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Ship Based Carbon Capture and Storage: A Supply Chain Feasibility Study

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Abstract

The maritime industry faces more and more restrictions on the amounts of greenhouse gases, and particularly CO_2 which the IMO allows to be emitted by ships. Carbon capture technology promises to be able to significantly reduce the CO_2 emissions on ships and is most compatible with LNG powered vessels by filtering the CO_2 from the exhaust gases. This research is focused on the question: "what to do with the CO_2, once it has been captured on board?". A threefold feasibility study is conducted to prove the feasibility of the supply chain from ship based carbon capture on a technical, economical and emissions related level. The supply chain consists of a capture, transportation and end-of-life phase. Each phase is assessed for technical, economical and emissions related feasibility. Both internal factors such as offshore transportation distance, onboard CO_2 storage capacity and Capital Expenditures (CAPEX) of a carbon capture system, as well as external conditions such as carbon tax and utilization revenue have proven to be the most impactfull elements which keep the payback time of the investment in carbon capture within a reasonable time of 3 to 5 years, while maintaining the possibility to reach the IMO2030 and IMO2050 CO_2 emission reduction targets of 40% and 70% respectively.

Keywords: CO_2, Carbon Capture, Storage, Utilization, Supply chain, Feasibility study, Systems engineering, Life cycle model.

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1 Introduction

The energy transition from fossil fuels to renewable energy sources has a major impact on many industries worldwide. In the shipping and offshore industry, which contributes about 3.1% of the global CO_2 emissions (Smith et al., 2014), much is being done to reduce emissions. During this energy transition, the biggest shift can be seen in the form of sustainable solutions worldwide in the field of electrification and efficiency optimization. Shipping, however, is seen as a hard-to-abate industry. This means that 'simply' electrifying or making engines more efficient is often not considered possible.

The International Maritime Organization IMO, a governing body for shipping with 174 member states, sets targets to limit emissions from ships. With regard to CO_2 emissions, the IMO has set a target to reduce emissions by 40% by 2030 compared to 2008, and 70% by 2050 (IMO, 2018).

In addition to the pressure from the IMO, a carbon tax is also looming on the horizon (Minkelis, 2020), which means that the prevention of emissions into the atmosphere is being further stimulated. In some industrial applications (power plants/waste incineration plants) on land, emissions are prevented by capturing CO_2 from the exhaust gases of industry (AVR, 2019). Research is currently being conducted into the feasibility of this carbon capture technology on board ships. Previous research has already shown that carbon capture has the highest potential on board ships sailing on LNG (Monteiro, 2020). The properties of an LNG ship ensure that the costs of the capture installation can be drastically reduced.

CO_2 that is captured on a ship leaves the system in a liquid state. The core of this research lies in the question of what to do with the CO_2. Storage on board, transport and end-use are the most important factors here. These three phases cover the supply chain of CO_2, captured on board ships. The general feasibility of the technology can only be demonstrated if this supply chain is properly mapped. Feasibility of the supply chain is viewed in three areas:

- **Technical feasibility** gives an overview of which technical solutions are available and feasible.
- **Economic feasibility** provides insight into the payback time of the technology if, in addition to the investment costs, the costs associated with transport, tax and end use are also included.
- **Emission related feasibility** indicates whether the CO_2 that is captured will not be emitted during transport, and nullifies the usefulness of carbon capture; and whether

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the ultimate goals of emission reduction of IMO2030 and IMO2050 are feasible.

Research objective and research questions

Scientific research into the supply chain of liquid CO_2 captured on board ships has not yet been conducted. The aim of this research is to map the supply chain in such a way that ship owners can make informed decisions about the conditions under which the technology could be feasible. This research will consist of a feasibility analysis that will examine the supply chain of ship-based carbon capture.

The feasibility of the supply chain will first be investigated on a technical basis by executing a performance analysis of the main technical components that could make up this supply chain, such as different ways to store the CO_2 on board, different transportation options, and different end uses. This is followed by an analysis focused on the costs and emissions of these different technical components, in which various scenarios are analyzed from which the most influential (external) effects and optimization opportunities emerge.

The research is guided by the following main research question: *"Which technical, economic and emissions-related conditions predominantly determine the feasibility of a conceptual supply chain of liquid CO_2 that is captured from the exhaust gases of LNG powered offshore Vessels?"*. In figure 1 sub-questions 1 to 6 are listed.

This paper will answer these questions. First, a section will be devoted to the methodology used. Then follows a section on the needs of the shipping industry in which the technical feasibility is demonstrated by means of a literature analysis, an operational and technical analysis of the supply chain options and a multi-criteria performance analysis. Subsequently, scenarios are defined in which the costs and emissions of the entire supply chain will be determined. These are then analyzed in the results section, which also demonstrates a supply chain design based on a case study. Finally, there is a section with conclusions and recommendations.

2 Methodology

The research is structured within the framework of the systems engineering system life cycle model of Kossiakoff (Kossiakoff et al., 2011). This model offers a step-by-step plan to develop a technique from initial technical opportunities to final operational implementation. The first step in the life cycle model is the **concept development** phase. In this paper this phase is elaborated in detail (see figure 1), which consists of three sub-phases. The sub-phases of concept development are: 1) needs analysis, 2) concept exploration and 3) concept definition. These are the first exploratory steps that are important for the development of new technology, and mainly intended to make a narrow down strike and arrive at conceptual designs of a supply chain for ship-based carbon capture and demonstrate the feasibility on the level of technology, costs and emissions. In later phases of the systems engineering life cycle model, concepts are worked out and engineered in more detail, but this falls outside the scope of this research. Concept development consists of:

- **Needs analysis:** In order to arrive at a conceptual design, an analysis must first be done of the driving need that is the reason for conducting this research. The needs of the shipping industry and the ship owner are analyzed. It also looks at which technically feasible solutions for the supply chain are available.
- **concept exploration:** In this phase, scenarios are designed and explored on the basis of a model to demonstrate the economic and emissions-related feasibility.
- **Concept definition:** In this phase, the main conditions that affect the overall feasibility of the supply chain are presented. These results follow from an analysis of the previously designed scenarios. The feasibility is also demonstrated here on the basis of a case study.

3 Needs analysis

The purpose of the needs analysis is to start with a need and technical opportunities, and to reduce them to a set of suitable technical solutions. The literature study first looks at the research that has already been carried out in the context of the supply chain of ship-based carbon capture. Subsequently, the requirements from a ship owner's point of view are determined, and finally an overview of the technically feasible supply chain options is presented (economic and emissions related feasibility are shown in chapter 4).

3.1 literature study

The scientific research into the supply chain of carbon capture and storage is mainly focused on the technological development of the system itself, and in particular on the application of the system to land-based industrial CO_2 sources (e.g. coal-fired power stations or waste processing companies). With carbon capture systems, the exhaust or flue gases are led through an absorption shower containing a concentration of a solvent (for example ammonia). This solvent takes a large part of the CO_2 out from the flue gas, after which clean exhaust gases leave the exhaust pipe. The amount of CO_2 that can theoretically be captured depends on a number of design parameters and operational conditions, such as gas flow velocity, dimensions of the installation and variability in engine speed. The ratio of CO_2 that is captured and CO_2 that would be emitted without carbon capture is called "capture

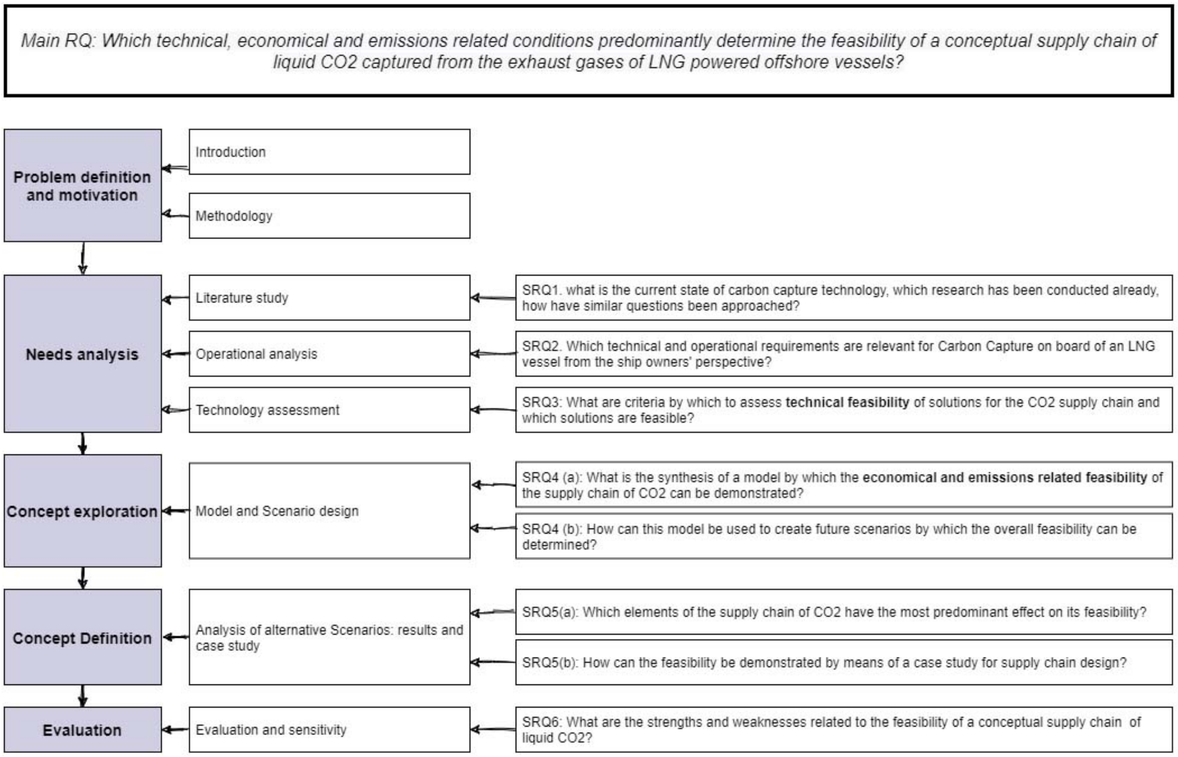

FIGURE 1: Research Methodology incl. structure of the paper and sub research questions, adapted from (Kossiakoff et al., 2011)

rate". A capture rate of 80% to 90% is realistically achievable for ships. The CO_2 is then simply said boiled out of the solution. The solvent is returned to the absorption shower, with which a closed system applies for the solvent. The CO_2 is cooled and compressed to liquefy, after which it is stored on board. Previous research by (Akker, 2017) shows that the system can best be integrated on board ships that sail on Liquefied Natural Gas (LNG), because these ships have large amounts of cold available (LNG is stored in liquid form at -162 Degrees Celsius) that can be used to cool and thereby liquefy the CO_2. The heat from exhaust gases can be used to boil the CO_2 from the solvent. Operating the system results in an estimated increase in fuel consumption of 2-5%[1]. By making smart use of the technology already on board, costs can be limited. The estimated costs for ship-based carbon capture are between € 100 and € 150 per tonne of CO_2 captured (Monteiro, 2020).

The amount of CO_2 strongly depends on the capture rate and the operational profiles of the ship. Assuming a capture rate of 80%, burning 1 m^3 LNG will result in approximately 0.9 m^3 liquid CO_2 outflow (Ros, 2020).

Value of CO_2

CO_2 emission is generally seen as a negative waste process, which should be avoided as much as possible. However, shipping is seen as a hard-to-abate industry due to the fact that it is isolated, self-moving 'small' power plants with high capacities. Capturing and transporting CO_2 is in itself a costly exercise, but under certain circumstances it can be made attractive.

1. **Carbon Tax:** Currently in some countries there is a tax on the emission of CO_2 for some polluting industries (Asen, 2019). Shipping has so far been excluded from initiatives such as the Paris Agreement and the European Emission Trading System (ETS). Recent developments indicate that shipping no longer falls under such measures (Minkelis, 2020). In the future scenario where a tax is levied on every ton of CO_2 that a ship emits, capturing this CO_2 may have financial benefits for a ship owner, as money can be saved this way which otherwise would have to be paid to tax.
2. **Utilization revenue:** a good example of a system where the costs of carbon capture can pay for itself is the OCAP (Organic CO_2 for Assimilation by Plants) network in Rotterdam, NL. CO_2 is captured from industrial processes in the port area and via pipelines to greenhouses in the Westland over a distance of ± 30km. Here

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[1] Estimated and verified by experts from Conoship (NL)

the CO_2 is sold for € 50 to € 100 per tonne to greenhouse growers who use it to enrich plant growth (OCAP, 2020). This is just one example of the potential income that can be made from selling CO_2. This can also be a factor for ship-based carbon capture that can help the technology to pay for itself.

3.2 Operational Analysis

From a ship owner's perspective, there are a number of considerations of importance regarding the implementation of carbon capture. A distinction is made between two types of ships. Firstly, a cargo ship (type 1) that regularly sails from port to port. The advantage of this type of vessel is the fact that it has a constant operational profile and a relatively easy to predict amount of CO_2 produced per trip. The second type of vessel is the offshore work vessel (type 2), such as an offshore heavy lift crane vessel. This type of ship has an unpredictable operational profile, whereby the required power can fluctuate strongly with short power peaks. A ship of the second type rarely enters ports and works offshore as much as possible, which leads to an increase in complexity for the supply chain. The reason for this distinction lies in the fact that this research is part of a larger collaboration that investigates the feasibility of ship-based carbon capture, in which a large offshore crane vessel that runs on LNG provides the use case (DerisCO_2). The size of this ship has the advantage that there is a lot of space on board to store the capture installation and storage on board. The disadvantage is that it is a unique ship, and the feasibility for this type of ship does not necessarily apply to the first type of ship.

The requirements from the perspective of both ship types can be stated as follows:

- **Emission minimalization:** The goal of carbon capture is to capture as much CO_2 as is technically and operationally feasible. The CO_2 emission during the transport of the liquid CO_2 must not be so high that it nullifies the avoided emission during capture.
- **Minimize costs:** For companies, costs are often a driving factor in decision-making. This study is based on the requirement that the investment in the carbon capture installation must be recouped within 3 to 5 years (specified by Heerema, N.D.)
- **Minimize Operational Impact:** A ship owner's business model aims to use the ship as much as possible. The impact of carbon capture on board leads to a limitation of usable transport space for cargo ships, or the need to unload CO_2 offshore for work vessels. These are both considerations where compromises will have to be sought and which costs will have to be calculated. However, this is very different per ship (type, size, sailing distance, design philosophy of the owner). It is therefore only mentioned in this study as a consideration that may affect feasibility, but it is not discussed in further detail.

TABLE 1: Predicted daily amount of storage needed at a 96MW crane vessel for different operational conditions (Heerema n.d.)

Operational mode	**CO_2 production per day [mt/day]**	**CO_2 production [m^3/day]**
Working	80	72.66
Sailing	110	99.91
Idle	27	24.52
Port	35	31.79

This research is further on mainly focused on the crane vessel. The reason for this is that 1) the supply chain for this ship is more complex, and therefore more relevant to map out and 2) the type of ship will be used in further research into the integration of the system, and the owner of such a ship has provided the researchers with useful details.

3.3 Technology Assessment

The supply chain of ship-based carbon capture can be divided into three main phases. First, the**capture phase**, which relates to everything that happens on board the ship (size and type of storage tanks on board). Second, the**Transport phase**, which looks at the offshore and onshore transport of liquid CO_2. Offshore transport is especially relevant for ships that rarely enter the port (type 2). Third, we look at the end-of-life of the CO_2, the **utilization phase**. In this phase, matters such as revenue are discussed. These three phases are explored to get an idea of the technical feasibility of the supply chain of CO_2. Each technical solution is tested against different criteria, namely 1) technology readiness level, 2) Safety, 3) Compatibility with other parts of the supply chain, 4) Scalability and 5) availability. In table 2 the results of this multi criteria performance analysis can be found.

Capture phase

In table 1 one can see the quantities of CO_2 that are produced per day per operational mode. The ship used as a use case has a fuel (LNG) storage capacity of 8000 m^3. The amount of CO_2 storage capacity that will be installed on board the ship limits the time it can sail in any operational mode before the storage is full and needs to be emptied/offloaded. Two technically feasible solutions can be chosen for the storage of the liquid CO_2 on board. The first option to look at is **fixed tanks**. The ship owner chooses a fixed volume of storage capacity. The second choice is **containerization**, where the CO_2 will be stored in twenty-foot tank containers. This solution provides more flexibility, since it can be predetermined how much CO2 will be captured. The disadvantage could be that it is more labor-intensive (e.g. (dis)connecting containers, re-allocation containers on the ship), which collides with the criterion of 'minimal operational impact'. Finally, the capture phase looks at a **hybrid storage** solution, in which both fixed tanks and containers are used.

Transportation phase

When the storage on board is full, a ship has to come alongside to unload the CO_2. The amount of storage determines the interval at which to unload, the type of storage determines the type of ship that comes alongside. If fixed tanks have been chosen, a CO_2 carrier/tank ship is required to take the liquid LCO_2 off the vessel. This is the same type of ship as used in LNG bunkering operations. Due to the different physical properties of LNG and LCO_2, different tanks are needed, and the storage and transport for LNG cannot be used for LCO_2. If the LCO_2 is stored in containers, it is best to transport them via an offshore supply vessel (OSV). An offshore crane vessel as used in this research is visited on average once every three weeks by such a supply vessel, whereby the CO_2 containers can be loaded onto the OSV with a crane. Unless the end use is directly at a port, the CO_2 must also be transported by land. If containers are used, it can be transported by road, rail or inland waterway vessel. If the CO_2 is transported in a liquid gas carrier, the most logical connection is a pipeline, as mentioned earlier in the OCAP example.

Utilization phase: end-of-life

There are many applications for liquid CO_2, some of which are already in use (for instance carbonation of soft drinks, medical applications, fire extinguishers, use in greenhouses), and some still under development (including synthetic fuels, raw materials for materials). These kinds of applications are called **utilization**, and there is an LCO_2 market for this. Besides utilization, another popular application is in the form of **storage**. This involves pumping large amounts of LCO_2 into an empty oil or gas field. Reservoirs of this kind have been used for some time for CO_2 storage (Equinor, 2020). The global underground storage capacity is estimated to be between 5200 and 27200 Gigatons (Christiaanse, 2018). To illustrate: a crane vessel annually produces about 50000mt CO_2, which equates to [0.000001%] of the total storage capacity. Permanent storage is seen as a non-revenue generating end-of-life solution, in contrast to the utilization options. There is a combination of storage and utilization in the form of **Enhanced Oil Recovery** (EOR), where CO_2 is used to push oil out of hard-to-reach rock formations for extraction. There is a revenue generating process behind this, namely a sales price of ± 13-35€/tonCO_2 (Rubin et al., 2015).

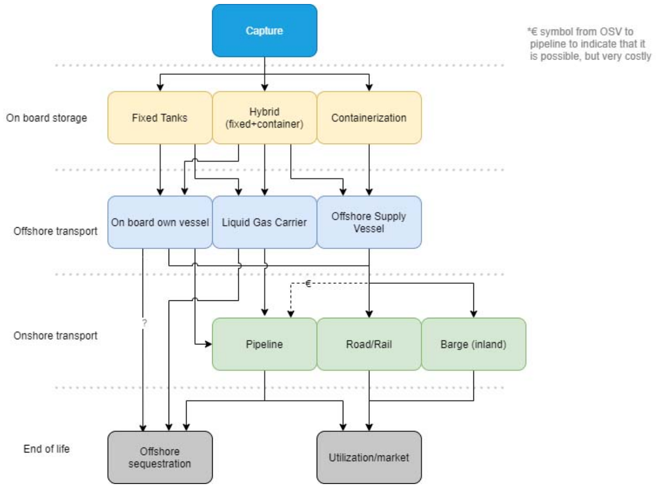


FIGURE 2: Graphical overview of technically feasible supply chain paths

TABLE 2: Performance matrix from a technical feasibility standpoint for the whole supply chain of ship based carbon capture

	TRL [1-9]	Safety [1-3]	Compatibility [1-3]	Scalability [1-3]	Availability [1-3]
Capture					
fixed tanks Independent	9	2	1	1	1
fixed tanks Integral	9	3	1	1	1
Containers	9	2	3	3	3
Offshore Transportation					
Liquid gas carriers	6	3	2	1	1
Own vessel	9	2	3	1	3
Offshore supply vessel	9	3	2	2	2
Storage barge	6	3	2	1	1
Onshore Transportation					
Pipeline	9	3	3	2	2
Road	9	2	2	3	3
Rail	9	2	2	2	3
Inland waterway	9	3	3	1	1
Utilization					
Materials: solvents/pharmaceuticals/fertilizer/urea	9	3	3	2	2
Direct: Dry ice, beverages, fire extinguishers	9	3	3	2	2
Horticulture	9	3	3	2	2
Sequestration onshore	9	1	3	1	1
Sequestration offshore	9	3	3	1	1

technical feasibility

In itself, each considered option discussed so far is technically feasible. However, not every solution fits in well with the next phase. Figure 2 shows how the various technical solutions for the supply chain of LCO_2 are related and which options are more or less compatible. The choice that most determines the technical composition of the chain is the first choice to be made by the ship owner, namely the type of storage on board.

4 Concept exploration

The next step in the design of a supply chain concept is concept exploration. After the technical feasibility has been demonstrated in the previous sections, the study now delves deeper into the costs and emissions of the supply chain. This is done on the basis of a model that shows the relationship between supply chain variables. The full threefold feasibility is ultimately demonstrated through supply chain scenarios, where realistic combinations of technologies are explored to identify which factors have the most influence on this overall feasibility and provide insight for the decision-making process of ship owners.

4.1 Supply chain model design

The model represents the costs and emissions of the supply chain of a scenario. A single scenario consists of the three supply chain phases as discussed earlier (capture, transport, utilization). There is an element of time to each scenario, so that the final costs and emissions can be expressed in euros and tonCO_2 emissions per period (usually one year). Each technical choice as described in section 3 has a value for the key performance indicators (KPIs) 'costs' and 'emissions'. Since the total emissions over a period in which the vessel is sailing are known (amount of fuel consumed during all different operational modes), the costs and emissions are expressed in €/tonCO_2 and tonCO_2/tonCO_2 respectively. Every ton of CO_2 that is therefore emitted, captured, transported and / or sold etc. has a value for these two KPIs. Apart from the total costs and emissions per period, it is also shown which contribution to the total each part of the supply chain makes. In addition to adding costs and emissions, the model is also suitable for creating scenarios, whereby results can be generated that say something about the circumstances in which a scenario meets the requirements as mentioned in section 3.2. In terms of payback period, a simplified return on investment calculation is performed by adding the annual (positive) returns from the scenario (assuming a profit can be made) to the (negative) investment costs in year zero. If a scenario were to repeat itself every year, there will come a point where the investment pays off. The circumstances under which a positive result can be turned are on the one hand selling the CO_2, and on the other hand saving on CO_2 tax (if present in the scenario). The model also looks at the CO_2 emitted during an entire scenario. If the emission savings compared to the situation in which no carbon capture would be done is more than 40%, or 70%, it can be said that the ship owner will achieve the IMO2030/2050 targets in that specific scenario.

4.2 Model assumptions

Since the study is based on the use case of a single offshore heavy lift vessel, and conducted in collaboration with the company operating the vessel, the data is mainly based on this one, type 2 vessel. The company has given access to the operational details of the ship such as fuel consumption, emission data and operational details. Generalized numbers are used in this paper unless numbers are from external or public sources. Tables 6 and 7 in the appendix provide an overview of the key figures that have been calculated using the model. Many of the values used in this study are assumed values based on realistic comparable situations. The reason for this is the fact that the research largely covers a new technique that has not yet been applied. The reliability of the data is less relevant for making the model than for generating results and ultimately drawing conclusions. For this reason, a sensitivity analysis is presented later in the discussion surrounding the results, in which it is indicated which assumptions influence the final results to a greater or lesser extent.

4.3 Scenario designs

A common strategy when it comes to scenario analysis is to start with a basic scenario (TEBODIN, 2011). Especially with complex models where many parameters converge, it is common to start with a basic scenario. From there, a single parameter is iteratively changed to observe the effect on the results of that one parameter.

Base scenario

A period of one year in which the ship is operational is considered. During this period, the vessel will be working 50% of the time, 30% of the time in transit, and 20% of the time in port or idle, with associated emission characteristics. The vessel carries 550 m^3 fixed tanks and 25 TEU tank containers, with a total of 1,100 m^3 in hybrid storage capacity. This gives the vessel a minimum operational time of 11 days before the tanks are full (the operational mode where most fuel is burned is during transit). A hybrid storage mode has been chosen for the base case because it is preferred by the company's operational managers due to to the flexibility that this option offers. The costs associated with capture have been estimated at 100 €/tonCO_2, which is an (optimistic) estimated value for ship based carbon capture, resulting from previous research (Monteiro, 2020). The ship is on average at a distance of 100km offshore during the year, and the end user is 50km from the loading point in the port, connected by pipeline. This is again based on the example of the OCAP pipeline in Rotterdam.

Scenario sets

Parameters are varied based on the aforementioned scenario to create several sets of scenarios. Table 8 in the appendix shows the choices in this variation. The main variations relate to distance (off- and onshore), storage capacity, operational mode and cost of capture. The latter, cost of capture, is expressed in €/tonCO_2 captured, and is an estimated value that includes capital expenses (CAPEX), operational expenses (OPEX), installation costs, system costs, man hours, engineering costs, etc.

The above basic scenario is relatively arbitrary and therefore not necessarily the best performing scenario. Therefore, a second variation run is performed, where the best performing scenario of the first iteration (table 8) is used as the base case for a second iteration. This iteration varies with respect to increase in engine efficiency (i.e. 25% lower emission of CO_2), skipping the land transport by disposing the CO_2 directly offshore in a permanent storage location, and finally, the scenario where the system's investment cost decreases by 25%. See table 9 for details.

The results are expressed per scenario in the two main indicators, namely the payback period ("under which circumstances is it limited to 3-5 years?") And the total emissions throughout the year ("does the scenario meet the IMO2030/IMO2050 targets of 40% respectively 70% CO_2 reduction?").

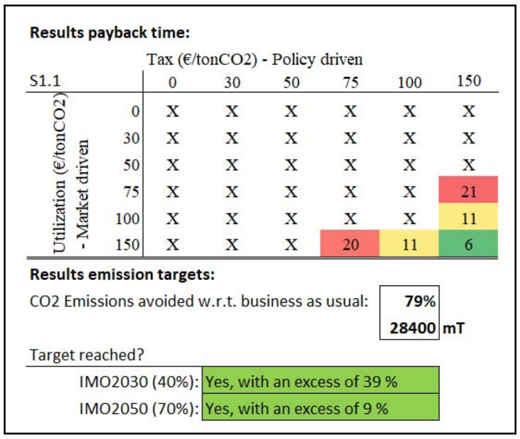
The defined scenarios provide a set of candidate concepts, the feasibility of which can be determined in terms of costs and emissions.

5 Concept Definition

The results are expressed in payback time and emission savings. The payback period depends on the amount of the CO_2 tax and the amount at which the CO_2 can be sold on the market. These two conditions are displayed in a combination matrix. The emission savings of the supply chain are also measured on the basis of the IMO2030/IMO2050 targets.

5.1 Results base scenario

It was found that there is no realistic circumstance whereby the base case, scenario 1.1 (table 8), has a payback period of less than 5 years. See image 3. Even under the most optimistic market conditions (utilization price) and policy conditions (tax level), the investment has a payback time of 6 years, which means that the scenario does not meet the criteria. Looking further within the first 6 sets of scenarios, there are conditions that are more favorable.



Results payback time:

		Tax (€/tonCO2) - Policy driven					
S1.1		0	30	50	75	100	150
Utilization (€/tonCO2) - Market driven	0	X	X	X	X	X	X
	30	X	X	X	X	X	X
	50	X	X	X	X	X	X
	75	X	X	X	X	X	21
	100	X	X	X	X	X	11
	150	X	X	X	20	11	6

Results emission targets:

CO2 Emissions avoided w.r.t. business as usual: **79%** **28400** mT

Target reached?

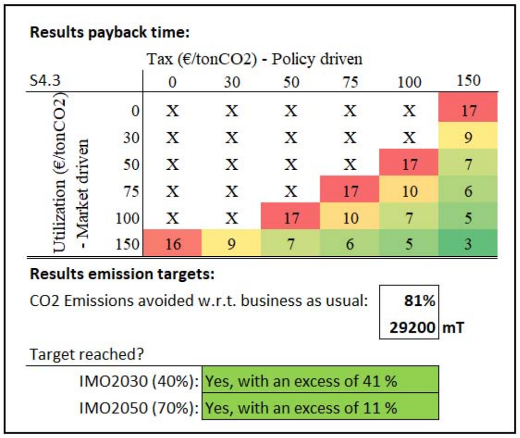
IMO2030 (40%): Yes, with an excess of 39 %

IMO2050 (70%): Yes, with an excess of 9 %

FIGURE 3: Results scenario 1.1. Payback time in years. Conditions marked with an X have a paybackt time >30years, which equals the typical lifetime of a vessel

5.2 Results first iteration

The best performing scenario from the first iteration set is scenario 4.3. This scenario looks at a 25% reduction in investment costs with respect to the base case, relatively short transport distances (100km offshore, 50km onshore) and a large amount of storage capacity (2,200 m^3) during the offshore work, with an offloading interval of 29 days applies. Figure 4 shows these results. The range of feasible conditions with regard to payback period increases. The total emissions in the supply chain also decrease, as an offloading vessel has to come less often to unload the CO_2 (due to this larger storage capacity).



Results payback time:

		Tax (€/tonCO2) - Policy driven					
S4.3		0	30	50	75	100	150
Utilization (€/tonCO2) - Market driven	0	X	X	X	X	X	17
	30	X	X	X	X	X	9
	50	X	X	X	X	17	7
	75	X	X	X	17	10	6
	100	X	X	17	10	7	5
	150	16	9	7	6	5	3

Results emission targets:

CO2 Emissions avoided w.r.t. business as usual: **81%** **29200** mT

Target reached?

IMO2030 (40%): Yes, with an excess of 41 %

IMO2050 (70%): Yes, with an excess of 11 %

FIGURE 4: Results scenario 4.3. Best result form first iteration

Table 3 shows an overview of the results, expressed in the effect of some essential parameters on the payback period. The minimum and maximum impacts are determined by the smallest and largest change in payback time measured as a result of adjusting one of these parameters. A positive value indicates an increase in payback time, which is negative for the feasibility of the system. The further apart the values are, the more significant the influence of that parameter on the result.

The most polluting scenario in the first set is scenario 2.1, where the most kilometers are covered in the supply chain. In this scenario, 75% of the emissions are still avoided, compared to the business as usual case, which indicates that the IMO2050 targets can be achieved in this and all other scenarios.

5.3 Results second iteration

With scenario 4.3 as the new base case, 3 more scenarios have been tested. In table 9 in the appendix you can see what the variations are for this set. The results of this second iteration are summarized in figure 5. The red line in this figure indicates the maximum payback period of 5 years. All points below that line are feasible combinations. A line

TABLE 3: Effect on payback time from variations of scenario parameters.

Effect on Payback Time of:	Min	Max
Onboard storage x2	-20%	-65%
Offshore distance x2 For COC €100	+25%	+130%
Offshore distance x2 For COC €75	+60%	+75%
Cost of capture -25%	-17%	-60%
Onshore distance x2	0%	+14%

indicates the course of either utilization price or tax level, while the opposite parameter is fixed at a price of € 150. For example, the course of the bottom row and rightmost column from figure 4 can be seen as the green lines in figure 5. This figure shows that the scenario that creates the most feasible conditions is to reduce investment costs in the form of capital expenses (CAPEX) (scenario 9). Then reducing the emissions by 25% (Scenario 7), and finally skipping the offshore transport phase. The latter is mainly due to the fact that in the model the price per m^3 of fixed storage is linked to the capacity, while for containers a fixed amount is charged for installing the connecting infrastructure to containers, and this is not affected by the amount of storage/containers.

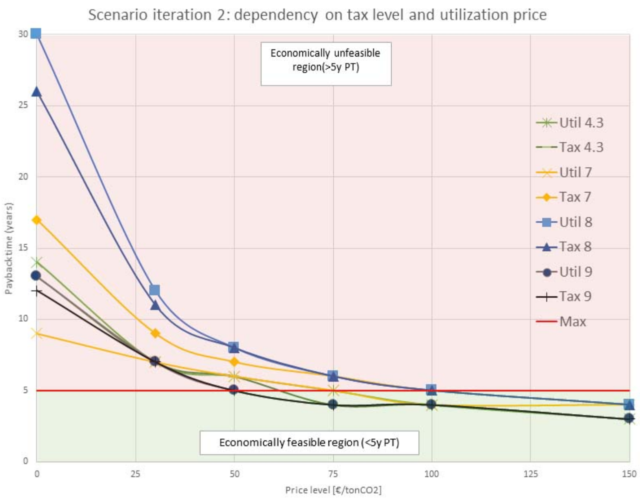


FIGURE 5: Results second iteration: scenario 7, 8 and 9

5.4 Case study

To demonstrate the feasibility, a supply chain has been designed on the basis of a case study. The design contains the most decisive conditions as shown by the results analysis. The emphasis is put on feasibility from a ship owner's point of view.

For a period of one year the ship will operate off the coast of Dutch waters at an average of 100 km from the port of Rotterdam to install a wind farm. During this year, the ship is at work about 50% of the time, 30% of the time cruising between sites, and 20% of the time the ship is stationary or in port for maintenance. The onboard carbon capture installation captures an average of 82% of the CO_2, whereby the ship uses an average of 2% more LNG than would be the case if no carbon capture were done.

- **Capture Phase:** The ship owner has the type of hybrid storage on board where there are built-in fixed tanks with a size of 1100 m^3 and space for 50 22 m^3 tank containers.
- **Transportation Phase**: The CO_2 is transported with liquid gas carriers and offshore supply vessels, which come along once every 29 days to unload. The CO_2 is pumped ashore in an OCAP pipeline citep OCAP2020. The average length of this pipeline transport is 50km.
- **Utilization phase:** The pipeline ends in the glass horticultural greenhouses in the Westland to be used to promote plant growth. The CO_2 is sold here, for which the ship owner can receive € 75 - € 150 per tonne of CO_2.

An external condition is that there is a carbon tax of €75 - €150 per ton CO_2. The ship owner has invested €16.5M in the carbon capture installation, and can capture the CO_2 at a cost of €75 per tonne of CO_2. The payback period under the above conditions is shown in table 4. In figure 6 the supply chain is visualized.

TABLE 4: Effect on payback time from variations of case study parameters.

Payback time	Taxation (€/tonCO2)			
		75	100	150
Utilization (€/tonCO2)	75	13	8	5
	100	8	6	4
	150	4	4	3

For the condition where the tax and sales price both have a level of €150/tonCO_2, the case study can be summarized as in table 5.

TABLE 5: Results case study

Results of full case study (1 year)	Value	Unit
Total distance traveled by OSV/LGC	2517	km
Total distance traveled via pipeline	629	km
Total amount of CO_2 emitted by supply chain	6884	mT
Total amount of CO_2 saved with respect to business as usual	29200	mT
Costs for shipowner without carbon capture	5,407,000	€
Cost of supply chain per year	€ 655,121.27	€
Total profit per year	€ 4,753,000.00	€

The strategic considerations faced by a ship owner in the decision-making process regarding the feasibility of an investment in carbon capture can be summarized as follows:

- Does the ship comply with the IMO2030/IMO2050 targets if carbon capture is used?
- What are the technical implications for the ship, i.e. how much space is there on board the ship for storage?
- At what cost of capture price can the CO_2 be captured on board?
- What is the average distance at which the ship can operate offshore? Any doubling in distance can increase payback time by 25% to 60%. Emissions from the supply chain are also affected by distance, although the effect of costs on feasibility is greater. A liquid gas carrier can sail almost 9000km with 1100 m^3 on board before emitting as much as it transports (TEBODIN, 2011).
- What are the external conditions that can affect the payback period? A carbon tax combined with the sales of CO_2 can generate income for both parameters at price levels of € 75- € 100 per tonne of CO_2, which influences the payback period.
- What is an acceptable payback period for the ship owner?

It is important to emphasize that every ship is different and every ship owner has different answers to these questions.

5.5 Evaluation and sensitivity

Strengths: The results obtained through the methodology used, a ship owner can understand the aspects of the supply chain of CO_2 that are most decisive when it comes to the circumstances under which an investment in ship based carbon capture could be feasible. By looking at three different levels (technical, economic, emissions) and by indicating the critical elements for each level, the ship owner knows where the focal points lie. **Weaknesses and sensitivity:** The fact that the influence of tax and selling price in figure 5 has a high spread for the zero points (points on the y-axis) is due to the way in which the payback period is calculated. If this payback period would be graphically represented, each payback calculation starts on the negative y-axis at the investment cost in year zero. In the case of (positive) income, a linear relation is created that eventually crosses the x-axis at year 'x'. This crossing indicates the payback period. The external circumstances (Utilization and tax) influence the slope of this line. The sensitivity to the results of a small change in these parameters has a greater effect for the high payback values than for the low values. The difference indicates an inaccuracy in the calculation method, due to this linearization effect (see figure 7. However, for these sensitive conditions there is no payback period that meets the criteria. Only the values getting near and below the red line in figure 5 are relevant, where the model is less sensitive.

6 Conclusion

In this paper, the conditions for feasibility of the supply chain of ship-based carbon capture have been demonstrated in terms of technical feasibility, economic feasibility and feasibility in terms of emissions.

The technical feasibility has been demonstrated by means of a multi-criteria performance analysis of different technical options to compose the supply chain. The choice of on-board storage technology largely determines the technical possibilities further down the chain, and has therefore been identified as a critical choice in the design of the supply chain. Doubling storage capacity can reduce payback time by 20% to 60%.

For the transport phase, the distance the CO_2 travels offshore is more decisive than the distance onshore. Doubling the total distance traveled offshore can increase the payback time by a quarter to more than twice as long. This effect becomes less significant when the cost of capture decreases by 25%.

Economic feasibility is the most determining factor in the entire scenario analysis. The criterion of a payback period of 3-5 years means that there are many conditions under which a scenario would not be feasible. The investment can only be paid back under the conditions that money can be earned by selling the CO_2, or CO_2 tax saved by emitting less compared to the business as usual case. The costs of either the carbon capture installation in the form of CAPEX, or translated into a general cost of capture parameter (including opex and installation costs), both have a significant positive effect on the payback period.

The feasibility in terms of emissions has a less strong effect on the design of the supply chain itself. The emissions that are released in the supply chain of carbon capture, as well as the emissions that cannot be captured due to operational and technical limitations of the carbon capture system, are so small in relation to economic limitations that under each scenario considered in this study, the emissions reduction targets of IMO2030 and IMO2050 can be achieved.

This answers the main question: *"Which technical, economic and emissions-related conditions predominantly determine the feasibility of a conceptual supply chain of liquid* CO_2 *that is captured from the exhaust gases of LNG powered offshore Vessels?"*.

In the design of the supply chain of ship-based carbon capture, a design must be sought in which both on-board storage can be maximized and the distance over which the CO_2 must be transported can be minimized. Also, looking for ways to lower the capital cost of the system has a major

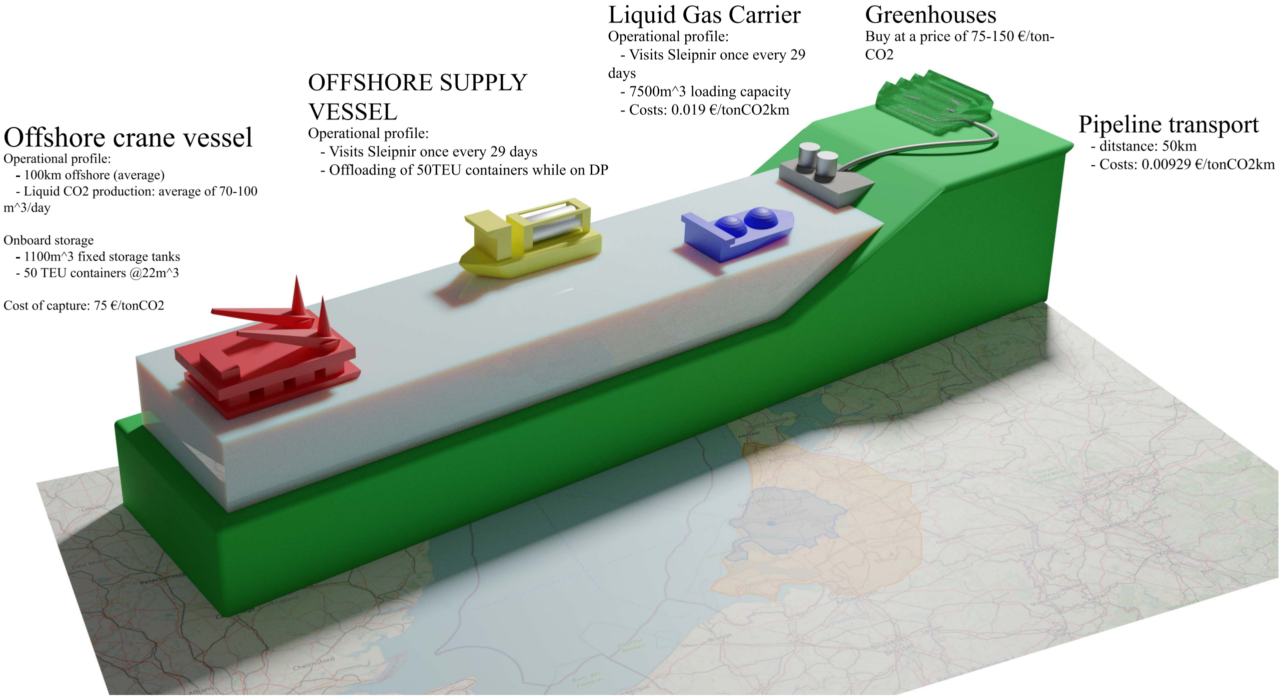


FIGURE 6: Visualisation of supply chain from case study (own figure)

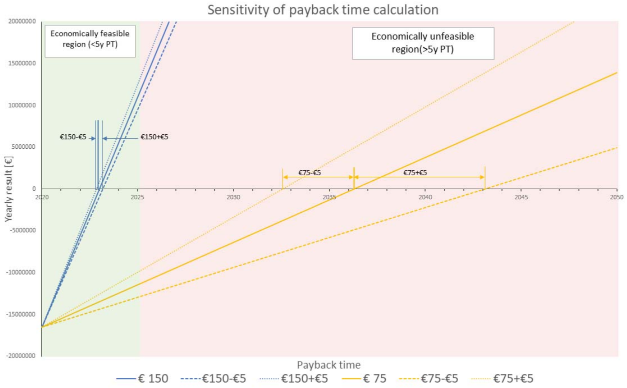


FIGURE 7: Sensitivity due to linearization effect

impact on the payback period. Ship-based carbon capture technology is a very effective way to reduce emissions for large offshore LNG powered work vessels. It therefore has great potential for a ship owner to achieve the IMO2030 and IMO2050 targets. The general feasibility for this type of vessel is largely determined by the highly optimistic boundary conditions. These are conditions that are beyond the control of the ship owner. The previously mentioned uncertainties and assumptions in the data lead to discussion and recommendations for further research.

7 Discussion and further research

This research concerned a topic that is still very new and unexplored. Little scientific data is available to guarantee its accuracy. The lack of data also provides little insight into the error variance of this data. The fact that the research was commissioned by a commercial company has at no time led to influencing the results of this company. The author of this paper has been given all the freedom and access to internal data that was needed, without directing towards specific results. Overall research into ship-based carbon capture is at an early stage. The use case with the offshore heavy lift crane vessel is useful for developing certain parts of the technology, but the uniqueness of this vessel may have an adverse effect on large-scale applicability to other vessel types as well.

In addition, the disruptive nature in the CO_2 market of ship-based carbon capture can also influence the feasibility. As the adoption of the technology increases in popularity among ship owners, more CO_2 will be marketed, which in turn entails the risk of market saturation.

An important discussion point is the question whether a CO_2 tax will only target purely CO_2 emissions, or whether it also concerns CO_2 equivalent emissions. In this case other greenhouse gases are converted to an equivalent with respect to the global warming potential of CO_2. It is therefore important to investigate the concept of methane slip, a negative side effect of LNG engines, which has not been considered for this study. In that case, the outcomes would likely be negatively affected.

For this study it has been assumed that the only positive revenue generators are the sale of LCO_2 and tax savings. However, it is also conceivable that political subsidies may be available for the implementation of these types of systems. This could drastically reduce the cost of capital, benefiting the payback period. For example, the Norwegian government recently invested € 1.5 billion in a large-scale carbon capture (Upstreamonline.com, 2020).

Another economic point of discussion is whether there might not come a time when the cost of capture would decrease to such an extent that it could become economically beneficial for a ship owner to produce and sell more CO_2, thereby overshooting the point, and more fossil fuels are burned.

The transport of CO_2 has been shown to be a major cost item. A recommendation for future research would be to investigate the possibilities for applications of CO_2 on board, in which, for example, synthetic fuels can be produced on board. This would render the whole supply chain issue obsolete.

Ships operate on a global scale. This study mainly looked at European conditions. For a complete life cycle analysis, the opportunities in other places in the world must be examined in more detail.

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Appendix

A1: Assumptions overview

TABLE 6: Economical assumptions and calculated constants

Economical assumptions and calculated constants				
parameter	**Value**	**Unit**	**Source**	**Comment**
Capture				
Cost of capture	100	euro/tonCO2	(Monteiro, 2020)	Assumed to be this value, from estimations by TNO/ASPEN+
Transportation offshore				
Container daily lease price	4.93	euro/day	[2]	
Offshore supply vessel charter rate	21411.5	euro/day	[3]	
Offshore supply vessel trip dependent cost	0.01314	euro/tonkm	(Dosen and Langeland, 2015)	
Liquid gas carrier transport price	0.019	euro/tonkm	(Kler et al., 2016)	
Transportation onshore prices				
Road	0.07	euro/tonkm	[4]	
Rail	0.267	euro/ton (100km)	[5]	
Pipeline	0.00929	Euro/tonkm	[6]	
Inland barge	0.03429	Euro/tonkm	[7], [8]	
Utilization costs				
onshore sequestration low	6.195	Euro/tonCO2	(Rubin et al., 2015)	
onshore sequestration high	11.504	Euro/tonCO2	"	
Offshore sequestration low	7.965	Euro/tonCO2	"	
Offshore sequestration high	17.699	Euro/tonCO2	"	
Sequestration profit EOR sales low	13.274	Euro/tonCO2	"	
Sequestration profit EOR sales high	35.398	Euro/tonCO2	"	
Horticulture sales price	50.00	Euro/tonCO2	[9]	and interviews
Utilization sales assumed	50.00	Euro/tonCO2	(Lloyds Register & UMAS, 2017)	

TABLE 7: Emissions related assumptions and calculated constants

parameter	**Value**	**Unit**	**source**	**comment**
Emissions base case				
Work	95	mT CO2/day	Heerema	rounded value
Transit	130	mT CO2/day	Heerema	rounded value
Daily LCO2 production with 82% capture rate and 102% LNG usage				
Work	80	mT/day	Calculated	
Transit	110	mT/day	Calculated	
Transportation offshore				
Liquid gas carrier	8.633*10^{-}6	mT/tonnekmCO2	(Aspelund et al., 2009)	
Offshore supply vessel	0.1385	mt/km	[10]	Amount of CO2 left outside of this equation (i.e. same for 1 ton or 100 tonnes)
On board own vessel	130	mt/day	Heerema	
Onshore transportation				
Road	1.032*10^{-}6	mT/tonnekmCO2	[11]	
Rail	3.5*10^{-}6	mT/tonnekmCO2	(McKinnon, 2007)	
Inland barge	3.5*10^{-}6	mT/tonnekmCO2	(McKinnon, 2007)	
Pipeline				No CO2 emissions in ideal situation
Utilization emissions				
Materials vector				No CO2 emissions in ideal situation
Direct utilization				Depending on the input value chosen (0-100%)
Horticulture				No CO2 emissions in ideal situation
Sequestration				""

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[2] https://www.truckscout24.com/containers/used/tank-container

[3] https://pdfs.semanticscholar.org/093d/b02cd056369cbbad8a29faf252ef641ead82.pdf

[4] https://www.researchgate.net/publication/313532536_Comparative_model_of_unit_costs_of_road_and_rail_freight_transport_for_selected_European_countries

[5] https://www.dbcargo.com/resource/blob/1437702/aaf76bed01bee46244c84e0242e2b498/dbcargo_pricesandservices_2018_en-data.pdf

[6] https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_chapter4-1.pdf

[7] https://www.ccr-zkr.org/files/documents/om/om11II_en.pdf

[8] https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_chapter4-1.pdf

[9] https://www.wur.nl/upload_mm/6/1/4/dec254ef-27b4-42d3-8153-feeac0e2ee2f_20121129%20energy%20matters%20CO2%20uit%20andere%20bronnen%2029%20nov%202012.pdf

[10] https://ec.europa.eu/environment/air/pdf/chapter2_ship_emissions.pdf

[11] https://publications.tno.nl/publication/34620445/oCrCGA/TNO-2016-R10449.pdf

A2: Overview of scenarios

Table 8: Overview of scenario variations 1-6 first iteration

Scenario set	Scenario subset	Description	Default parameters	Variation
1			Hybrid (50/50) OSV/LCG Offshore distance 100km Onshore distance 50km pipeline Cost of Capture €100	
	1.1	Sailing, small storage	1100 m^3 $storage$ 11 days offloading interval	
	1.2	Sailing, large storage		2200 m^3 $storage$ 22 days offloading interval
	1.3	Working, large storage		2200 m^3 $storage$ 29 days offloading interval
2			Hybrid (50/50) OSV/LCG Onshore distance 50km pipeline Cost of Capture €100	**Offshore distance 200km**
	2.1	Sailing, small storage	1100 m^3 $storage$ 11 days offloading interval	
	2.2	Sailing, large storage		2200 m^3 $storage$ 22 days offloading interval
	2.3	Working, large storage		2200 m^3 $storage$ 29 days offloading interval
3			Hybrid (50/50) OSV/LCG Offshore distance 100km pipeline Cost of Capture €100	**Onshore distance 100km**
	3.1	Sailing, small storage	1100 m^3 $storage$ 11 days offloading interval	
	3.2	Sailing, large storage		2200 m^3 $storage$ 22 days offloading interval
	3.3	Working, large storage		2200 m^3 $storage$ 29 days offloading interval
4			Hybrid (50/50) OSV/LCG Offshore distance 100km Onshore distance 50km pipeline	**Cost of Capture €75**
	4.1	Sailing, small storage	1100 m^3 $storage$ 11 days offloading interval	
	4.2	Sailing, large storage		2200 m^3 $storage$ 22 days offloading interval
	4.3	Working, large storage		2200 m^3 $storage$ 29 days offloading interval
5			Hybrid (50/50) OSV/LCG Onshore distance 50km pipeline	**Offshore distance 200km** **Cost of capture €75**
	5.1	Sailing, small storage	1100 m^3 $storage$ 11 days offloading interval	
	5.2	Sailing, large storage		2200 m^3 $storage$ 22 days offloading interval
	5.3	Working, large storage		2200 m^3 $storage$ 29 days offloading interval
6			Hybrid (50/50) OSV/LCG Offshore distance 100km pipeline	**Onshore distance 100km** **Cost of capture €75**
	6.1	Sailing, small storage	1100 m^3 $storage$ 11 days offloading interval	
	6.2	Sailing, large storage		2200 m^3 $storage$ 22 days offloading interval
	6.3	Working, large storage		2200 m^3 $storage$ 29 days offloading interval

Table 9: Overview of scenarios 7, 8 and 9

Scenario	Description	Default parameters	Variation
7	Engine emissions -25%	Hybrid (50/50) OSV/LCG Offshore distance 100km Onshore distance 50km pipeline COC €75 2200 m^3 storage CAPEX €16.5M	Emissions factor 0.75 40 days offloading interval
8	No onshore transportation	Offshore distance 100km COC €75 2200 m^3 storage 29 days offloading interval Emissions factor 1 CAPEX €16.5M	0 km onshore Liquid gas carrier 100%
9	CAPEX -25%	Hybrid (50/50) OSV/LCG Offshore distance 100km Onshore distance 50km pipeline COC €75 2200 m^3 storage 29 days offloading interval Emissions factor 1	CAPEX €12.357M