On the international level, the London Protocol is forming a barrier. It is not allowed to dump waste from one country to another country. Bilateral agreements have to be made between countries to allow transboundary transport of CO2 for storage purposes (Reyes et al., 2021). Moreover, on the national level, a chicken-egg problem can be observed. The current Dutch CCS projects stated that they are willing to build infrastructure, but they need emitters that are willing to participate. Emitters need the infrastructure and also funding to bridge the gap between transportation and storage costs. On the other hand, the public authorities want a guaranteed available infrastructure available before providing funds. Also, this problem should be solved to stimulate CCS implementation. Nevertheless, also drivers for CCS engagement are expected. The EU Emissions Trading System (ETS) is expected to stimulate companies investing in decarbonization by making business cases for companies financially more attractive (Reyes et al., 2021; Buirma, 2020).

5 Model and Scenario Generation

In the previous phases of the research, the introduction, methodology and other analyses were performed to outline the context of this research. Bridging the gap between the previous phases and obtaining results requires a model and scenarios for simulation. Therefore, in this section, the model and scenario generation will be explained.

5.1 Model Objective

The purpose of the model is to allow a simulation for realistic transport trajectories in a CCS chain. Therefore, it is needed to incorporate relevant transportation requirements to approach a realistic simulation. Furthermore, the model should present the KPI output in a transparent and interpretable way.

5.2 Model Terminology and Design

The model is composed of three types of variables. The first type of variables is the **independent variables**, which forms the input of the system and is not influenced by the other variables. The second type of variables is the **dependent variables**, which presents the KPI output. These variables are calculated by the model. The KPIs of the model mainly correspond with the formulated KPIs of Table 1. Only the operational capacity is slightly changed in the cycle time of a transport mode. The last type of variables is the **intermediate variables**, which are calculated internally in the model but do not represents the KPI output. The relation between the variables and the model is depicted in Figure 6.

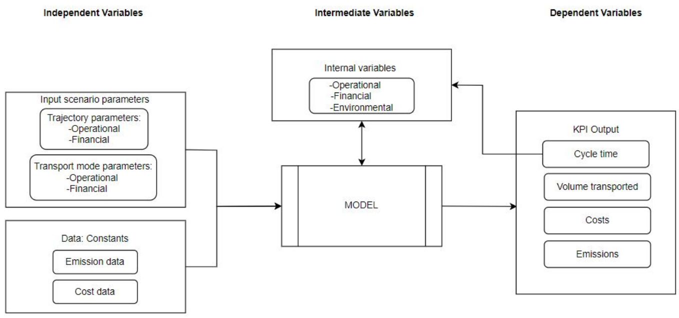


Figure 6: Relation between the variables and the model

5.3 Modelling Assumptions

In this section, the main differences in modelling the different transport modes are explained. An overview of the base-case model is presented in Appendix A.

The waterway and roadway transport modes are modelled with discontinuous transportation flows. First, from the Port of Rotterdam, an empty trip is executed to the emitter, and then from the emitter, the cargo is transported back to the Port of Rotterdam. Following this way of modelling, the annual transported volume of the mentioned transport mode will be calculated. For the pipeline mode, two fixed annual volumes are given. One pipeline of 2.5 MTPA and one pipeline of 10 MTPA will be evaluated. Both pipelines are assumed in the model with a continuous transportation flow.

The costs per year for the waterway and roadway modes will be calculated based on the operational profiles and scenario characteristics. For estimating pipeline costs, interpolation will be performed. The data of interpolation is found in studies about modelling pipelines in CCS chains within Europe (Knoope et al., 2013; ZEP, n.d.). The trajectory distance will be multiplied by the value for costs per km, derived from interpolation.

Regarding the reporting of emissions, two methods for calculating the emissions will be used. The first one is called the KOTUG calculation whereby the number of litres per cycle will be calculated and thereafter converted to annual litre consumption. The number of litres of diesel per cycle and the number of annual cycles will be multiplied by the emissions factor for kg CO2 per litre of diesel. The second method is from CE Delft, whereby the transport performance will be considered. The annual tonne-kilometre of a transport mode will be calculated and then multiplied by an emission factor for tonne-kilometre. Another important remark is that the emission factors correspond with Thank-to-Wheel values. Thus, only the emissions resulting from operating the transport services will be considered. This will only be done for the roadway and waterway modes, thus not for the pipeline.

The following comparison is made, concerning the emission savings of the E-Pusher compared to a general barge. Based on the operational profile of the E-Pusher in a certain scenario, the emissions of a barge with an equal operational profile are calculated. This is because the capacity and cycle time of a barge are expected to be higher compared to the E-Pusher. Guaranteeing a fair comparison requires the actual emissions of a barge based on the E-Pusher's operational profile. Besides, for all considered transport modes, the costs and energy consumption for compressing the CO2 are crossed out against each other.

5.4 Scenario Generation

Generating scenarios is forming the last step before executing the simulation in this research. It is chosen to build four scenarios based on different distances. The distances are based on the distance between the expected CO2 terminal in the Yangtzehaven in the Port of Rotterdam and a potential emitter derived from the Aker Carbon Capture map. The emitters are modelled for a very short (∼ 25 km), short (∼ 65km), medium (∼ 155km) and large distance (∼ 235 km). First, the model simulates a general, diesel-propelled, barge transport in CCS. Then, adjustments will be made to the model for transportation by truck, pipeline, and E-Pusher. Noted should be that for the barge and the E-Pusher the waterway distances are derived, for truck transport the roadway distance and for pipeline transport the euclidean distance. To summarise, in total are four scenarios built, whereby in each scenario four transport modes are modelled. These modes are the general barge, truck, pipeline and the E-Pusher. An overview of the modelled system is given in Figure 7. Another overview of the all the modelled scenarios and configurations is presented table-wise in Appendix B.

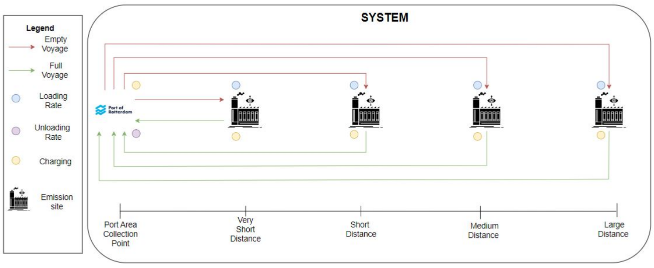


Figure 7: System design

Part IV
Integrate

6 Results

In this section, the relevant results will be highlighted. To keep this research paper concise, it is chosen to only present the overall results and not present the KPI output table for each individual scenario. Furthermore, it should be noted that KPIs are set against each other to make fair comparisons.

The first KPIs that are set out against each other are the annual volume transported and the total costs. The resulting trade-off presented, is the costs in euros per ton transported. In Figure 8, the costs in euros per ton are presented for all the transport modes over all the scenarios. The lines indicate the different modelled transport modes. Each bullet point on a line indicates the approximate distance of a scenario. The euros per ton for the truck transport were in such a higher range that it is not presented in the graph. Thus, truck transport has extremely high costs per ton compared to the other modes. Also, for the pipeline of 2.5 MTPA it was found in literature that it is not economically feasible to implement a pipeline of 2.5 MTPA at large distances. Therefore, the 2.5 MTPA is only modelled for the first three scenarios. Comparing the costs per ton of the 2.5 MTPA pipe to the other modes, it can be seen that the other modes have significant lower costs per ton for the three scenarios. Nevertheless, not all the modelled pipeline configurations perform with high costs per ton. The pipeline of 10 MTPA has the lowest costs per ton at a very short distance. If the distance increases, the costs per ton of the pipe of 10 MTPA will not be the lowest anymore. Mainly, the waterway modes have the lowest costs per ton over all distances, except for a very short distance. Especially, the barge performs with the lowest costs per ton. The E-Pusher's cost per ton is slightly higher compared to the barge over all the distances.

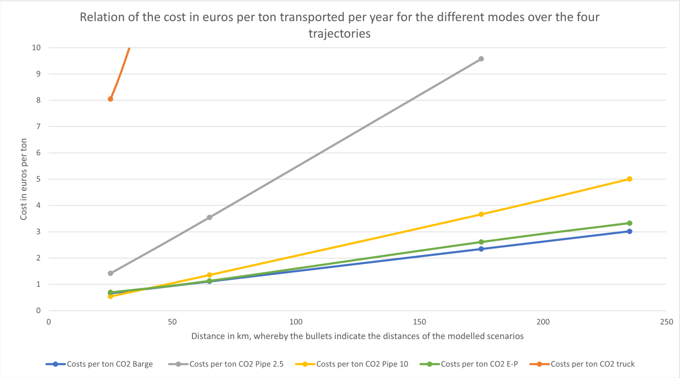


Figure 8: Relation of the costs per ton over the distances

Regarding the emissions, a barge and a barge based on the E-Pusher's operational profile perform similarly for all distances. Therefore, the results of those could be generalised. The E-Pusher has zero TTW emissions, the direct savings of emissions at certain distances for deploying the E-Pusher could be derived from the graph. Following the results from the KOTUG calculation, the annual emissions savings in kg CO2 per ton transported for the different distances are approximately 0.26 at 25 km, 0.68 at 65 km, 1.83 at 175 km, and 2.46 at 235 km.

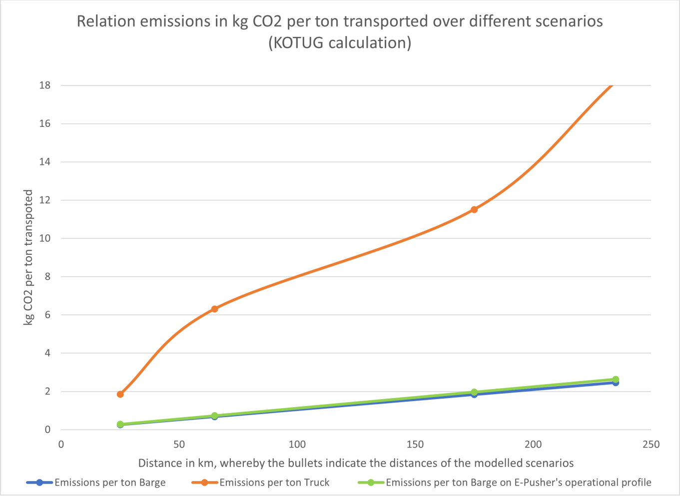


Figure 9: Relation of the emissions per ton over the distances

Also in Figure 10, the emissions per ton are presented. These results are derived by following the method of CE Delft for calculating the emissions. Remarkable is that the annual emissions per ton in the CE Delft calculation are slightly higher than one and a half times the emissions per ton in the KOTUG calculation.

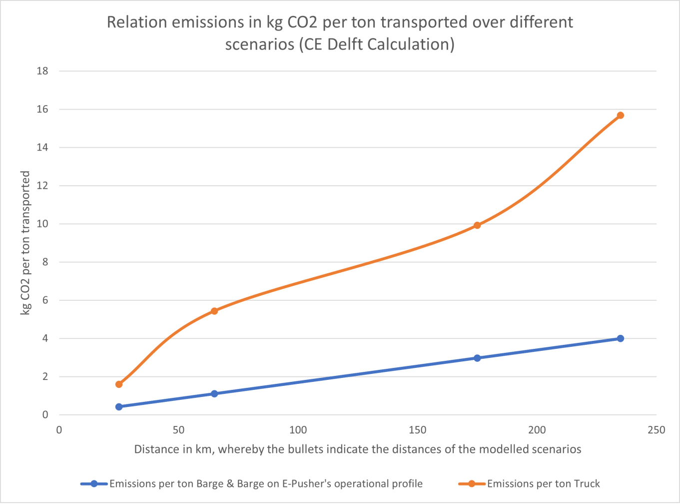


Figure 10: Relation of the emissions per ton over the distances

In Figure 11, the net CO2 percentage is given. The net CO2 is calculated by subtracting the emissions during transportation from the annual volume transported. As can be seen, the net percentage of CO2 decreases from very short distances to large distances with 0.22 %, given the KOTUG emission calculation.

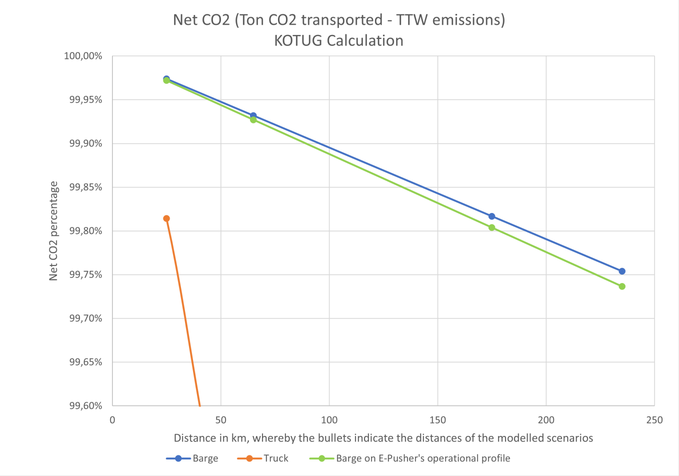


Figure 11: Net CO2 derived from the KOTUG calculation

In Figure 12, the net CO2 is presented similarly presented as in Figure 11. However, below it is presented for the CE Delft calculation. The same pattern could be observed as for in the KOTUG calculation. The net CO2 percentage decreases with 0.36% from very short distances to large distances.

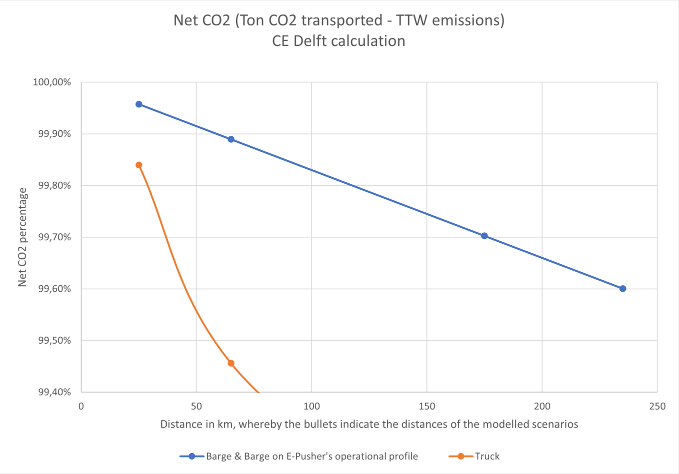


Figure 12: Net CO2 derived from the CE Delft calculation

Part V

Evaluate

7 Sensitivity Analysis

A high number of developments or uncertainties exist that potentially can influence the obtained results. Therefore, in this section, the highlights of the impact of an increase and decrease of some modelled variables on the obtained results are presented.

The first shown results of the sensitivity analysis are a 50% increase or decrease in the pipelines' CAPEX. A decrease is realistic because existing pipelines could be used which will drastically decrease the CAPEX of a pipeline. An increase is also realistic in case the pipeline should be built near rivers or residential areas. What can be observed from Figure 13, is that a decrease in the pipeline CAPEX leads to a different position of the pipe as transport mode, concerning the costs per ton. The red line indicates that the pipeline of 10 MTPA will be the transport mode with the lowest costs per ton till short distances. The pipe performs with equal costs per ton at medium distances, compared to the E-Pusher. Only, at larger distances, the E-Pusher would have lower costs per ton than the pipeline of 10 MTPA.

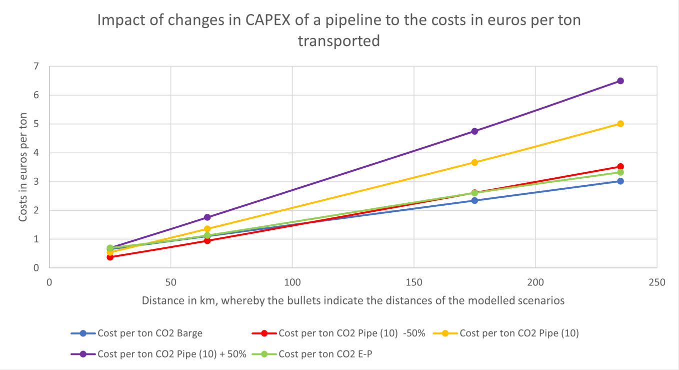


Figure 13: Sensitivity of costs per ton to halved CAPEX pipeline

Likewise the CAPEX decrease of the pipeline, also, a halved load degree for the waterway vessels have a huge impact on the positions of the general barge and the E-Pusher. The halved load degrees are realistic because of low water levels and waterway restrictions on the Rhine. In the case of halved load degrees, the pipeline of 10 MTPA performs with the lowest costs per ton over all scenarios.

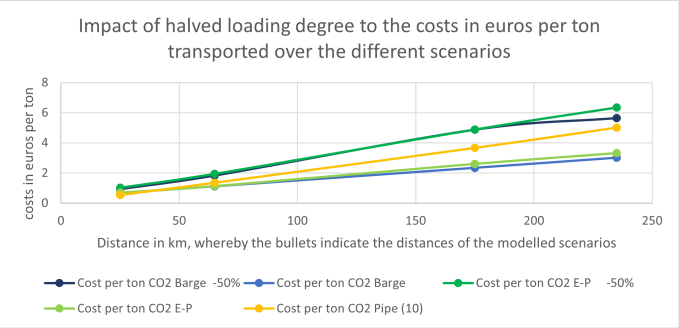


Figure 14: Sensitivity of costs per ton to halved load degree

Regarding the costs per ton, a 50% increase in the diesel prices or a halved energy price would give the E-Pusher a slightly more advantageous position than in the base case, but the developments do not have a similar impact as the depicted developments in this chapter and are therefore not depicted.

8 Conclusion

The main goal of this thesis was to determine to what extent electrified ship transport can play a role and what the emissions impact is if electrified ship transport would be deployed, in the transportation stage of CCS chains.

The E-Pusher from KOTUG was evaluated as electrified ship mode in this research.

Derived from the research goal was the following main question: ***"Which requirements and conditions determine to what extent the E-Pusher could be a suitable inland transport mode for liquid carbon within the transport stage of a CCS chain, and what are the emission effects to the CCS chain if the E-Pusher is deployed?"*** The answer to the main question is threefolded.

First, regardless of the transport modes, several barriers related to CCS implementation should be overcome. CCS projects, potential emitters and public authorities need a more extensive collaboration for stimulating CCS implementation. Also, the issues arising because of the London Protocol needs to be solved. On the other hand, ETS is found as a potential enabler for CCS implementation because the driver creates incentives for participators in CCS.

Second, regarding the position of the E-Pusher in CCS compared to the other modes, the E-Pusher is not outperformed by the other modes and might be even competitive. The E-Pusher has slightly more costs per ton for transporting CO2 than the barge, which has the lowest costs per ton. For very short distances, a pipeline of 10 MTPA will perform with the lowest costs per ton. Nevertheless, potential developments with a significant impact on the E-Pusher's position compared to the other modes are found. A halved CAPEX for a pipeline, which is realistic when a pipeline is already established, has a negative effect on the position of the E-Pusher. Also, a halved load degree, which is realistic because of low water levels and waterway restrictions, dangers this position.

Third, regarding the potential emission savings of the E-Pusher, the findings of this research are in line with the findings of Weihs et al. (2014). Also in this research, increase the emissions from barge transport if the distance increases. The E-Pusher could have more emission savings for longer distances. The percentage net CO2 decreases from very short distances to large distances with 0.22 % for the KOTUG calculation and 0.36 % for CE Delft calculation.

9 Discussion and Recommendations

The contribution of this research to the existing scientific literature, about transport modes in a CCS chain, lies in the fact that a sustainability factor is added to evaluate the different transport modes. The adapted framework of Konings (2009) and derived KPIs provided the opportunity to outline the emission effects of a zero-emission vessel in a CCS chain. This is not done in earlier academic research. Resulting from the conclusions and limitations of this research, new research topics are found. Which are described below.

Firstly, operational validation for both the transport modes and the trajectory characteristics as well as the E-Pusher's configuration in this research is recommended. Examples of trajectory characteristics that might have an impact on the results of this research are stronger currents, lower water levels, and poor weather. Regarding the E-Pusher's energy requirement, it is interesting to validate the simulation results in practice. Now the technical-operational features are only derived from simulation results. For pipeline modelling, building restrictions might be encountered that do not allow a Euclidean distance, and thus could impact the costs of implementing a pipeline. Also, Knoope et al. (2015) provide a more accurate method for estimating pipeline costs than the method that is used in this research. For further research, it is recommended to use the method of Knoope et al. (2015) and obtain all relevant parameters and corresponding values for pipeline modelling.

Moreover, it is recommended to investigate the most accurate method for reporting emissions of transport services in CCS chains. This research considered a first method for reporting the emissions based on fuel consumption, called the KOTUG calculation. The other method, called the CE Delft method, considers the transport performance for the emission calculations. The results from both methods are different from each other but indicate the same KPI. Another aspect that could extend the scope of this research is to consider also emissions from manufacturing processes of the different components of the transport modes. In this research, only TTW emissions are assumed.

Next to that, expert consulting led to the assumption that the compression costs can be neglected in this explorative phase of determining the CO2 transportation costs. This is because the costs are assumed to be crossed out against each other for the different transport modes. Similarly, this is assumption is made for the energy consumption of compressing the CO2. In further research stages, incorporating the compression costs and energy requirements for transporting the CO2 can widen the scope of this research and provide the results concerning the costs and emissions with more reliability.

Finally, further research is recommended concerning the potential network of CCS. It is interesting how robust the results of this research are if different network typologies are evaluated. For instance, a more detailed hub-and-spoke network, with more intermediate hubs whereby the load could be bundled is a possibility to investigate. Regarding a CCS network perspective and electrification of transport modes, it is also interesting to obtain more insight into how to design and evaluate a potential charging infrastructure network for electric vessels in CCS chains.

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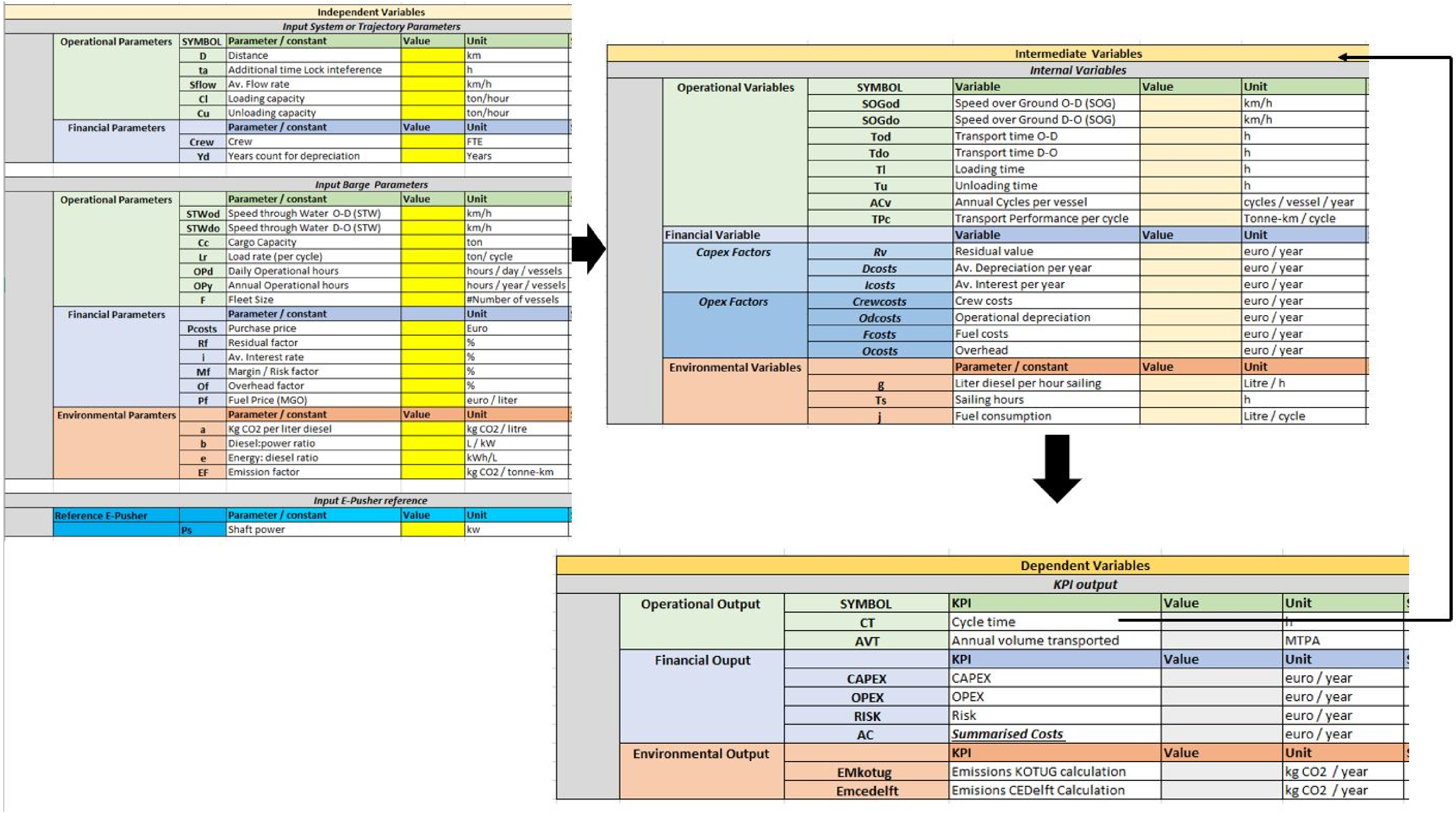
10 Appendix A: Overview of the Model



Independent Variables

Input System or Trajectory Parameters

Operational Parameters	SYMBOL	Parameter / constant	Value	Unit
	D	Distance		km
	ta	Additional time Lock inteference		h
	Sflow	Av. Flow rate		km/h
	Cl	Loading capacity		ton/hour
	Cu	Unloading capacity		ton/hour
Financial Parameters		Parameter / constant	Value	Unit
	Crew	Crew		FTE
	Yd	Years count for depreciation		Years

Input Barge Parameters

Operational Parameters		Parameter / constant	Value	Unit
	STWod	Speed through Water O-D (STW)		km/h
	STWdo	Speed through Water D-O (STW)		km/h
	Cc	Cargo Capacity		ton
	Lr	Load rate (per cycle)		ton/ cycle
	OPd	Daily Operational hours		hours / day / vessels
	OPy	Annual Operational hours		hours / year / vessels
	F	Fleet Size		#Number of vessels
Financial Parameters		Parameter / constant		Unit
	Pcosts	Purchase price		Euro
	Rf	Residual factor		%
	i	Av. Interest rate		%
	Mf	Margin / Risk factor		%
	Of	Overhead factor		%
	Pf	Fuel Price (MGO)		euro / liter
Environmental Paramters		Parameter / constant	Value	Unit
	a	Kg CO2 per liter diesel		kg CO2 / litre
	b	Diesel:power ratio		L / kW
	e	Energy: diesel ratio		kWh/L
	EF	Emission factor		kg CO2 / tonne-km

Input E-Pusher reference

Reference E-Pusher		Parameter / constant	Value	Unit
	Ps	Shaft power		kw

Intermediate Variables

Internal Variables

Operational Variables	SYMBOL	Variable	Value	Unit
	SOGod	Speed over Ground O-D (SOG)		km/h
	SOGdo	Speed over Ground D-O (SOG)		km/h
	Tod	Transport time O-D		h
	Tdo	Transport time D-O		h
	Tl	Loading time		h
	Tu	Unloading time		h
	ACv	Annual Cycles per vessel		cycles / vessel / year
	TPc	Transport Performance per cycle		Tonne-km / cycle
Financial Variable		Variable	Value	Unit
Capex Factors	*Rv*	Residual value		euro / year
	Dcosts	Av. Depreciation per year		euro / year
	Icosts	Av. Interest per year		euro / year
Opex Factors	*Crewcosts*	Crew costs		euro / year
	Odcosts	Operational depreciation		euro / year
	Fcosts	Fuel costs		euro / year
	Ocosts	Overhead		euro / year
Environmental Variables		Parameter / constant	Value	Unit
	g	Liter diesel per hour sailing		Litre / h
	Ts	Sailing hours		h
	j	Fuel consumption		Litre / cycle

Dependent Variables

KPI output

Operational Output	SYMBOL	KPI	Value	Unit
	CT	Cycle time		h
	AVT	Annual volume transported		MTPA
Financial Ouput		KPI	Value	Unit
	CAPEX	CAPEX		euro / year
	OPEX	OPEX		euro / year
	RISK	Risk		euro / year
	AC	***Summarised Costs***		euro / year
Environmental Output		KPI	Value	Unit
	EMkotug	Emissions KOTUG calculation		kg CO2 / year
	Emcedelft	Emisions CEDelft Calculation		kg CO2 / year

Figure 15: Overview of variables, parameters and KPIs

11 Appendix B: Scenarios and Configurations

Table 2: Overview of scenarios with corresponding configurations and distances

Scenario	***Configuration***	***Distance***
1. Rotterdam Yangtzehaven - Botlek	1.1 Barge	25 km
	1.2 Truck	25 km
	1.3 Pipeline	20 km
	1.4 E-Pusher	25 km
2. Rotterdam Yangtzehaven - Moerdijk	2.1 Barge	65 km
	2.2 Truck	85 km
	2.3 Pipeline	50 km
	2.4 E-Pusher	65 km
3. Rotterdam Yangtzehaven - Arnhem	3.1 Barge	175 km
	3.2 Truck	155 km
	3.3 Pipeline	135 km
	3.4 E-Pusher	175 km
4. Rotterdam Yangtzehaven - Duisburg	4.1 Barge	235km
	4.2 Truck	245 km
	4.3 Pipeline	195 km
	4.4 E-Pusher	235 km