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Model for a maritime logistic supply chain for captured CO_2 in Sweden.

Performance of a quantitative analysis of CO_2 ship transport systems in a Swedish context by establishing a suitable model tested in collaboration with Swedish stakeholders

Master's thesis in Mobility Engineering

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Performance of a qualitative and quantitative analysis of ship CO_2 transport systems in a Swedish context by establishing a suitable model tested in collaboration with Swedish stakeholders.

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Abstract

This master's thesis report presents the results of the research carried out for the design of an optimal marine logistic chain for CO_2 transportation in Sweden. The effectiveness of CO_2 transport systems is related to the output of the Carbon Capture (CC) facilities, inland feeder traffic, intermediate storage hubs and type and cost of liquefaction plants among others.
The solution is reached by means of a mathematical model built up so that the optimal fleet logistic can be found for a specific defined scenario, i.e., number of vessels that compounds the fleet, sizes of the ships in terms of its cargo capacity and sailing speed. Additionally, a cost breakdown of the mentioned logistic chain is presented in order to identify the origin and percentage of each variable contributing to the total cost.
Results from this study indicate that the largest contributor to the CCS chain considered is the liquefaction process, followed by the fleet cost. In addition, medium pressure transport is always the most expensive option in comparison with low pressure transport and using the largest ship capacity is almost always more economical. This is because the increase in the cost of buffer storage is not as great as the increase in the cost of the fleet due to the increase in the number of ships per fleet.

Keywords: CCS, CCU, maritime logistics, CO_2, maritime decarbonization, Sweden, supply chain.

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Gemma Bruguera Matute, Gothenburg, June 2023

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Antonio Juan Castro Molinero, Gothenburg, June 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

CAPEX	Capital Expenses
CC	Carbon Capture
COP	Convention Of the Parties
CCS	Carbon Capture and Storage
CCS-RI	Carbon Capture and Storage Readiness Index
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CII	Carbon Intensity Indicator
CO_2	Carbon dioxide
DC	Direct Cost
DWT	Deadweight Tonnage
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency for Existing Ships Index
EU ETS	European Union Emissions Trading System
GHG	Greenhouse Gas
GWP	Global Warming Potential
HP	High Pressure
IMO	International Maritime Organization
LCO_2	Liquefied CO_2
LNG	Liquefied Natural Gas
logiCO_2	Maritime logistic supply chain for captured CO_2
LP	Low Pressure
LPG	Liquefied Petroleum Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environment Protection Committee
MIP	Mixed Integer Program
MP	Medium Pressure
NLS	Noxious Liquid Substances
NPV	Net Present Value
OPEX	Operating Expenses
ROA	Real Option Approach
SEEMP	Ship Energy Efficiency Management Plan
TDC	Total Direct Cost
TPC	Total Plant Cost
TTW	Tank-to-Well
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
VLSFO	Very Low Sulphur Fuel Oil
WHO	World Health Organisation
WTT	Well-to-Tank

Nomenclature

Below is the nomenclature of indices, sets, parameters, and variables that have been used throughout this thesis.

Parameter	**Name**	**Unit**
α	Annual payment	€m
ρ	Cargo density	t/m^3
P	Pending loan	€m
j	interest rate	-
m	Loan return period	y
T_o	Operational Time	h
T_{rt}	Round-trip Time	h
T_{moor}	Mooring Time	h
T_{umoor}	Unmooring Time	h
T_{pin}	Port Entry Time	h
T_{pout}	Port Exit Time	h
T_l	Loading Time	h
T_u	Unloading Time	h
T_b	Buffer Storage Time	h
T_c	Cargo transportation temperature	°C
P_c	Cargo transportation pressure	bar
d	Sailing distance	km
v	Sailing speed	knots
x_i	Number of ship type	-
c_{x_i}	Ship capacity	kt
c_b	Buffer storage capacity	kt
a	Total amount of CO_2 to be transported within the planning horizon	Mt
a_{x_i}	amount of CO_2 transported by ship type i during the planning horizon	Mt
R_b	Flow rate of the buffer storage	t/h
C_H	Hiring Cost	€m
C_S	Sailing Cost	€m
C_B	Buffer Storage Cost	€m
C_{BO}	Buffer Storage Operational Cost	€m

C_{BCH}	Buffer Storage CAPEX in the planning horizon	€m
C	CAPEX of the capacity under consideration	€m
C_o	CAPEX for the reference capacity	€m
S	Capacity under consideration	$MtCO_2/y$
S_o	Reference capacity	$MtCO_2/y$
n	Scaling exponent	-
C_L	Liquefaction Cost	€m
C_{LC}	Liquefaction Investment Cost or Liquefaction CAPEX	€m
C_{LVO}	Liquefaction Variable Operating Cost	€m
C_{LFO}	Liquefaction Fixed Operating Cost	€m
C_R	Reconditioning Cost	€m
C_{RC}	Reconditioning Investment cost or Reconditioning CAPEX	€m
C_{RFO}	Reconditioning Fixed Operating Cost	€m
C_{RVO}	Reconditioning Variable Operating Cost	€m
C_T	Total Cost	€m

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1

Introduction

Although weather deviations can be provoked naturally (i.e., via variations in solar cycle), it is observable that since the 1800s, humankind is the main contributor of climate change due to use of fossil fuels, such as coal, oil or gas (United Nations, n.d.).

According to Hausfather and Friedlingstein (2022), atmospheric carbon dioxide (CO_2) concentrations are 51% above pre-industrial levels and is the largest contributor to greenhouse gas emissions. In order to achieve global climate goals, emissions need to decrease rapidly rather than just stabilise.

Therefore, to fight against climate change and thrust the transition towards a sustainable development, Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU) are increasingly gaining importance among industries and political organisms. Although Carbon Capture (CC) technology is already available, further improvements in terms of processes optimisation, new infrastructure (or adaptation of the existing one) and supply chain logistics need to be carried out. This master's thesis presents an study and optimisation of a maritime logistic supply chain of Carbon Capture, Utilisation and Storage (CCUS) in Sweden.

1.1 Background and problem description

Different definitions for climate change are provided by organisations: The World Health Organisation (WHO) in turn defines climate change as long lasting variation in time on the climate, due to natural reasons or caused by humankind activity (WHO, 2016). It is considered by United Nations (UN) as the deviation of the weather patterns and temperature in a long-term basis (United Nations, n.d.).

Climate change threatens people with food and water scarcity, increased flooding, extreme heat, more diseases, and economic losses. Human migration and conflict can be a result too. Communities may adapt to climate change through efforts like coastline protection or expanding access to air conditioning, but some impacts are unavoidable (WHO, 2016). Poorer countries are responsible for a small share of global emissions, yet they have the least ability to adapt and are most vulnerable to climate change (United Nations, n.d.). The shipping industry contributes in an important extent to global climate change, deteriorating the atmosphere with CO_2 emissions. Nevertheless, due to its own international nature, it is not an option to reduce it or stop it, since world economy would be deeply affected (Karin Andersson, 2016). Therefore, new solutions must be found in order to maintain maritime trade at current levels (or increasing it) while reducing its climate footprint. In section 1.1.2 the shipping strategy for a decarbonization path is presented.

In order to have a general picture of the current situation, in Fig.1.1 it can be seen the (a) global energy supply and (b) the CO_2 by sector. Specifically, the two figures illustrate the distribution of the total energy and the contribution of CO_2 emissions by each sector, respectively.

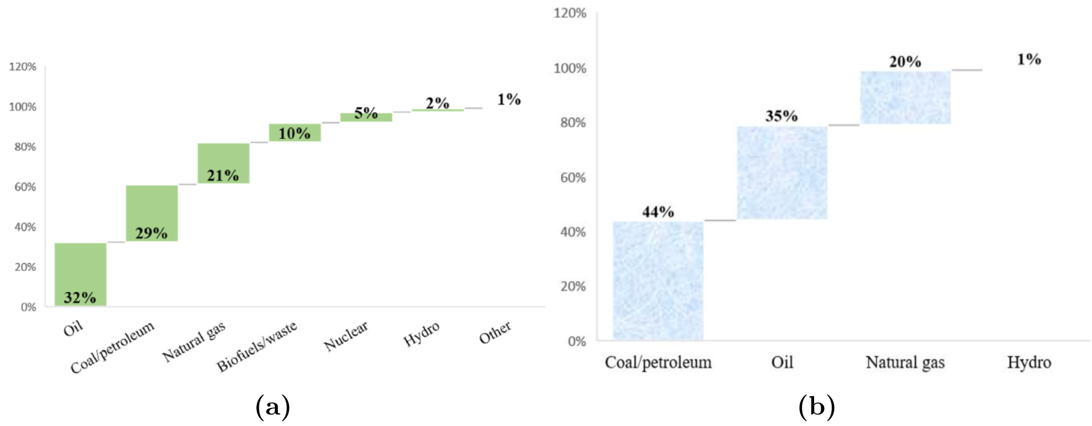


Figure 1.1: (a) Energy supply and (b) its CO_2 emissions by sector. (Adopted from Ishaq et al., 2022)

It can be seen in Fig. 1.1 how the global dependence in non-renewable source of energy is high and thus the emissions related to it. The goal is to change, within the near future, the source from which the needed energy is harvested focusing on renewable energies, such as wind, solar or hydro-power. Nevertheless, this is not an easy transition that can be carried out in an immediate way, since energy demand is higher than what, currently, renewable energies can provide. Therefore, some transitional solution must be found to start reducing CO_2 concentration in the atmosphere and avoid keep emitting more as the global economy, industry and transportation processes keeps operating.

A solution found is to capture and store this CO_2, thus avoiding emissions into the atmosphere. To do so, a new market needs to raise in order to be able to deal with such big gas amounts and transported it from emitters to receivers. CO_2 can not only be stored, but used to help in different industrial processes, as it has been used in oil or food industry (Al Baroudi, Awoyomi, Patchigolla, Jonnalagadda, & Anthony, 2021). Moreover, currently, there are ongoing projects that requires CO_2 to produce new greener fuels as it can be e-Methanol (Liquid Wind, 2023) with a clear perspective of growing in the next following years.

1.1.1 Current and upcoming regulations in shipping industry

An environmental friendly operation must be achieved by the fleet in charge of the transportation of the CO_2, as this carried and sequestrated amount cannot be with counterbalance with the vessels emissions. Therefore, some background on what regulations must be fulfilled by the liquefied CO_2 carriers is presented.

Throughout the history of shipbuilding industry, regulations, standards and laws have been gradually established. Regarding policies related to climate, the most important achievements are listed below:

- In 1973 parties of the International Maritime Organization (IMO) agreed to the the International Convention for the Prevention of Pollution from Ships (MARPOL), which currently consists of six Annexes.

- In 1992 is created in Rio de Janeiro the United Nations Framework Convention on Climate Change (UNFCCC), who established a diplomatic framework for the negotiation of further protocols regarding Greenhouse Gas (GHG) concentrations in the atmosphere. Nevertheless, did not specifically mentioned maritime GHG emissions.

- Amendments to MARPOL Annex VI that carried out the regulation for making the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) mandatory were first discussed during the 58^{th} Marine Environment Protection Committee (MEPC58) and adopted at the MEPC62 held in 2011, entering into force from 1^{st} of January of 2013.

- In 2015, the Paris agreement is developed during the 20^{th} Convention Of the Parties (COP21). It aims to pursue efforts to keep the temperature increase below 1.5°C compared to preindustrial levels (UNFCCC, 2023).

In addition, IMO establish a regulation for new vessels consisting on calculating their ship's EEDI, which must be less than the prescribed for that type of ship by the IMO. This is applied to vessels with Gross Tonnage[1] $GT \geq 400$, for which the legislation is put in action on 1^{st} of January of 2023. Some exceptions are contemplated. When it comes to existing (and new) vessels, they shall carry on board a SEEMP Karin Andersson (2016), which consist on:

- A specific plan for each ship that establishes a management process for implementing energy efficiency measures for the ship's operations and a process for continuous improvement.

- It should incorporate best practices for the energy efficient operation of ships, such as improvements in speed management throughout a voyage or the management of route optimisation that have been previously analysed.

Furthermore, other indexes that must be taken under consideration for existing ships is the Energy Efficiency for Existing Ship Index (EEXI) and the annual operational Carbon Intensity Indicator (CII). The former is related to the technical design of the vessels based on a reduction factor with respect to EEDI and should be predicted from the technical department of a shipping company. The later aims to a continuous improvement in the operational carbon intensity of the ship by monitoring, documenting and verifying against the required annual CII (IMO, 2019).

1.1.2 CCUS and shipping industry

It is worth of mention that when waste is transported (i.e., liquefied CO_2), it must be assured that the industrial activity (transport in this case) will not emit more CO_2 into the atmosphere than what it is removing. Therefore, this environmental regulations are of major importance to be met by the logistic activity.

[1]Nonlinear measure of a ship's overall internal volume

In the light of this, a shift towards a sustainable lifestyle of humankind based on renewable energies is necessary in order to cope with future regulations. Nevertheless, a transition period is needed before the required infrastructure and technology are available to be able to rely entirely and solely on green energy. Hence, CCSU is a suitable solution since it could be ready to use as a mature technology in the near future.

North Europe (mainly Norway and United Kingdom), together with United States of America, Canada, Australia and China are leaders in CCS Readiness Index (CCS-RI), meaning that they lead the capability for creating an environment that enables commercial deployment of CCS (Havercroft & Consoli, 2018).

Regarding Scandinavian countries, four Liquefied CO_2 (LCO_2) tankers under the Norwegian flag are currently operating. In addition, the Northern Light project[2] is planned to start operating in 2024. Therefore, there is an emerging need for efficient and cost-effective CO_2 transportation methods between emitters and receivers or storage facilities. Moreover, according to the Swedish government, a strategy for negative greenhouse gas emission (SOU 2020:4) is required. Therefore, supplementary measures are needed to achieve the net zero emission plan in 2045 reaching negative emissions thereafter (Biermann et al., 2022). One of these measures is CCUS, which, as it can be seen in Fig. 1.2, is divided in several phases:

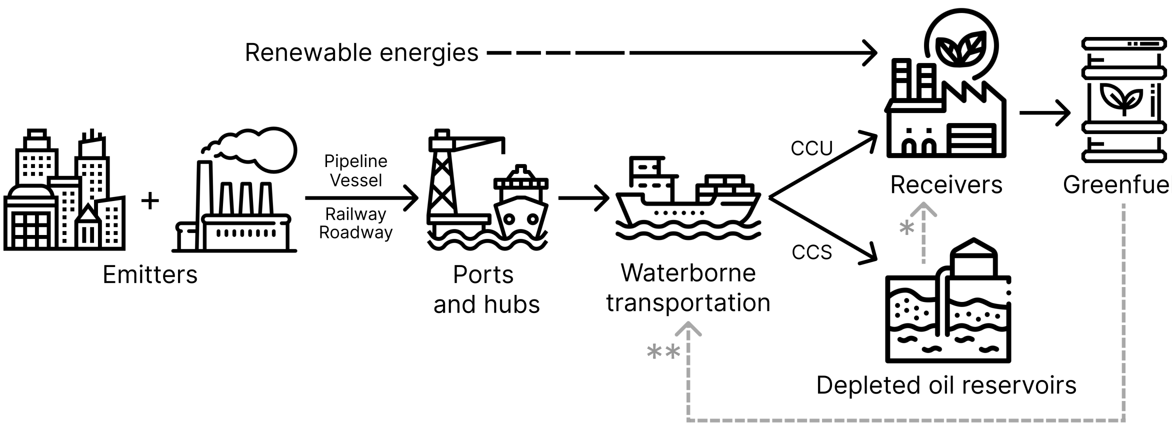


Figure 1.2: CC cycle. *Stored CO_2 can subsequently be used for industry processes. **In an ideal future, greenfuels will feed transportation methods.

First, CO_2 is produced as a result of the normal operation of industry and cities. This CO_2 is then captured[3] and transported from the emitters via pipeline (in a gaseous state) or by means of a train and/or truck logistic chain (in a liquid state). Onshore transportation considerations are further explained in the following chapters. Consequently, once LCO_2 is available at the port, vessels in charge of its offshore transportation are loaded and ready to head either to CCS or CCU receivers. CCS receivers use depleted oil reservoirs to permanently store the CO_2, while CCU use CO_2 as a raw material to achieve new products such as fuels.

[2]First planned infrastructure designed to build up a cross-border, open-source CO_2 transport and storage network. Phase I is designed to handle 1.5 $MtCO_2$/y. Phase II is projected to deal with a total of 5 $MtCO_2$/y. In addition, a 7500 m^3 LCO_2 carrier will be operating in 2024 (Northern Lights, 2023).

[3]Currently several technologies exists to capture CO_2. Nonetheless, what they are and how they work are out of the scope of this thesis.

Therefore, specific plan is needed to achieve profitable logistic results for the vast range different particular situations depending on CO_2 amount to be transported, location of sources and sinks, size of needed fleet, buffer storage capacity, etc.

1.2 Scope and objective

The purpose of this thesis is to design an optimal maritime logistic chain for waterborne CO_2 transportation in Sweden. Hence, given inputs such as amount of CO_2 to be transported and distance between harbours, which is the most cost-effective way of transportation in terms of number of required vessels, as well as its technical characteristics, such as cargo capacity and sailing speed.

The aim is to be able to know the optimal solution for a specific case. Every company or facility have its own characteristics in terms of location, sailing restrictions (e.g., maximum length, beam and/or draft), and amount of CO_2 emissions.

Therefore, the research questions to be answered by this thesis are:

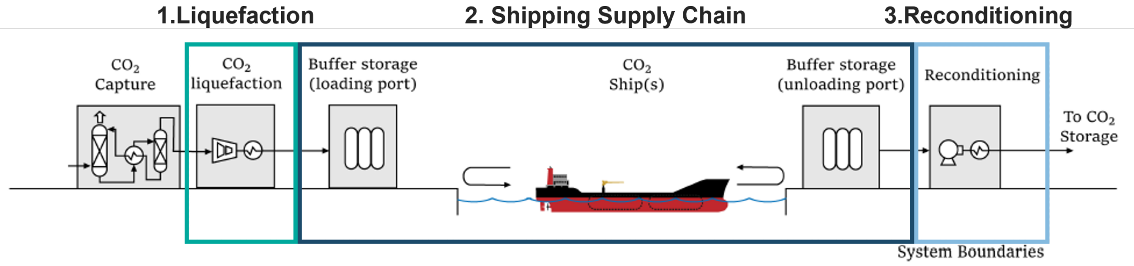
- Which is the optimal maritime logistic solution for a particular case emitter under its unique circumstances in terms of location and amount of CO_2?
- What is the cost of this solution?

To that end, a mathematical model is developed so that it can be applied to any route. The inputs of the model are the distance between two ports, the CO_2 flow rate to be transported and the fuel with which the ship operates. These parameters can be ajusted according to the case under study. The output of the model is the optimal maritime logistic solution from an economic point of view. That is to say, the answer would provide the number of vessels that compose the fleet, their technical characteristics, such as cargo capacity and sailing speed and the number of round voyages they have to complete annually. Answering the research question is intended also to provide understandings and insights of which barriers already exist in the CCUS market in Europe in general and in Sweden in particular.

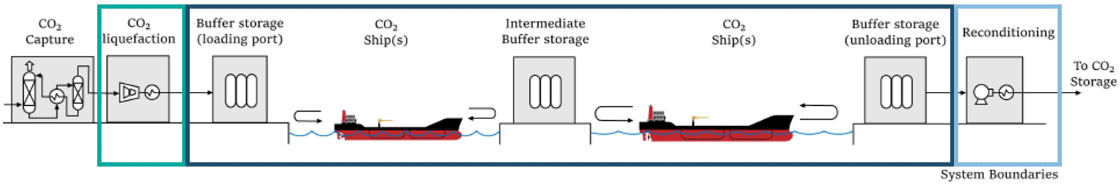
1.3 System boundaries

In this study, the CCS chain is divided in three parts: (1) The CO_2 liquefaction process, (2) the shipping supply chain, and (3) the CO_2 reconditioning process. The shipping supply chain considers buffer storage and shipping and is added to the model through a techno-economic assessment (Sections 3.2 and 3.3). With regards to the CO_2 liquefaction and reconditioning process, these are added to the model by means of an economic assessment (Section 3.3.3) based on data obtained from the literature review.

It is assumed that the CO_2 liquefaction process takes place at the carbon capture facility and then transported by ship either (a) to the final port, where it is reconditioned and injected into final storage (Fig. 1.3a), or (b) to a hub and from there to the final port (Fig. 1.3b). In addition, for both scenarios the shipping supply chain is always considered between two ports. This can be seen in Fig. 1.3 where the system boundaries for both scenarios are shown.



(a) Direct Route.



(b) Considering a hub.

Figure 1.3: System Boundaries for CCS supply chain under study

The liquefaction plant at the emitting source is assumed to be as described in Deng, Roussanaly, and Skaugen (2019). This study performs a techno-economic analysis of the liquefaction process considering ten different pressures as an output. According to the aforementioned study, the liquefaction process can be divided as follows:

1. CO_2 compression train,
2. pre-cooler, liquefier and flash tank,
3. recirculation flash and compressor,
4. ammonia refrigeration cycle.

Moreover, CO_2 enters the CO_2 compression train at 1 bar and 40°C after capture and exits at the desired pressure. The present study, as it is explain in Section 3.2.2, considers 7 bar and 15 bar pressure, therefore, the data for these pressures are used. During this study, the term low pressure is used to refer to 7 bar and -49.1°C and medium pressure to refer to 15 bar and -28.2°C, these values can be seen in Table 3.2 and Fig. 3.4. For both scenarios, after the liquefaction process, the CO_2 is send to the buffer storage where it is stored in liquid form at the port terminal and loaded onto the ship via cargo handling system. Then, it is transported by ship to the receiving port terminal which for scenario (a) would be the final port terminal while for scenario (b) is an intermediate port terminal, known as hub. In scenario (a), CO_2 is unloaded and stored in the terminal port and then reconditioned to the necessary conditions for pipeline injection into the final storage site. For scenario (b), CO_2 is unloaded to the intermediate port and then loaded to another ship that sails the route from there to the final port, where the CO_2 is unloaded and stored and later reconditioned in the same way as scenario (a).

Note that the CO_2 capture process is not part of the system. Additionally, the cost of loading and unloading CO_2 is not included in the model as it is a small percentage compared to the other costs (Orchard et al., 2020).

Furthermore, all scenarios assume that pure CO_2 is transported, as impurities vary among emitters, and that CO_2 is liquefied after capture at the emitting facility. This implies that the CO_2 transport from the liquefaction facility to the buffer storage is in liquid form and therefore, arrives by truck, train or ship. Nonetheless, for simplicity and because this configuration may vary from case to case and transport by ship is not always an option, the transport, if needed, between the liquefaction facility to the buffer storage is not considered in the model.

It is worth mentioning that carrying out the liquefaction process at the emitting facility is not always the most optimal or viable option, as for facilities outside the port terminal but sufficiently close to it, pipeline transport may be more optimal. In such cases, the liquefaction takes place at the port terminal and the CO_2 would arrive at the terminal at high pressure ($\sim$ 90 bar), so the condition before liquefaction is different from the condition assumed in the model, and hence the liquefaction cost changes.

1.4 Outline of the report

This report is divided as follows. The current chapter introduces the research question and the background to the project by providing the motivation and scope of the project. Additionally, the limitations and the boundaries of the model are presented. In order to answer the research question and develop the model, the following approach is followed. Firstly, a literature review (Chapter 2) is performed to give an understanding of the studies conducted to date on CO_2 transport. It can be seen that numerous studies focus on CO_2 transport by pipeline and that more research is needed on CO_2 transport by ship. From there, data is collected and analysed to identify the main inputs required for the model to perform the techno-economic assessment presented in Chapter 3. The technical assessment is presented in Section 3.2, in which a logistics model according to the defined inputs is develop, and the economic assessment is presented in Section 3.3. Then, the mathematical model is applied to a three specific scenarios and the results are shown in Chapter 4. Finally, the discussion, conclusions and further work are presented in Chapter 5, Chapter 6 and Chapter 7, respectively.

1.5 Limitations and assumptions

Limitations:

- Estimated fuel consumption of main and auxiliary engines by means of similar existing ships and empirical formulas.
- No differentiation between biogenic and fossil CO_2.
- Vessel main particulars estimated by means of empirical formula.
- Fuel cost is set to the average between upper and lower bounds.

Assumptions:

- Assumed that the ship is connected to the shore grid while on harbour. Hence no fuel consumption during docking time.

- The amount of CO_2 to capture will be stable in the near future.
- No difference in fuel consumption for ice class vessels or when sailing across ice.
- Both main and auxiliary engines use the same fuel.
- Ice class vessels same price as non-ice class ones.
- Table 1.1 shows the assumptions made regarding the condition of CO_2 at different stages of the CCS chain.

Table 1.1: Condition of CO_2 at different stages of the CCS chain.

Condition before Liquefaction	Transport Condition	Condition after Reconditioning
1 barg 20°C	Low Pressure	100 barg 5°C
1 barg 20°C	Medium Pressure	100 barg 5°C

2

Literature review

Although multiple studies regarding CCS technology are carried out, much remains to be studied regarding its practical implementation. Studies also need to bring together experience from existing projects and establish logistic chain models. In this chapter, the available information in the literature is gathered in order to have an overview of the current market and research field situations by presenting the new technologies, specifically in regards to waterborne transportation, and the costs and challenges associated to it.

2.1 Background

Over the years, carbon dioxide (CO_2) has been transported through pipelines, specially in North America due to the availability of large quantities and clean natural sources of CO_2 (Neele, Haugen, & Skagestad, 2014). A pipeline infrastructure to transport CO_2 requires a continues flow of compressed gas, has a high cost-distance dependency (Al Baroudi et al., 2021) and requires a high initial capital investment (Element Energy, 2018). Yet another option that is increasingly attractive is the ship transport mode. Both technologies, pipelines and vessels, are affected by the economies-of-scale, of which pipelines does it to a greater extent (Bennæs et al., 2022; Kjärstad, Skagestad, Eldrup, & Johnsson, 2016; Knoope, Ramírez, & Faaij, 2015). This means that the more volume of CO_2 available for transportation, the more cost-efficient. Different studies (Decarre, Berthiaud, Butin, & Guillaume-Combecave, 2010; Kjärstad et al., 2016; Neele et al., 2014; Roussanaly, Jakobsen, Hognes, & Brunsvold, 2013; Skagestad, Mathisen, Henrik Eldrup, & Aksel Haugen, 2011) consider pipeline transport of CO_2 a more cost-effective option when distances[1] are relatively short and volumes are considerably high.

Carbon dioxide has been also transported in small quantities, between 800 m^3 and 1200 m^3, by ship for food industry (Al Baroudi et al., 2021; Decarre et al., 2010; Neele et al., 2014; Sköldberg et al., 2021). Studies on bigger scale of liquid CO_2 transported by ship began in the early 2000s (Aspelund, Mølnvik, & De Koeijer, 2006; **?**). Aspelund et al. (2006) was one of the firsts to study the viability of ship-based transport of CO_2 and the study was carried out for the Nordic countries. The study claims that a feasible economical large-scale ship transport of CO_2 could be carry out by means of semi-pressurised vessels near the triple point (-52°C and 6.5 bar), what would also help to avoid dry ice formation in the loading and unloading processes. The research foresees two main options for the (un)loading of the cargo. Either by means of a Submerged Turret Loading (STL) unloading offshore, a direct terminal to terminal service, or a combination of both

[1]To take into account the distant ratio which is defined by the geographical context (e.g., derouting of the pipeline to avoid mountains, natural reserve, etc.)

technologies.

Since then, several studies have been carried out to develop a cost-effective large-scale CCS chain. These studies focus on different areas, such as technical aspects, methodology to be applied and economic and techno-economic assessments of the CCS chain.

2.2 State of the art

Technical assessment studies (Element Energy, 2018; Roussanaly, Brunsvold, & Hognes, 2014; Roussanaly et al., 2013) focus on the defined system, i.e., elements of the CCS chain, such as loading and offloading equipment, intermediate storage, ship design or liquefaction. With regard to ship design, **?** and Aspelund et al. (2006) presents a 20000 m^3 capacity vessel at a pressure around the triple point, i.e., low pressure, while Decarre et al. (2010) presents a 30000 m^3 capacity vessel where CO_2 is transported at -30°C and at a pressure of 15 bar, i.e., medium pressure (Table 3.2). More recently, Roussanaly, Deng, Skaugen, and Gundersen (2021) carried out a depth comparison between these two CO_2 shipping transport conditions with a volume fixed at 20 $MtCO_2$ and a distance of 2000 km and concluded that the most cost-effective option is to transport CO_2 at 7 bar. Nonetheless, it should be noted that all these studies (Aspelund et al., 2006; Decarre et al., 2010; Roussanaly et al., 2021; **?**) have been conducted with a fixed capacity/volume at a fixed distance, which are parameters that have a large influence on the model as it will be discussed further in Chapter 3.

As for intermediate buffer storage, based on LNG shipping experience, Yoo et al. (2013) suggest a storage capacity 20% above the ship capacity (i.e., 120%). On the other hand, Berger, Kaarstad, and Haugen (2005) assumed the capacity of the temporary storage as 150% of the ship capacity while Bjerketvedt, Tomasgard, and Roussanaly (2020) concludes that taking into consideration uncertainties, such as weather delays the most efficient solution is to have an intermediate storage capacity of 118% since it would avoid the increased cost of recovering from delays by increasing the sailing speed. Several Norwegian shipping companies state that they experience longer delays, like the extreme weather scenario, for short periods of time during a normal winter season. The STAwave-method[2] of estimating travelling times may be a source of error in extremely heavy weather. This, in combination with planned and unplanned maintenance, could cause an increase on the buffer capacity (Bjerketvedt et al., 2020). Nevertheless, if the risks of higher future fuel prices and ship breakdowns is taken into account, buffer capacity will rise up to 173%.

2.3 Methodology for logistic analysis

Regarding methodology studies, J. Jakobsen, Tangen, Nordbø, and Mølnvik (2008) introduces a methodology for CO_2 logistic chain analysis to contribute to a cost-efficient development of large-scale CCS logistic chain. Based on that, other studies regarding methodology have been carried out with support from the BIGCCS Centre and performed under the Norwegian research program Centres for Environment-friendly Energy Research

[2]Is related to the calculation of the added resistance due to waves. STAwave-1 is a correction method for ships that may suffer of a limited pitch and heave. STAwave-2 is a correction method with frequency response achieved by empirical methods (Magnussen, 2017).

(FME) (J. Jakobsen et al., 2011; J. P. Jakobsen, Roussanaly, Brunsvold, & Ananthara-man, 2014; J. P. Jakobsen, Roussanaly, Mølnvik, & Tangen, 2013). In J. P. Jakobsen et al. (2014), the methodology is called iCCS and is intended to provide a tool in which a multiple techno-economic and environmental criteria assessment is carried out to evaluate different CCS chains. Studies such as Roussanaly et al. (2013), Roussanaly et al. (2014) and Roussanaly et al. (2021) use the mentioned methodology to carry out the studies. Moreover, Nam, Lee, Lee, and Chung (2013) uses a mixed integer program (MIP) to optimise the cost of CO_2 transport by ship by optimally locating the liquefaction plant and determining the optimal fleet size, ship type and service frequency of the route to cover the annual CO_2 to be transported between the established sources and sinks. Bennæs et al. (2022) also uses a MIP model to determine the optimal design of a European supply chain for CCS presenting a new MIP model for the Ship-Based CCS Logistics Problem (SCLP). This new MIP model assumes that the CO_2 arrives to the ports through pipeline in a pressurised state so the CO_2 is liquefied and stored at the port before being transported.

2.4 Techno-economic assessment

Additionally, economic and techno-economic assessment studies (Coussy, Roussanaly, Bureau-Cauchois, & Wildenborg, 2013; Decarre et al., 2010; Mathisen, Skagestad, Eldrup, & Haugen, 2013; Roussanaly et al., 2014, 2013) focus on the development of an economic and efficient model by comparing the costs[3] between transporting CO_2 by pipeline and by ship often as a function of distance and cargo capacity. Kjärstad et al. (2016) present in his study the break-even point as a function of distance and volume between both means of transport, while (Roussanaly et al., 2014) shows the benchmark between offshore pipeline and shipping as transport means to an offshore reservoir. The results for both studies can be seen respectively in Fig. 2.1 and Fig. 2.2.

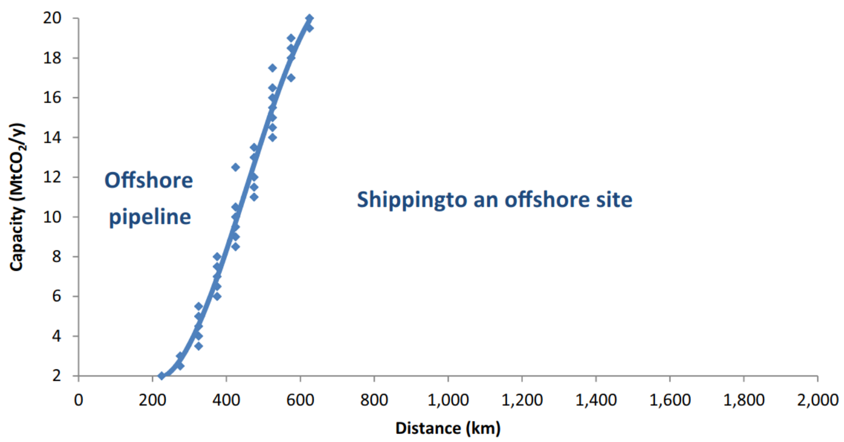


Figure 2.1: Offshore pipeline and shipping benchmark to an offshore reservoir. (Adopted from Roussanaly et al., 2014).

[3]Costs for ships can be divided in five main parts: 1) Cost of the chosen fleet (crew and sailing costs); 2) storage costs (investment and operating costs); 3) liquefaction; 4) CO_2 reconditioning (i.e., process to meet up the conditions required for its transport, and/or injection, such as dehydration, cooling, etc); and 5) loading/unloading.

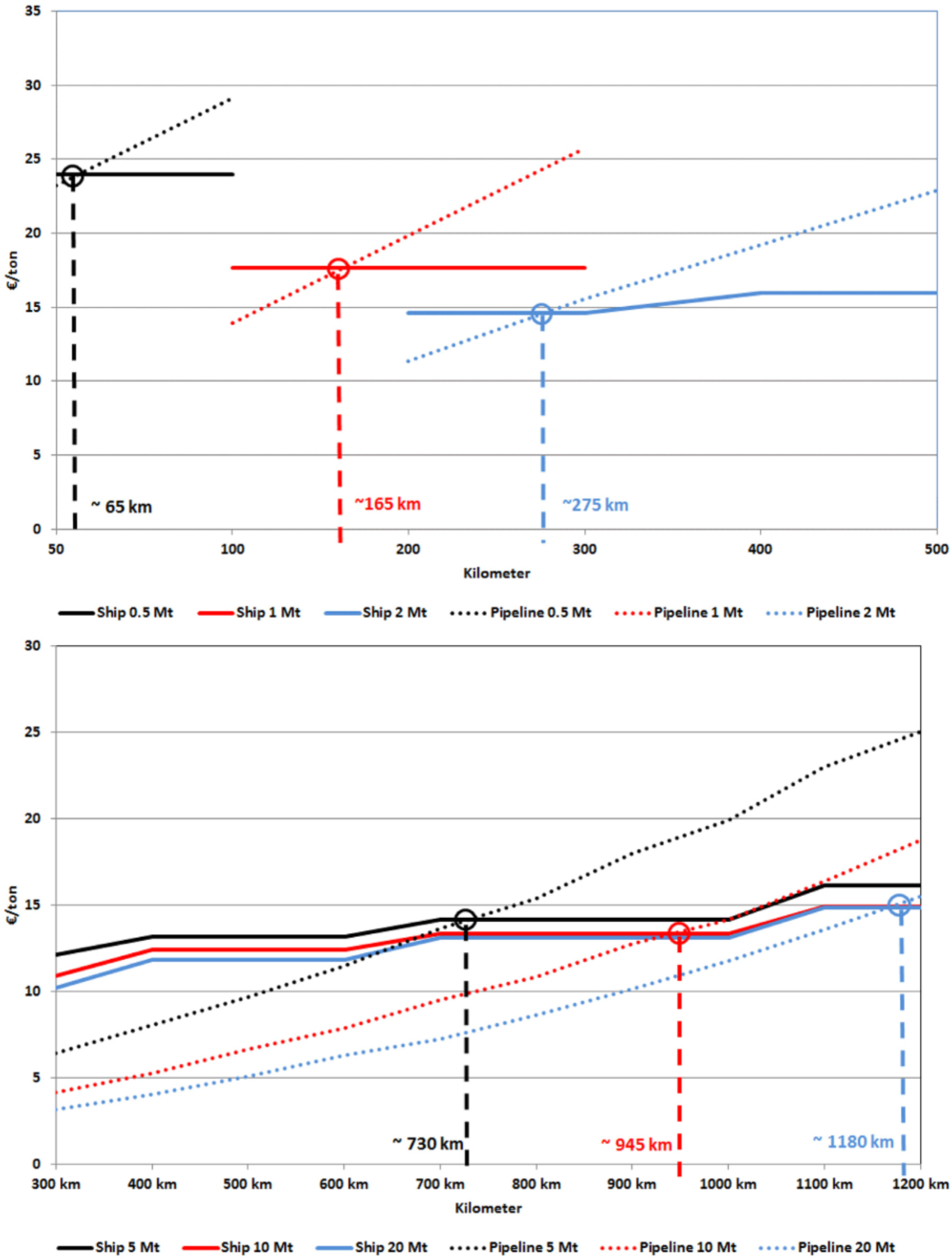


Figure 2.2: Break-even point for ship and pipeline transport cost, €/tCO_2, as a function of yearly transport volume and distance. (Adopted from Kjärstad et al., 2016).

The figures above show which is the best transport option for a given capacity-distance ratio, as well as where the boundary between the two options lies.

Models in literature often follow a Net Present Value (NPV) approach for the economic calculations and thus disregarding the flexibility and uncertainties[4] present in the process. NPV model assumes that volumes, costs, and revenues of a project are known over

[4]According to Knoope et al. (2015), typical key uncertainties are: 1) Storage volume of the reservoir; 2) coal price; 3) electricity price; 4) fuel oil price; 5) CO_2 price; 6) utilisation rate of the emissions source plant (may decrease in the future due to renewable energies).

the whole project duration and adaptation after the investment decision is not required. Although the project costs and revenues are the same, different political nature, leads to different discount rates and thus different NPV. For example, a national authority use a lower discount rate than an oil company, since the former one is dealing with higher risks (Roussanaly et al., 2014).

In reality there are uncertainties and companies will need adapt to changing situations. Therefore, Knoope et al. (2015) (in agreement with Roussanaly et al. (2014) and Coussy et al. (2013), recommends to take into account uncertainties in the investment costs in order to reach more accurate results) carried out a study applying a Real Option Approach (ROA), where flexibility is taken into account to calculate a more accurate cost-effectiveness of the project. As a result, the study shows that the certain specific cases would be profitable when a ROA is applied, while NPV approach states the opposite. This is of major importance since adding the value of flexibility can prevent a profitable project from being dismissed if the NPV gives a negative result.

A general conclusion is that, unlike pipeline infrastructure, CO_2 transport by ship does not require a large initial investment. Hence, it could be an attractive option for early CCS logistic chain during the ramp-up phase (Kjärstad, Skagestad, Eldrup, & Johnsson, 2015; Kjärstad et al., 2016; Knoope et al., 2015; Nilsson, 2014). Therefore, ship-based transportation mode could simplify and speed up the CCS infrastructure deployment in the decision making process phase by offering a lower investment threshold. Hence, stakeholders could be more willing to invest despite the high initial financial risk[5] (even in the absence of government involvement). The main reason is the lower CAPEX and the characteristic flexibility of ship transport compared to pipelines (Nilsson, 2014). CAPEX for CO_2 ships available in literature is gathered in Fig. 2.3 by Knoope et al. (2015). Such study, also affirms that, on the contrary, OPEX are around 50% larger for ship transport compared to pipelines. Orchard et al. (2020) also collects the investment costs from the literature (see Fig. 2.4) and, as it is more recent, it is the one used for the estimation of CAPEX in this research, as explained in Chapter 3. Decarre et al. (2010) states that in the case of offshore storage, i.e., from port to offshore storage, transport by ship is a more economical option than pipeline for distances over 350 km, and in the case of port-to-port for distances over 1100 km. Nevertheless, Yoo et al. (2013) carries out an economic assessment showing that CO_2 shipping can play an important role in transporting large volumes of CO_2 from various sources, even in distances between 200 and 300 km.

[5]The first-of-a-kind effect, which is unavoidably attached to uncertainties along the whole investment process. This could lead to higher investment costs due to, for instance, sub-optimal design, additional construction costs, delays, underutilised pipelines over the first years, etc. (Roussanaly et al., 2014)

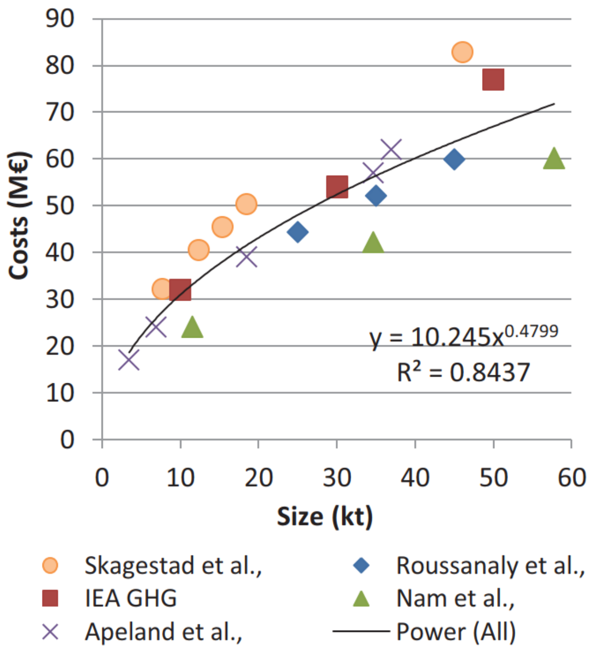


Figure 2.3: CAPEX for CO_2 ships available in literature. (Adopted from Knoope et al., 2015).

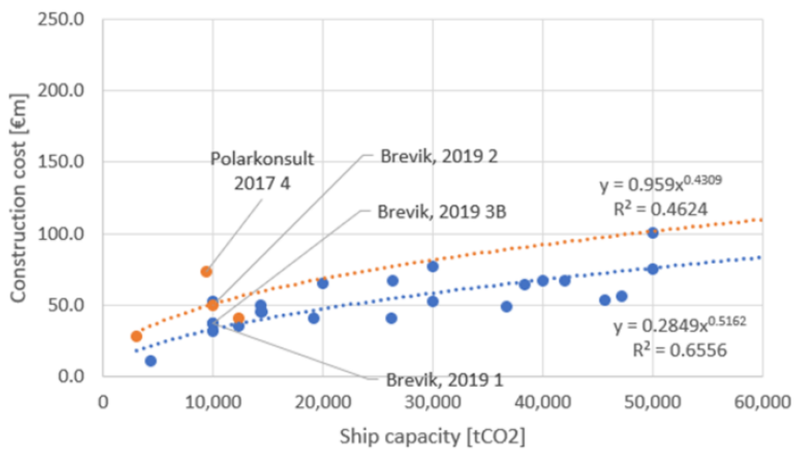


Figure 2.4: Ship construction cost data and corresponding fitting curves for low and medium pressure. (Adopted from Orchard et al., 2020).

The literature shows the costs of each process within the whole logistic chain. According to d'Amore, Romano, and Bezzo (2021), the total cost of the transportation phase stands for the 6-18%, while Bennæs et al. (2022) present a 35-40% of the total costs for liquefaction[6]. Within transportation costs, Knoope et al. (2015) present that a 20-30% is directly related to the ship and 70-80% is in relation to harbour facilities, liquefaction unit, offloading and conditioning equipment. It is worth to mention that the liquefaction costs are barely dependent of the mass flow, since the energy consumption per tonne of CO_2 is nearly constant, while the remaining costs decrease with increasing mass flow. Furthermore,

[6]Liquefaction is directly related to the cost of the electricity. Thus, a rise in electricity price results in an increase of the total costs of the ship-based CCS logistics system

Bjerketvedt et al. (2020) claims that the conditioning and shipping are the main costs of the transportation and gives some quantitative data for a particular case: Conditioning has a cost of 15.4 €/tCO_2, where the cost of electricity reach half of it with 7.8 €/tCO_2. When it comes to the shipping, the cost is of 13.8 €/tCO_2, from which 4.1 €/tCO_2 corresponds to the fuel cost. The total energy cost for these processes is 11.8 €/tCO_2. Finally, the remaining costs of the transport chain are due to the buffer storage (concept introduce before in this chapter) with 2.9 €/tCO_2 and the reconditioning at 1.7 €/tCO_2.

The optimal size and capacity of vessels are closely related to the expected volume of CO_2 to transport and this is linked to a seasonal variation. Hence, the question arises as to what will be the most economically optimal; whether to have a reduced number of vessels but with a larger cargo capacity, or instead to have a larger number of vessels with a more modest cargo capacity. Bjerketvedt et al. (2020) present the answer to this question: based on the achieved results, he states that the variation in CO_2 emissions due to the change of seasons lead to the option of larger ship, since the increased fuel consumption caused by its size is offset with the fact that smaller ships would need to increase their power and speed in order to comply with the larger CO_2 volumes during peak season. Furthermore, the study claims that the seasonal storage of the CO_2 is not a cost-efficient strategy in any case compared to increasing the vessel capacity. Therefore, it is proved that the seasonal variations in emissions in the source has a relevant impact on the optimal design of the transport chain.

Weather conditions is also directly related to seasons i.e., harsh sailing conditions are more often during winter. For instance, larger wave heights are expected during these periods. As a result, the ship speed would decrease, being small ships more sensitive to these events compared to larger ones. Thus, yet another reason in favour of big vessels (without forgetting to include to this list the aforementioned concept of economies-of-scale).

One further matter to have into account when studying a new infrastructure, is always the new risks that these new technologies and processes may cause on personnel dealing with them in particular and society in general. Aspelund et al. (2006) carried out a hazard identification (HAZID) and a preliminary hazard and operability (HAZOP) analyses. As an example, shows that since CO_2 is heavier than air, the later one would be displace to upper layers. Hence, gas detectors must be installed to avoid potential suffocation of crew members in a leakage event. Regarding the societal risk[7], mitigation procedures are not required in order to obtain an acceptable risk level (d'Amore, Mocellin, Vianello, Maschio, & Bezzo, 2018). The costs for maintaining societal risk levels below dangerous levels is lower than 0.41€/tCO_2, that is the 11% of the overall transport costs. Therefore, the implementation of mitigation measures within an European CCS SC shall not be an economic obstacle when planning a safe transport infrastructure.

2.5 Legal aspect

Regarding the legal aspects of CCS, Nilsson (2014) introduced the main points to have into account:

[7] Societal risk is defined as the health risk that a number of people (population in this case) are exposed to that is triggered by certain hazardous incident in a defined region.

- The European Union Emissions Trading System (EU ETS) does not mention specifically transport of CO_2 by ship. The current solution is an integration of vessels into the ETS on a case-by-case basis, which is a cumbersome, high time consuming and costly process for individual project operators.
- Sequestrate CO_2 in a sub-seabed geological reservoir is prohibited for the Parties to the London Dumping Protocol.
- The CCS Directive prohibits the storage of CO_2[8] in any reservoir that extends beyond the territory of an EU member.
- Currently, biogenic CO_2 is not covered by the EU ETS, which is counter-productive since this biogenic CO_2 would contribute to the financial viability by increasing the total CO_2 volume available and thus benefit from the economies-of-scale.
- Swedish government position regarding biogenic CO_2 is that it should receive equal treatment as fossil fuels CO_2. Moreover, Swedish government claimed that *"ship transport of CO_2 is a likely prerequisite, at least initially, for making CCS commercially interesting"*.

Thus, the author recommendations are to 1) give a clearer definition for the term "captured CO_2"; 2) more consideration regarding potential market failures shall be shown; and 3) define and constrain accurately the role and competence of each authority in the CCS infrastructure building up process.

2.6 CCS potential in Sweden

As for the Nordic countries, in particular Sweden, CO_2 emissions come from paper, steel, cement, refineries and chemical industries, which are considered small-medium sized industries as the emissions are typically between 0.1-1.0 $MtCO_2$/year. In addition, the distances between sources to potential storage sites are relatively long, 300 km or, in many cases, considerably more (Kjärstad et al., 2016). Thus, CO_2 shipping is often a more suitable transport mode. Moreover, many industries are located on the coast line and the volumes of CO_2 that need to be transported are not high. Therefore, hubs are needed in order to form clusters of near small emitters so that enough CO_2 could be gathered in order to carry out a profitable process (Kjärstad et al., 2015, 2016; Nilsson, 2014). Sköldberg et al. (2021) takes into consideration Swedish emissions from different industries and identifies, based on location and emissions size, four main clusters for local collaboration. Clusters such as Västkusten/Vänern, Skåne/Danmark, Ostkusten/Mälardalen and Gävle area. It could be less costly to transport the CO_2 by ship 800-1300 km further to the west than sequestrating it in a nearest reservoir (e.g., within the Baltic Sea) due, for instance, to bad injectivity[9], which is believed to be limited as it is the storage capacity in the Baltic sea (Kjärstad et al., 2016; Nilsson, 2014). Notice that higher injectivity capacity means less costs €/tCO_2.

[8] CO_2 emitted by the combustion of organic material.

[9] Defined as the pressure differential of certain reservoir pressure that is required in order to be able to inject a unit volume of fluid in a given unit of time. Although it can be expressed by means of any combination of pressure, volume and time, is typically defined by psi per barrel per day (psi/bbl/day) (Law Insider, n.d.).

Additionally, Karlsson, Normann, Odenberger, and Johnsson (2023) presents an study of the current situation in Sweden in terms of emitters location, and optimal potential hubs sites so that the total emissions within Sweden could be gathered for its marine transportation in a cost-efficient way. In this regard, a future scenario is also studied to account with the market evolution, where more emitters will join to the logistic chain. It takes into account both types of CO_2 emissions, i.e., fossil and biogenic, and how both could be handled, either separately or jointly. This matter is further discussed in Section 4.2 and used to support the selected approach in this thesis.

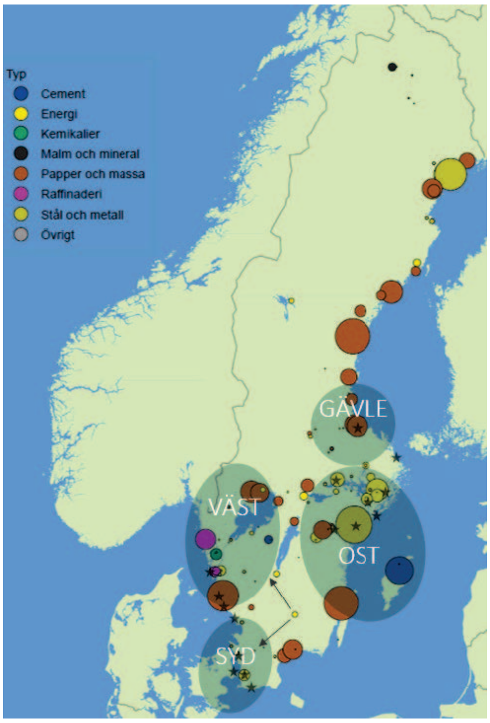


Figure 2.5: Swedish industries by sector and four main clusters. (Adopted from Kjärstad et al., 2016).

On the one hand, as seen throughout the literature review, several studies have focused on optimising transportation models based on techno-economic assessments comparing transportation by ship and transportation by pipeline. On the other hand, studies to date that consider CO_2 transport by ship focus on the technical aspects and optimisation of the whole chain. That is, as instance, how to optimise the liquefaction process or at what temperature and pressure it is most feasible and economical to transport CO_2 by ship, however, the transport itself is set as a fixed parameter to the model. Hence, there is no a consistent optimised model for the transportation of CO_2 by ship from sources to sinks.

As mentioned, CCS projects in Sweden are at an early stage, industries are considered to be small to medium size and thus the CO_2 production would not be available in large quantities if single emitters are considered, at least for the time being, and many of them are located along the coast. In addition, initiatives that aim to use CO_2 are emerging, like Liquid Wind (2023) who is interested in using the captured CO_2 for methanol production. Although CO_2 transport by pipeline is, as stated by the International Energy Agency (2020), a mature and established technology, and large-scale CO_2 transport by sea is in the demonstration phase, looking into the near future and taking into account the facts that have been established throughout the literature review and presented before in this chapter, it can be concluded that CO_2 transport by ship is the most favourable option for Sweden in the near future.

Thus, the next step in taking CCS to large scale is to optimise a logistics model to transport CO_2 by ship between different points of interest (sources and sinks), taking into account the volume to be transported, distances, ship capacities and hubs, producing the best transport model for different situations. Hence, according to the available literature the two main parameters that define each source characteristics for carrying out an economic and feasibility studio are the rate of CO_2 volume produced and available for transport at the source, and the distance from it to the injection site.

At the view of the gathered information, it can be found some interesting gaps in the literature that motivate this thesis topic:

- Not enough research on a cost-effective optimised solution for a maritime generic-ship based CO_2 transport can be found.
- Lack of mathematical models to study any potential scenario in terms of sea route, source and sink location and volume of CO_2 to be transported.

3

Methodology

In the current chapter, the methodology followed to develop the model in order to answer the research questions found in Chapter 1 is presented.

The purpose of the model is to determine the optimal maritime logistics of a CCS chain in Sweden. To that end, a techno-economic assessment is needed. First, the technical components considered for the development of the model are presented (Sections 3.1 and 3.2). The following is the cost evaluation assessment (Section 3.3) for each stage of the CCS chain according to the system boundaries shown in Fig. 1.3. Figure 3.1 shows the methodology followed for the techno-economic assessment, the first half being the technical part and the second half the economical part.

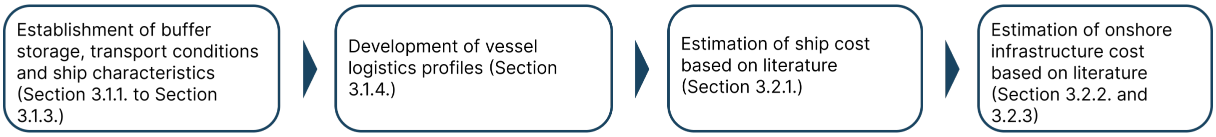


Figure 3.1: Techno-Economic Assessment Approach

3.1 Model overview

In this section is presented how the model (i.e., logiCO_2) is built up, and how all parameters, variables, inputs and constraints are intertwined. Figure 3.2 depicts a general overview of the followed workflow.

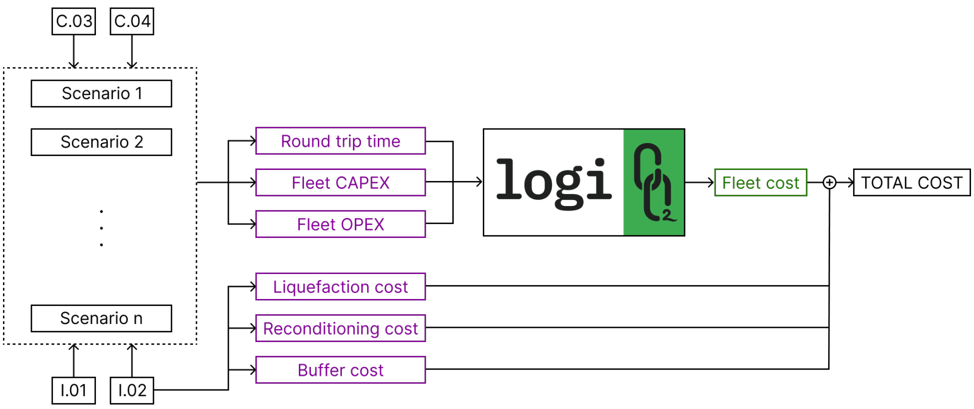


Figure 3.2: Workflow overview

It shall be remarked that, as it can be seen in Fig. 3.2, the inputs that the mathematical model use are the loading and unloading rate, buffer cost, CAPEX and OPEX. It is of highly importance to note for a full understanding of the system under discussion that, liquefaction and reconditioning costs are not parameters that the model takes into account for defining the optimum fleet. However, such costs must be added in order to get to know the total cost of the construction and operation of the required infrastructure.

Each considered scenario have its own characteristics. These are, primarily, its location, which will further define the sailing distance and the amount of CO_2 gathered, identify as I.01 and I.02 respectively. Additionally, a potential constraints for certain location is the ship size limitations, represented by C.04. Moreover, the type of fuel used can be defined by means of C.03. Hence, under certain conditions and specifications, inherent to a specific scenario, inputs for the model are defined for running the calculation to achieve the most cost-effective fleet solution. Finally, as already mentioned, the liquefaction and reconditioning costs are added to the fleet cost to get to know the total cost.

The model box is explained and illustrated in detail in the following section, so that the complex relation between all components, parameters, inputs and constraints can be presented.

The built model is shown in Fig. 3.3. For full understanding of the meaning of the numerous inputs and constraints that can be seen in the figure, refer to Table 3.1.

Table 3.1: Inputs and constraints applied in the model

Inputs (I)			
1.	Sailing distance	d	km
2.	Amount of CO_2 to be transported	a	t/y
3.	Ship operational time	T_o	h/y
4.	Ship lifetime	-	y
5.	Planning horizon	-	y
6.	Loading time	t_l	h
7.	Unloading time	t_u	h
8.	Port entry time	t_{pin}	h
9.	Port exit time	t_{pout}	h
10.	Mooring time	t_{moor}	h
11.	Unmooring time	t_{umoor}	h
12.	Cargo density	ρ_{LP}	[t/m^3]
13.	Cargo transportation temperature	T_c	[°C]
14.	Cargo transportation pressure	P_c	[bar]
Constraints (C)			
1.	Vessel cargo capacity	c	t
2.	Vessel speed	v	kn
3.	Fuel type	-	-
4.	L, B and T limitations	-	-
5.	Cargo pressure	-	bar
6.	Cargo temperature	-	°C
7.	Buffer storage capacity	c_b	m^3

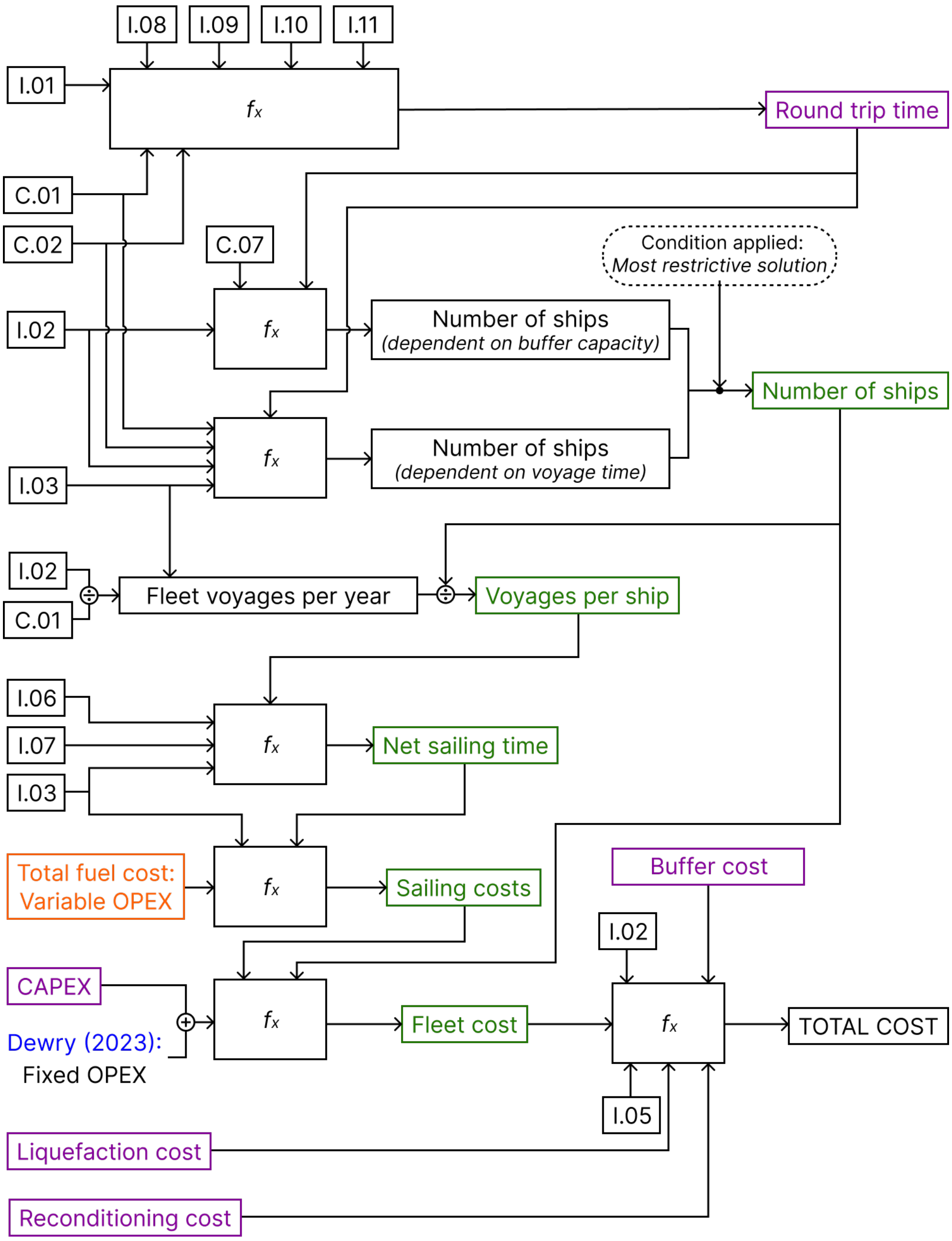


Figure 3.3: Workflow for the functioning of the model

As shown previously in Fig. 3.2, the chosen scenario define the main inputs (i.e., distance between ports and amount of CO_2 to be transported). Hence, according to these parameters, the cost for every single ship cargo capacity listed in Tab. 3.3, with a range of three speeds (i.e., 10, 14 and 16 knots) for each capacity, is calculated so that the most cost-effective solution can be identified among them.

First step is to calculate the round trip time, for which distance between harbours, port entry and exit time, mooring and unmooring operations are taken into account as well as vessel cargo capacity and speed. In addition, the previously calculated loading and unloading time is considered so that the round trip time is known.

Secondly, it is necessary to know the number of ships that make up the fleet, which will be the most restrictive solution among the two approaches defined below:

- Dependent on the buffer storage capacity: As mentioned in section 3.3.2 the buffer storage capacity is a 18% above the vessel cargo capacity to account to uncertainties as it can be delays due to weather or port congestion. Thus, the calculated round trip time is used so that relating it with the CO_2 volume to transport, and the buffer storage capacity, the minimum number of vessels needed to comply with required port arrivals rate to avoid the overfilling of the buffer storage is achieved.

- Dependent on the voyage time: This would be the other possible constriction that will define a minimum number of vessels. It cannot be less that the minimum needed fleet size to cope with the total amount of CO_2 to be transport in a defined period. In this study this period is one year, thus, the required quantity of ships are those that can deal with the total amount of CO_2 that is emitted in one year at the defined scenario. For this approach, vessel cargo capacity and speed are taken into account, as well as the CO_2 volume to be transported and the ship operational time, assumed to be 8400 hours per year.

The voyages per ship is then calculated by dividing the number of ships and the fleet voyages per year, which is a function of the CO_2 volume, the vessel cargo capacity and the ship operational time.

The voyages per ship is then used to get to know the net sailing time (i.e., disregarding mooring time where it is assumed that main and auxiliary engines are not being utilised) by relating it to the loading and unloading time and the ship operational time.

Now, the net sailing time (i.e., main and auxiliary engine are running) is used to calculate the sailing costs, which are directly dependent on the ship operational time and the variable OPEX calculated in section 3.3.1.2.

By adding the annual CAPEX and the annual fixed OPEX defined by Drewry (2021) and relating them to the sailing costs, and to the number of ships, it is thus calculated the whole fleet cost per year.

Finally, to estimate the total cost, the fleet cost shall be related to the buffer cost, liquefaction and reconditioning cost, the CO_2 amount and the planning horizon.

3.2 Technical Modelling

This section addresses the first two steps of Fig. 3.1, i.e, the technical analysis. The technical modelling in this study takes into consideration the shipping supply chain (the middle part in Fig. 1.3), that is, technical aspects regarding transport pressure, buffer storage and ship characteristics. With regards the CO_2 liquefaction and reconditioning process are added into the model just from an economical point of view and are assessed in Section 3.3.

Hence, from a technical approach and taking into consideration the mentioned aspects, the model provides an optimised shipping logistics to transport an amount of CO_2 between two ports. Therefore, the main inputs of the model are the distance and the CO_2 flow rate, as well as the fuel used to operate the ship. Nonetheless, the latter only has an economic impact and is assessed in Section 3.3

3.2.1 Buffer storage

In this study the shipping supply chain consists manly of buffer storage and shipping and is located between the liquefaction and the reconditioning processes in the CCS chain under consideration, as can be seen in Fig. 1.3. The model assumes that both processes are continuous, whereas the shipping logistics is considered discontinuous. Therefore, intermediate buffer storage is needed in the supply chain to integrate the whole chain.

As shown in Chapter 2, the studies conducted to date consider different capacities for buffer storage. Yoo et al. (2013) and Berger et al. (2005) suggest a storage capacity of 20% and 50% above the ship capacity, respectively, while Element Energy (2018) considers a buffer storage capacity of 20% above the ship fleet. Nonetheless, the present study, following Bjerketvedt et al. (2020), assumes that a total buffer storage of 18% above vessel capacity at each port is sufficient to account for uncertainties such as weather delays.

Furthermore, intermediate buffer storage and shipping logistics depend on optimal transport pressure, required fleet size (number of CO_2 tankers), and their mix (ship types or capacities) to transport a certain amount of CO_2 from emitter to permanent storage. The amount of CO_2 to be transported and the distance are input to the model, while the vessel capacity, number of vessels needed and speed are outputs. Therefore, as explained in more detail below, different vessel pressures, capacities and speeds are considered.

3.2.2 Pressure transport

Figure 3.4 illustrates the phase diagram of pure CO_2 and, as can be seen, at atmospheric pressure it exists only in a gaseous or solid state (Orchard et al., 2020). Therefore, to transport CO_2 in liquid state, it requires pressurisation and it can be from the triple point to the critical point. Within this range, three main shipping pressures are highlighted: low pressure (LP), which corresponds to pressures close to the triple point, medium pressure (MP), which corresponds to pressures around 15 bar, and high pressure (HP), which corresponds to pressures around the critical point.

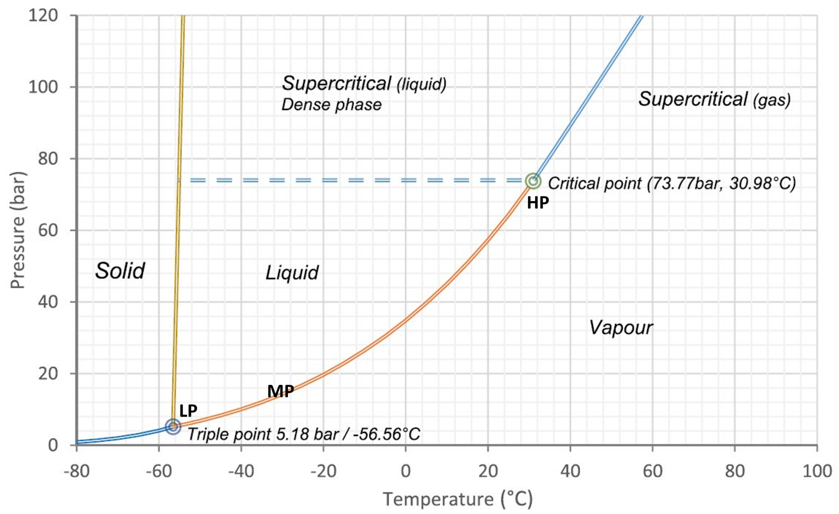


Figure 3.4: Phase diagram of pure CO_2 based on the Span and Wagner equation of state. (Adopted from Deng et al., 2019).

As described in Section 2.2, low pressure and medium pressure are the most discussed in the studies carried out, whereas high-pressure condition is not considered a cost-effective option due the high cost and low volumes (Orchard et al., 2020; Roussanaly et al., 2021; Seo, Huh, Lee, & Chang, 2016). With regards low-pressure shipping, it has been studied from a research perspective in studies such as Kather and Engel (2018) and Roussanaly et al. (2021). These studies state that is more cost-efficient than medium pressure, however, the technology is yet to be proven. In contrast, medium-pressure shipping does have application in industry as CO_2 is transported at this pressure on a small scale in food industry, and the technology is therefore more mature and ready. Nonetheless, CO_2 transport by ship at medium pressure poses a constraint on scaling up to accommodate further growth of CCS, whereas low-pressure transport enables significantly greater capacities, even though there is limited practical experience.

Thus, the present work considers low-pressure and medium-pressure conditions for the optimisation model. Table 3.2 shows the density and the pressure used in the model for low and medium pressure conditions. As can be seen, CO_2 at medium pressure transport condition has a lower density than at low pressure condition, which results in a less efficient storage. According to Brevik engineering AS (2020) a higher density increases the storage efficiency by around 10% compared to medium pressure transport condition.

Table 3.2: Pressure Condition factors. (Deng et al., 2019).

Factor	Low Pressure	Medium Pressure
CO_2 density [kg/m^3]	1133	1042
Pressure [bar]	7	15
Temperature [°C]	-49.1	-28.2

3.2.3 Ship characteristics

As mentioned above, low-pressure shipping allows bigger ship capacities than medium-pressure shipping. Based on Roussanaly et al. (2021) and Element Energy (2018), the maximum capacity for the medium-pressure ship option is set at 10 ktCO_2/ship. As with the current tank configuration available in the industry, a higher capacity is unlikely to be feasible due to pressure limiting the practical CO_2 diameter tank. Moreover, for the low-pressure option, the maximum capacity is 50 ktCO_2/ship as there is no reliable cost data for ships with bigger capacities (Roussanaly et al., 2021). Table 3.3 shows all the capacities under consideration.

Table 3.3: Ship capacities for low and medium pressure option.

Low Pressure transport Capacities [ktCO_2]	Medium Pressure transport Capacities [ktCO_2]
2.5, 5.0, 7.5, 10, 12.5, 15, 20, 25, 30, 35, 40, 45, 50	2.5, 5.0, 7.5, 10

Furthermore, a ship carrying CO_2 is, according to MARPOL (IMO, 1983), considered to be a tanker, more specifically a NLS (Noxious Liquid Substances) tanker. In general, tanker speeds range from 9 to 17 knots, with 9 to 15 knots being the most typical for oil tankers and 12 to 17 knots for chemical tankers (Shafran, 2022). Thus, three speeds in this range are considered for each ship type: 10, 14 and 16 knots and the speed is assumed to be constant throughout the voyage.

3.2.4 Shipping logistics

The main purpose of the model is to optimise the shipping logistics, i.e. vessel capacity, number of vessel and speed, to obtain the most economical cost. And the number of CO_2 carriers required and their capacity depend to a large extent on the amount of CO_2 to be transported and the distance of the route. Therefore, a logistics profile is developed for each type of ship and scenario.

There are two constraints on the number of CO_2 carriers required. One is the fleet must be able to transport the amount of CO_2/year entered as an input, considering that each ship has 8400 operating hours (T_o). And the other is that a ship must be at the port terminal before the buffer storage is completely full. So the model uses two different methods to calculate the number of vessels needed. One by considering the total travel time and the other by considering the time it requires filling the buffer storage, selecting the one that meets both conditions. In addition, the model assumes, for all scenarios, that all vessels in the fleet have the same capacity.

On the one hand, the travel time or round-trip time (T_{rt}), given by Equation 3.1, considers sailing time which depends on distance from port to port (d) and vessel speed (v), mooring (T_{moor}) and unmooring time (T_{umoor}), port entry (T_{pin}) and exit (T_{pout}) time as well as loading (T_l) and unloading (T_u) time. Therefore, the number of ships of type i (x_i) is obtained through Equation 3.2.

$$T_{rt} = 2\,\frac{d}{v} + T_{pin} + T_{pout} + T_{moor} + T_{umoor} + T_l + T_u \tag{3.1}$$

$$x_i \cdot a_{x_i} \geq a \tag{3.2}$$

In which, a is the amount of LCO_2 that needs to be transported during the planning horizon and a_{x_i} is the amount of LCO_2 that a vessel can transport during the planning horizon and it is defined by Equation 3.3 where c_{x_i} is the capacity of the vessel.

$$a_{x_i} = c_{x_i} \cdot \frac{T_o}{T_{rt}} \tag{3.3}$$

One the other hand, the model assumes that the amount of LCO_2 arrives continuously in the port throughout the year and that the buffer storage is operational all year round. Equation 3.4 gives the number of vessels of type i needed taking into account the time it takes to fill the buffer storage (T_b).

$$x_i \cdot T_b \geq T_{rt} \tag{3.4}$$

Where the T_b is given by Equation 3.5 in which c_b is the buffer capacity and R_b is the flow rate of the buffer storage

$$T_b = \frac{c_b}{R_b} \tag{3.5}$$

In Table 3.4 can be seen the ship logistics parameters for the model in more detail.

Table 3.4: Ship logistics parameters.

Input	**Low Pressure**	**Medium Pressure**	**Units**
Port entry & Exit Time	2	2	h
Mooring/Unmooring time	0.25	0.25	h
Loading/Unloading time	12.81	12.81	h
Ship operational time	8400	8400	h/y
Planning horizon	1	1	y
Operational speed	10, 14, 16	10, 14, 16	knots
Ship Capacities	2.5, 5.0, 7.5, 10, 12.5, 15, 20, 25, 30, 35, 40, 45, 50	2.5, 5.0, 7.5, 10	$ktCO_2$

The times shown in Table 3.4 are obtained from the literature review. The port entry and exit time as well as the mooring time are established in accordance with Orchard et al. (2020).

As for the loading and unloading time, it is obtained by means of literature research and finding the average for different ship sizes. Brownsort, Koornneef, Energy, Gas, and de Kler (2015) considers a fixed loading time of 15 h for four different vessel capacities: 10 kt, 20 kt, 30 kt and 50kt. Whereas Bennæs et al. (2022); ZEP (Zero Emissions Platform) (2011); Bjerketvedt et al. (2020); Roussanaly et al. (2021) consider a fixed loading time of 12 h for different vessel capacities. Equinor (2019) contemplate a loading rate of 800 tCO_2/h for a ship that transports 7500 tons of CO_2 while Losnegård, Nysæter, Knudsen, Belgaroui, and Forin (2020) contemplates 1200 tCO_2/h for the same ship capacity. Moreover, Orchard et al. (2020) considers a loading rate of 600 tCO_2/h for a ship that transports 10000 tons of CO_2. Therefore, the model considers 12.81 h as loading and unloading time, regardless of vessel capacity, since it is assumed that vessels with smaller capacities have a smaller flow rate due to the sizing and number of pumps while vessels with larger capacities have a higher flow rate.

Loading and unloading time should be further investigated since the time spend at port is highly dependant on it. The required time depends on the installed pumps at port or onboard of the ship that carry out the loading and unloading tasks. Since the fleet designed for this rather new market is expected to follow a shuttle transport system, would be a good option to use port facilities to install the needed pumps, so that bigger ones could be easier to install as size and weight of them would not be an issue. Furthermore, there can be found some advantages regarding the maintenance and/or replacing labours. In favour of on board installed pumps can be mention the higher flexibility for the ship, since can be docked also in ports with lack of enough big or none pumping systems.

3.3 Cost assessment methodology

This section shows the methodology followed to obtain the different costs. The mathematical model considers the cost of each component of the CO_2 shipping supply chain, i.e., liquefaction cost, buffer storage cost, CO_2 ship cost and reconditioning cost. Moreover, the cost methodology adopted can be divided in three groups: CO_2 ship cost, buffer storage cost and the cost of CO_2 liquefaction and reconditioning process. Table 3.5 shows an overview of of the method used to scale the cost of each component of the CCS chain under study and Fig. 3.5 shows an overview of the model.

Table 3.5: Overview of the cost methodology.

CCS chain component.	Cost Scaling
CO_2 Ship	**Investment costs** are scaled with ship capacity using curve fitting established by Orchard et al. (2020). **Fixed operational costs** are adopted from Drewry (2021). **Variable operational costs** explained in detail in 3.3.1.2.
Buffer Storage	**Investment costs** are scaled linearly with ship capacity. **Fixed operational costs** are a percentage of investment costs.
Liquefaction and Reconditioning	**Investment costs** are scaled using the cost power law Equation. **Fixed operational costs** are a percentage of investment costs. **Variable operational costs** are scale linearly with flow rate.

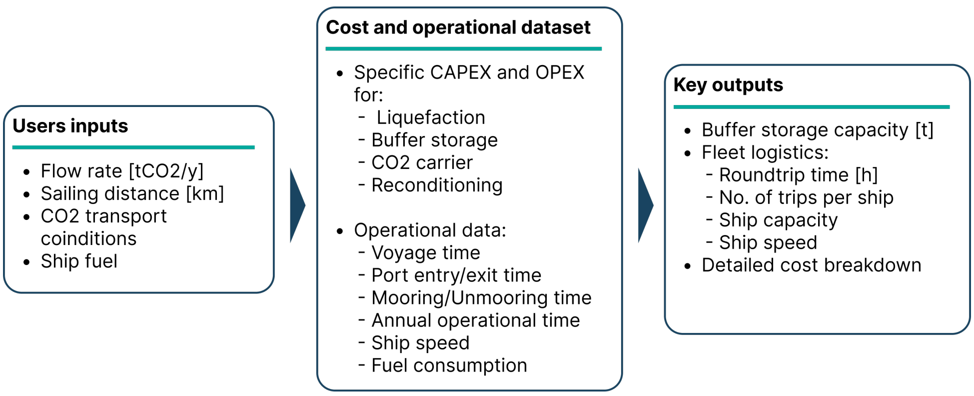


Figure 3.5: CO_2 shipping cost model.

Throughout the whole process of defining and calculating the parameters and variables required to achieve the desired results, certain inputs are necessary as well as the imposition of different constraints in order to achieve the desired result within the defined scope. I.e., time limitations, vessel size restrictions or type of fuel used by the ships, as well as specific requirements to be fulfilled with respect to the pressure and temperature conditions at which the cargo must be transported. These inputs and constraints are shown in Tab. 3.1.

The following calculations are carried out for low pressure values. Nevertheless, similarly, it is the process for medium pressure option, changing the input values accordingly.

3.3.1 CO_2 ship cost

The ship costs are divided into hiring costs, C_H, and sailing costs, C_S. The hiring costs consist of CAPEX and fixed OPEX, while the sailing costs are represented by variable OPEX. Below it can be seen listed in detail the groups and subgroups considered for building up the total costs in this thesis:

1. **Capital expenses (CAPEX)**: Defined as the costs that enable the shipowner to take possession of the vessel and represent, on the one hand, an item during a considered period, and, on the other hand, the financial costs arising from the use of borrowed capital (loan) to finance the vessel.

2. **Operation expenses (OPEX)**: Refers to those costs which must be paid in order to keep vessel seaworthy at all times and therefore fit for service. Additionally, these costs are divided in two subgroups so that the can be implemented in the model more accurately:

   (a) **Fixed OPEX**: Adopted from Drewry (2021).

      i. **Manning**: Crew salaries. Note that this cost does directly depend on crew size, different roles onboard as well as its close relation to different nationalities.

      ii. **Insurance**: Split in hull and machinery (H&M) and protection and indemnity insurance (P&I).

      iii. **Stores, spares and lubes**: Represent the costs of rental for stores, warehouses, etc and the purchase of the needed spare items. Lubes account for several required oils onboard designed for different specific tasks. Note that lube it is needed in any mechanical equipment that requires a reduction in friction, heat dissipation and meet certain cleanliness levels.

      iv. **Repair and maintenance (R&M) and dry-docking**: Which, in turn, can be divided in:

         A. Scheduled repairs: Routine maintenance, surveys, etc.

         B. Unscheduled repairs: Occurs due to accidents on the vessel.

         C. Hybrid repairs: Due to strategic decision with respect to market situation.

         D. Retrospective repairs: Imposed changes or updates triggered by mandatory incoming regulations.

      v. **Management and administration (M&A)**: Arises from the owner's management decisions such as tradings and also number and location of the offices since its location is attached to different taxation and regulations according to the local laws.

   (b) **Variable OPEX**: Defined as the sailing costs.

      i. Fuel consumption.

ii. CO_2 emissions tax.

iii. Harbour fees.

iv. Channels and/or canals fees (if applicable).

3.3.1.1 Hiring cost

The hiring cost depends mainly on the ship size and the number of vessels needed. Although costs such as maintenance and insurance usually increase with vessel age, due to their more often maintenance operations, hiring costs are consider constant over the vessel life. Moreover, the hiring costs are assumed linearly proportional to the number of vessels.

The total construction cost, i.e CAPEX, of each ship type is estimated by means of a curve fitting from the CO_2 ship cost database presented in Orchard et al. (2020). This can be seen in Fig. 2.4 where the orange curve corresponds to ships transporting CO_2 at medium pressure and the blue curve at low pressure. The x in the fitting curve corresponds to the CO_2 capacity transported by the ship. And the ship construction cost is given in millions of Euros (€m). The numbers of the regression line equations can be found in Table 3.6.

Table 3.6: Ship construction cost assumptions used in the model. (Adopted from Orchard et al., 2020).

CO_2 transport condition	Constant CAPEX €m/tCO_2	CAPEX Exponent
Low Pressure	0.2849	0.5162
Medium Pressure	0.959	0.4309

Regarding the capital expenditures involved in the vessels construction, there is a potential cost saving when several same-kind ships are built in the same shipyard. These savings depends on a wide range of factors, as are the size and complexity of the vessel, the total number of ships to be built and also the specific shipyard where it is going to be constructed, since its prices are closely related to its location in terms of national economy, materials market and prices, equipment, transportation costs, etc. Nonetheless, studies show an economy of scale in the shipbuilding process linked to savings between 5 to 30% per vessel.

Using a conservative approach, the following assumption is taken to calculate the CAPEX when more than one same-kind vessel is needed:

$$CAPEX_k = k * CAPEX_1 \tag{3.6}$$

where n stands for the number of vessels and $CAPEX_1$ are the capital expenses associated for one vessel and $CAPEX_k$ are the total costs for the construction of n vessels.

Once the total CAPEX is know for the most optimal solution for the case under study, two methods are proposed to calculate the annual payment of the loan, so that is up to the user to choose which one to use:

- French system: Equal annual payments including repayment of the principal and their associated interests.
- German system: The total payments over the repayment period of the loan do not remain constant, but are decreasing.

As in the calculation of the buffer storage cost, the French Devolution system is applied in order to obtain the CAPEX to be paid over the planning horizon. Applying Eq. 3.7 it can be known the annual payment:

$$\alpha = P\frac{j(1+j)^m}{(1+j)^m - 1} \tag{3.7}$$

Where α stands for the annual payment, j is the interest rate, m is the return period (in years) and P the pending loan[1] at the beginning of the year.

Therefore, the annual payment consists on a loan payment and an interest payment defined below:

$$\text{Interest payment} = \text{Interest rate} \cdot \text{Pending loan}$$
$$\text{Loan payment} = \alpha \text{ - Interest payment}$$

The block diagram depicted in Fig. 3.6 show the relation between the previously introduced parameters.

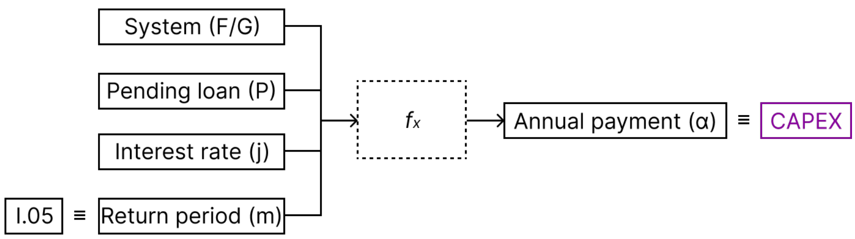


Figure 3.6: Workflow for CAPEX calculation.

Where F/G stands for French or German system. The return period is defined as input I.05 in Table 3.1 (planning horizon). As explained above, it can be seen in a graphical way how all parameters and conditions are consider inputs for a mathematical operation represented by f_x box[2], which will be used in later calculations, e.g., buffer cost.

It must be bear in mind that the return period of the loan[3] used as payment for the capital investment is set to ten years. Therefore, the prices shown in the tables of Chapter 4 are for the first ten years of operation. After this period, fleet capital investments are subtracted from the total costs, as its devolution period is completed.

[1] Corresponds to the ship price. Notice that it depends on the percentage of the total amount covered by the loan.

[2] Highlighted with dashed perimeter so that it can be identified when is applied in following processes.

[3] The loan is assumed to be the 80% of the fleet required CAPEX.

3.3.1.2 Sailing cost

Sailing costs are the major expenses in the transportation activity[4]. The main reason for this is the fuel consumption over the whole vessel life. As it can be found in the literature (Kjärstad et al., 2015, 2016; Knoope et al., 2015; Nilsson, 2014), the advantage of waterborne transportation of CO_2 is its low CAPEX comparing it to other options, but in the long term, considerably bigger OPEX must be faced. In order to estimate the mentioned fuel consumption for the wide range of vessels considered in this study, in terms of different capacities and velocities, the main engine and auxiliary engines powers are calculated by means of empirical formulas and adopting values for similar existing vessels. When it comes to the auxiliary engines power, the adoption of a valid value is based on the following considerations:

Liquid Natural Gas (LNG) vessels are excluded since cargo conditions when it comes to temperature are rather different to LCO_2. Liquid Petroleum Gas (LPG) carriers cargo conditions are similar, since it is transported in tanks integrated into the hull, as a tanker, therefore, is not consider a pressurised vessel as it is LCO_2 carriers, where CO_2 is transported into pressurised and refrigerated tanks. Finally, ethylene carriers are a similar options valid for the purpose when it comes to cargo transportation conditions.

Hence, an estimation of different fuel prices for the following next few years is adopted from Lagemann et al. (2023). An upper an lower bound are presented, as well as the Global Warming Potential (GWP) of each fuel in Well-to-Tank (WTT) and Tank-to-Wheel (TTW) phases. For this study only TTW GWP is considered and the average of the upper and lower bounds is selected for the calculations, thus, dealing with a margin of error of $\pm 50\%$ in the fuel cost. GWP is treated as a cost when considering the carbon taxes[5] that are applied to the amount of CO_2 emitted while sailing. The aim is to incentive consumers to carry out a transition towards greener energy sources and thus base its industrial processes in a sustainable way.

Carbon tax price depends on a wide range of parameters. For instance, when they are applied (i.e., current times or in next decades) since it follows an increasing price trend. Location is also of great importance, since different countries have different targets. Hence, the trend differ and so will the carbon price. An important differentiation must be done when it comes to the kind of economy that is involved. Advanced economies with net zero emissions target will have higher price on their carbon emissions than developing economies. Market and industrial sector are further characteristics to have into account. For instance, in the European Union, the EU ETS sets a price on carbon emissions from energy-intensive industries and power plants. The current price of carbon credits under the ETS is around 50 €/tCO_2 (European comission, 2022). In contrast, none of the states in United States has a carbon tax, although several states have implemented their own carbon pricing mechanisms (Carbon tax center, 2022).

Different carbon prices are tabulated in Tab. 3.7. Additionally, the values taken into consideration for fuel costs[6] and GWP can be seen listed in Tab. 3.8.

[4]Liquefaction costs is often the higher cost, nevertheless, this is consider outside the defined transportation activity, as it is a process carried out before the transport itself.

[5]Environmental tax that aims to reduce greenhouse gas emissions by putting a price on the carbon content of fossil fuels.

[6]Market effects are not accounted for.

Table 3.7: CO_2 tax [€/tCO_2] using a $ to € conversion factor of 0.91€/$. (Adopted from IEA, 2022).

Stated Policies Scenario	**2030**	**2040**	**2050**
Canada	49	56	70
Chile, Colombia	12	19	26
China	25	39	48
European Union	**82**	**89**	**103**
Korea	38	61	81
Announced pledges scenario			
Advanced economies with net zero emissions pledges	123	159	182
Emerging market and developing economies with net zero emissions pledges	36	100	146
Other emerging market and developing economies	-	15	43
Net zero emissions by 2050 scenario			
Advanced economies with net zero emissions pledges	127	187	228
Emerging market and developing economies with net zero emissions pledges	82	146	182
Other emerging market and developing economies	23	77	164

For this study, the selected carbon tax are the one highlighted in bold corresponding to European Union. To be on the safe side and accounting for fluctuations, the final value used for the carbon tax in this study is 95 $/t$CO_2$, which corresponds to 86 €/tCO_2.

The cost used from Tab 3.8 for building up the model can be found in the second, third and fourth column. As mentioned before, the TTW GWP is considered as a cost when the carbon tax is applied to it. Furthermore, the value taken for the estimation of the fuel cost due to its consumption while engines are running are set to the average between the upper and lower bound for each type of fuel.

Table 3.8: Fuels costs and GWP forecast. (Adopted from Lagemann et al., 2023).

Fuel	**GWP [gCO_{2eq}/kWh]**		**Bounds cost [USD/MWh]**	
	WTT	**TTW**	**Upper**	**Lower**
VLSFO	47.5	284.1	95	38
bio-Diesel	70	150	128	93
e-Diesel	0	4.5	423	131
LNG	66.6	238.8	81	32
bio-LNG	49.7	6	119	89
e-LNG	0	6	358	115
LPG	30	237.5	98.3	39.3
Methanol	112.7	253.4	210	90
bio-Methanol	112.68	3.24	97	66
e-Methanol	0	3.5	385	116
Ammonia	87.1	19	220	56
e-Ammonia	0	19	220	80
LH2	108.7	0	245	55
e-LH2	0	0	245	79

To particularise it to a specific case, the sailing costs are in terms of the distance between source and sink, Hence, depending on the speed, the sailing time and the docked time (loading and unloading) the sailing time differs and so it does the fuel consumption, since it is assumed that the main engine will not be operating while docked at harbour. It is assumed that electric power on board is achieved by means of shore grid, which means that auxiliary engines are also off during this time and therefore no fuel consumed by them either. This assumption is taken at the view of current and even tighten future restrictions when it comes to exhaust gas in areas near to population, where vessels cannot emit contaminants to the atmosphere, being the connection to shore grid the best solution. It shall be bear in mind that port fees would increase due to the energy consumption..

Figure 3.7 shows the process followed to calculate the total fuel costs or variable OPEX. Notice that fixed OPEX are adopted from literature, while, as explained before, the fuel cost is based on the estimated values for different fuels found in Lagemann et al. (2023).

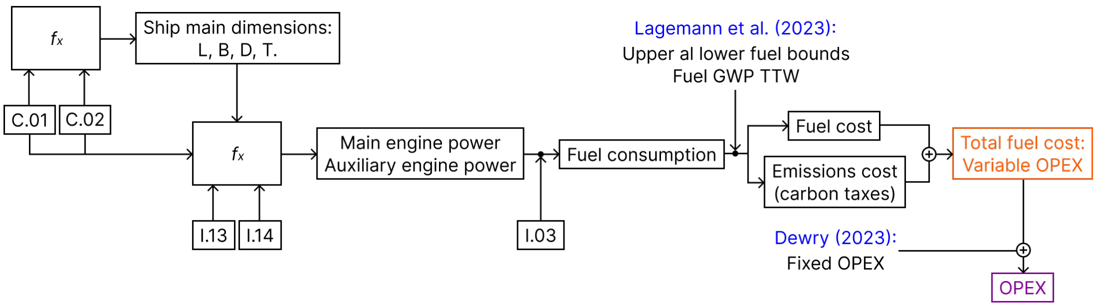


Figure 3.7: Depicted workflow of inputs, constraints, variables and steps to follow in order to calculate the OPEX.

Where C.01 and C.02 stands for constraints in vessel cargo capacity and speed respectively, I.03 represents the ship operational time and I.13 and I.14 are the inputs to account for the cargo transportation temperature and pressure. These parameters are defined in Tab. 3.1. Notice that *fx* box represents certain relation of operations and equations with respect to the inputs in order to achieve the desired output/variable.

It can be seen how all parameters are intertwined and at which stage of the process are they added into the equation. It can be observed that it mainly depends on vessel speed and cargo capacity (i.e., ship size) for which the hull forms are defined and thus the engine power and hence the fuel consumption.

3.3.2 Buffer storage cost

The buffer storage cost is composed by the investment cost (CAPEX) and operational cost (OPEX). The investment cost is proportional to the buffer storage capacity and, as indicated in Section 3.2, is 1.18 times the vessel capacity according to Bjerketvedt et al. (2020).

Figure 3.8 shows different buffer storage investment costs found in the literature review. All values are expressed in Euros per tonne of capacity of CO_2. When necessary, the following conversions have been used. 1 USD corresponds to 0.91 € and 1 £ corresponds to 1.14 € on Apr. 28th, 2023[7]. The data shown in Table 3.2 is used to convert from cubic metre to tonne of CO_2.

With regard to the most recent studies, Orchard et al. (2020) uses for the shipping model a cost of 1300 €/tCO_2 stored in the tanks for low pressure condition and 2770 €/tCO_2 for medium pressure condition. Whereas Roussanaly et al. (2021) considers 550 and 920 €/m^3 of CO_2 stored for the low and medium pressure shipping conditions, respectively. Additionally, Bennæs et al. (2022), based on the latter data, uses an investment cost of 478 €/tCO_2 for the low-pressure transport condition and 800 €/tCO_2 for the medium-pressure shipping condition.

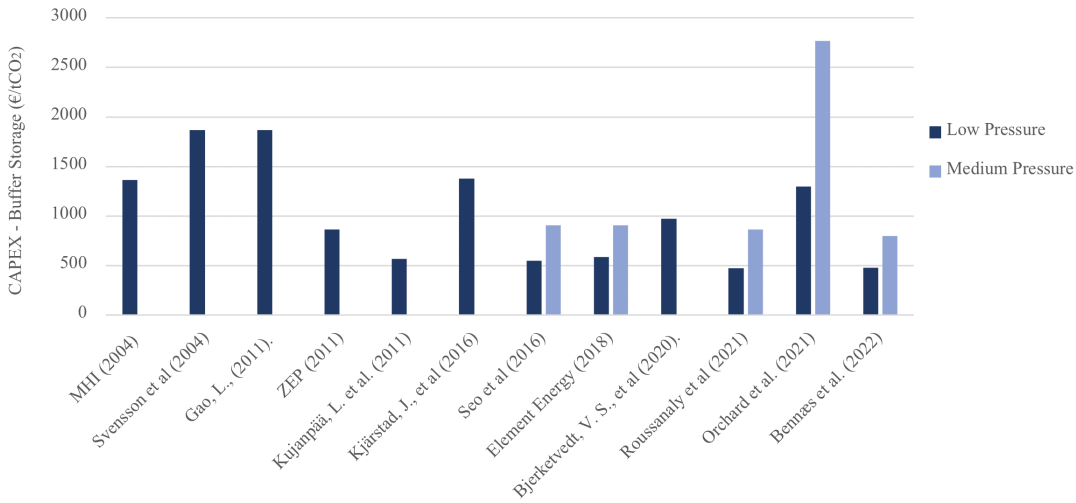


Figure 3.8: Buffer Storage Investment Cost from Literature Review.

For the transport model developed in this study, the CAPEX presented in Roussanaly et al. (2021) is used as it provides values for both the low pressure condition and the medium pressure condition. Additionally, the values are similar to other studies such as Element Energy (2018); Kujanpää, Rauramo, and Arasto (2011); Seo et al. (2016). Also, according to the literature review (Bennæs et al., 2022; Element Energy, 2018; Roussanaly et al., 2021), operational costs range between 5% and 6%. For the present study, the operational cost is set to 6% of the CAPEX. The values used in the shipping model can be seen in Table 3.9.

Table 3.9: Buffer storage cost assumptions used in the model

Transport CO_2 Condition	CAPEX	OPEX	Units
Low Pressure	485.44	6 %	€/tCO_2
Medium Pressure	882.92	6 %	€/tCO_2

As the planning horizon considered in the present work is one year, the model considers the CAPEX to be paid in the first year. This is calculated through the French Devolution System explained in Section 3.3.1.1 through Equation 3.7 with an interest (annual) rate of 8%, a loan percentage of 80% and a return time of 25 years.

[7] Assumed as fixed values for current time in this thesis.

Hence, the total buffer cost, C_B, is given by Equation 3.8 where C_{BO} is the operational cost of the buffer storage and C_{BCH} is the CAPEX cost in the planning horizon for the buffer storage.

$$C_B = C_{BCH} + C_{BO} \tag{3.8}$$

In Fig. 3.9 it can be seen the process followed to achieve the desired buffer cost. Notice that the dashed f_x box is the same method followed previously to calculate the annual CAPEX so that interest can be taken into account (see Fig. 3.6). Therefore, final buffer cost will be given in €m per year.

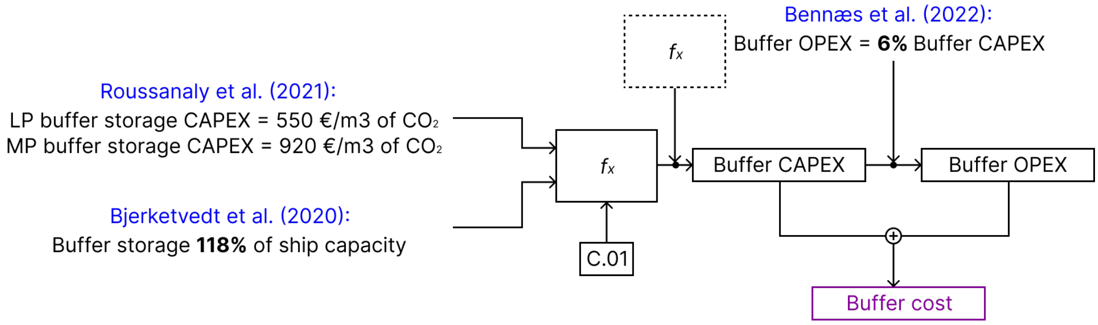


Figure 3.9: Workflow for buffer storage costs calculation

Where C.01 stands for the vessel cargo capacity, and the f_x dashed box represents the operations to calculate the annuities of the total cost accounting with the interest rate, as explained in Section 3.3.1.1.

3.3.3 Liquefaction and reconditioning process cost

It must be remarked that the cost methodology followed for the estimation of the liquefaction and reconditioning cost is the same. Nevertheless, as it is presented in the following sections, the inputs are different.

3.3.3.1 Liquefaction process cost

As mentioned before, the liquefaction process takes place in the carbon capture facility, therefore, there is a liquefaction cost for each emitter depending on the amount of sequestrated CO_2.

The CO_2 liquefaction cost considered in this study is based on Deng et al. (2019) and Roussanaly et al. (2021), which use a bottom-up approach to calculate the cost of liquefying 1 $MtCO_2$/year. As this study only considers pure CO_2, only data from the mentioned studies pertinent to pure CO_2 is taken into consideration. These costs are scaled to the capacities under consideration in this study as follows. The CAPEX is scaled using the cost power law shown in Equation 3.9.

$$C = C_0 \cdot \left(\frac{S}{S_0}\right)^n \tag{3.9}$$

Where:

- C is the CAPEX of the capacity under consideration [€m].
- C_0 is the CAPEX for the reference capacity (Deng et al., 2019) [€m].
- S is the capacity under consideration [$MtCO_2/y$].
- S_0 is the reference capacity (Deng et al., 2019) [$MtCO_2/y$].
- n is the scaling exponent, which is considered equal to 0.85 according to Roussanaly et al. (2021).

Deng et al. (2019) assesses the Direct Cost (DC) of each component of the liquefaction process being the Total Direct Cost (TDC) the sum of all direct costs. Then, a 15% of process contingencies is added to the total direct cost. Additionally, indirect costs accounts for 14%, owner costs accounts for 7% and project contingencies accounts for 20% of the sum of process contingencies and total direct cost, resulting in the Total Plant Cost (TPC). This total plant cost is calculated for both pressure conditions and are used as a reference CAPEX in Equation 3.9 in the model. The reference CAPEX costs can be seen in Table 3.10

Table 3.10: Reference Investment Costs for liquefaction process presented in €m.

CO_2 Transport Condition	Total Direct Cost (TDC)	Total Plant Cost (TPC)
Low Pressure	25.50	41.35
Medium Pressure	23.90	38.75

The investment cost obtained from the scaling is annualised using the French method presented in Section 3.3.1.1 through Equation 3.7 with a return time of 25 years and an interest rate of 8%.

Moreover, the fixed operational costs are set to 6% of the investment costs according to Bennæs et al. (2022); Deng et al. (2019); Roussanaly et al. (2021) and includes maintenance, insurance and labour costs and replacement of materials. Finally, the variable operational cost refers to electricity and cooling water, i.e. consumption of utilities, which depends on the energy consumption and are subject to electricity prices. Different studies (Bennæs et al., 2022; Deng et al., 2019; Roussanaly et al., 2021) use a electricity cost of 80 €/MWh, however, in recent years electricity prices have risen. Therefore, the average price recorded in European Union in 2022 has been chosen in line with Eurostat (2023), with a value of 179.5 €/MWh. Nonetheless, cooling water price is assume the same as Deng et al. (2019) with a value of 0.5 €m/tCO_2 and 0.6 €m/tCO_2 for low pressure and medium pressure condition, respectively. The consumption of utilities and the total variable operational cost used as a reference for both pressure conditions can be seen in Table 3.11. The variable OPEX is scaled linearly with the flow rate.

Table 3.11: Variable operational cost used as reference value for liquefaction process.

CO_2 Transport Condition	Electricity [kWh/tCO_2]	Electricity [€m/tCO_2]	Cooling Water [€m/tCO_2]	Total Variable OPEX [€m/tCO_2]
Low Pressure	96.30	17.29	0.5	17.79
Medium Pressure	90.40	16.23	0.6	16.83

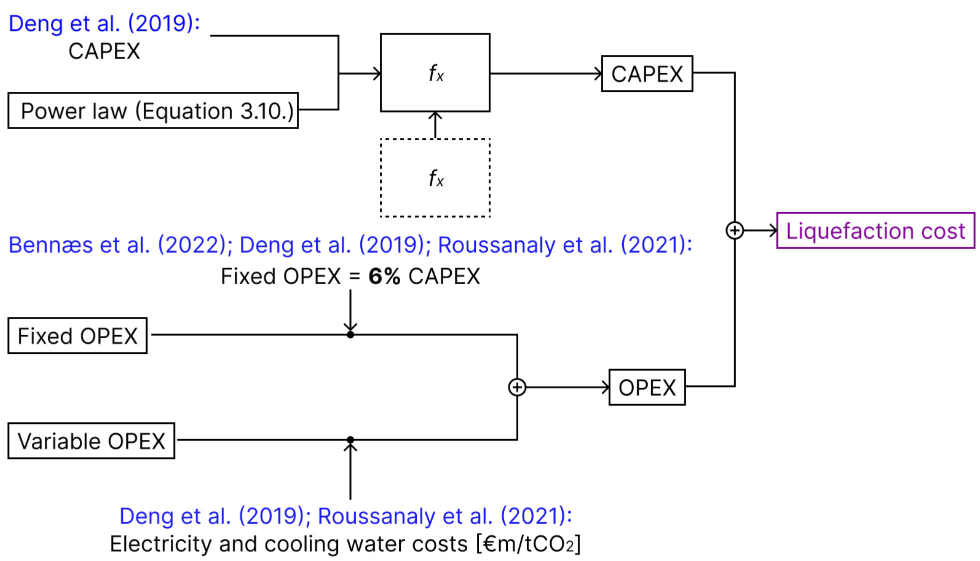


Figure 3.10: Workflow for liquefaction costs calculation

Where f_x dashed box is used to calculate, as in previous sections, the annual cost of the total expenses. Note that the consumption utilities of the liquefaction process vary significantly depending on the condition of the CO_2 prior to the liquefaction process.

As mentioned, the liquefaction process takes place after the CO_2 capture in the emitter facility and as shown in Table 1.1, the CO_2 condition after capture is 1 barg and 20°C. Therefore the values shown in Table 3.11 correspond to the consumption of conditioning the CO_2 from that condition to the desired transport condition. In the case that the CO_2 is liquefied at the port and arrives by means of pipelines from inland emitters in which the CO_2 is pressurised when it arrives to the liquefaction facility, the electricity consumption is lower. Bennæs et al. (2022) considers this situation and estimates an electricity consumption of 20 kWh/tCO_2 and 11.25 kWh/tCO_2 for liquefaction into 7 and 15 bar, respectively.

Finally, the total liquefaction cost (C_L) is given by Equation 3.11:

$$C_L = C_{LC} + C_{LFO} + C_{LVO} \tag{3.10}$$

Where

- C_{LC} is the CO_2 liquefaction investment cost,
- C_{LFO} is the CO_2 liquefaction fixed operating cost,
- C_{LVO} is the CO_2 liquefaction variable operating cost.

3.3.3.2 Reconditioning process cost

The LCO_2 after ship transportation and storage in the discharge port needs to be heated and compressed or pumped to a higher pressure (Orchard et al., 2020) to the necessary conditions for pipeline injection into the final storage under the sea bed. As shown in Table 1.1 it is assumed that the CO_2 condition before injection to the final storage is 100 barg and 5° (Orchard et al., 2020).

The cost methodology adopted for the calculation of CO_2 reconditioning process is the same as for the liquefaction process. The investment costs has been scaled though Equation 3.9 from the reference values expose in Orchard et al. (2020) in which a techno-economic study to transport CO_2 by ship is carried out for four different scenarios. For this study, data from scenarios 1 and 2 are used, which correspond to transport by ship between two ports at low and medium pressure. The flow rate of the study is 1.80 $MtCO_2/y$ for low pressure transportation and 1.76 $MtCO_2/y$ for medium pressure transport condition. Acording to Orchard et al. (2020) reconditioning the CO_2 from low pressure to the desired conditions 4.21 €/tCO_2 and from medium pressure 4.10 €/tCO_2. The reference values used for scaling the investment cost for the reconditioning process can be seen in Table 3.12.

Table 3.12: Reference investment costs for reconditioning process

CO_2 Transport Condition	Investment Cost [€m]
Low Pressure	7.58
Medium Pressure	7.22

The investment cost obtained from the scaling is annualised using the French method presented in Section 3.3.1.1 through Equation 3.7 with a return time of 25 years and an interest rate of 8% (Bjerketvedt et al., 2020).

Furthermore, the fixed CO_2 reconditioning OPEX cost is set to 11% of the CAPEX (Orchard et al., 2020), while the variable OPEX depends on the energy consumption. According to the same study, the energy consumption is 2.53 kWh/tCO_2 to condition CO_2 from low pressure into the desired conditions and and 2.30 kWh/tCO_2 from medium pressure. The electricity price is the same as that used for the liquefaction process. Additionally, the variable operational costs are scaled with the flow rate. Table 3.13 shows the reference values used.

Table 3.13: Variable operational costs used as a reference value for reconditioning process.

CO_2 Transport Condition	Variable OPEX [kwh/tCO_2]	Variable OPEX [€/tCO_2]
Low Pressure	2.53	0.45
Medium Pressure	2.30	0.41

Finally, the total reconditioning cost (C_R) is given by Equation 3.11:

$$C_R = C_{RC} + C_{RFO} + C_{RVO} \tag{3.11}$$

Where

- C_{RC} is the CO_2 reconditioning investment cost,
- C_{RFO} is the CO_2 reconditioning fixed operating cost,
- C_{RVO} is the CO_2 reconditioning variable operating cost.

The total cost of the CCS shipping chain is given by Equation 3.12. Being the first term the buffer storage cost, the second and the third terms the ship or fleet cost and the forth and five terms the reconditioning and liquefaction costs, respectively.

$$C_T = C_B + C_H \cdot x_i + C_S \cdot x_i + C_R + C_L \tag{3.12}$$

Following the same procedures as in previous sections, a workflow chart is presented in order to explain the relation between all inputs required for the calculation of the reconditioning cost. Figure 3.11 show this by means of a simplified block diagram:

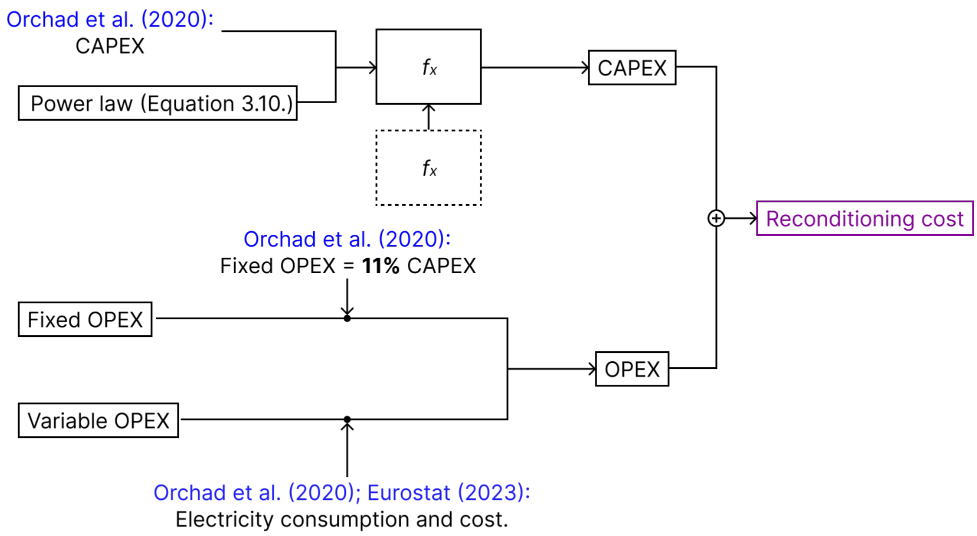


Figure 3.11: Workflow for reconditioning costs calculation

Similarly to Section 3.3.2, the approach to implement the annual CAPEX is one more time represented by the dashed f_x box (see details in Fig. 3.6). As it can be seen the reconditioning depends in two main inputs: Amount of CO_2 to be transported and the CAPEX for the reconditioning. Furthermore, the relation between reconditioning CAPEX and OPEX is found in literature and applied to this study. Finally, total reconditioning cost is the summation of capital and operational expenses.

4

Results

In this chapter the model is applied to specific scenarios to evaluate its results and analysed the information it can be reached by implementing it. Validation of the model is presented and discuss it. Moreover, results for all the specific cases under consideration are shown and discussed.

4.1 Validation

The validation of certain approach, model or result is of major importance in a research study in order to consider it acceptable. To validate the results that the developed model retrieve, the results must be verified. This is achieved by comparing the current study results with literature. The effectiveness in addressing the research questions introduced in chapter 1 reached by the model results is discussed. Therefore, the aim is to provide a comprehensive evaluation of our model.

Table 4.1 compare the results achieved by Bennæs et al. (2022) and the current study (denoted as c.s.):

Table 4.1: Validation of the results by comparison

Loading port	**CO_2 amount**	**Sailing distance**	**Cargo capacity [kt]**		**No. of ships**		**No. of roundtrips**		**Sailing speed**	
	[Mt]	[km]	Bennæs	**c.s.**	Bennæs	**c.s.**	Bennæs	**c.s.**	Bennæs	**c.s.**
2025 Scenario										
Antwerp	-	-	-	-	-	-	-	-	-	-
Dunkirk	3.00	1137.1	45	45	1	1	66.67	66.67	10.96	14
Rotterdam	3.95	1037.1	50	50	1	1	79.00	79.00	12.29	16
Wilhelmshaven	1.35	853.7	15	20	1	1	91.48	67.50	12.46	10
2030 Scenario										
Antwerp	8.7	1153.8	45	45	3	3	193.00	193.33	10	14
Dunkirk	5.0	1137.1	40	40	2	2	125.00	125.00	10	14
Rotterdam	50.3	1037.1	50	50	15	14	1006.00	1006.00	10	14
Wilhelmshaven	14.3	853.7	45	45	4	4	317.78	317.78	10.12	14
2050 Scenario										
Antwerp	45.5	1153.8	50	50	14	13	910.00	910	10.11	14
Dunkirk	10.0	1137.1	50	50	3	3	200.00	200.00	10.96	14
Rotterdam	261.3	1037.1	50	50	76	69	5226.00	5226.00	10.07	14
Wilhelmshaven	72.4	853.7	50	50	18	17	1448.00	1448.00	10.35	14

At the view of the results, it can be concluded that the model retrieve valid results, since the obtained numbers are highly similar to results found in literature. Certain differences are due to the different assumptions taken i.e., port entry and exit time, loading and unloading time (depending in the pumps flow rate), available time of vessel per year (off-time due to maintenance), etc.

Locations outside Sweden are selected only for validation purposes. Nevertheless, it shall be notice that the model main inputs are, as mentioned before, amount of CO_2 to be transported and sailing distance. Therefore, it can be used any where on the globe by just using this two inputs.

4.2 General

As it is explained in previous chapters, results are directly related to the amount of CO_2 to be transported and the distance to cover. Therefore, different scenarios are under study.

Thus, it shall be known where the sources and receivers are, as well as the amount of CO_2 that it is gathered. To do so, a previous study of emitters and sinks locations is carried out. In this study, only one final storage is considered, which it is found in Kollsnes, Norway. The location of potential hubs are based on the known existing CCS projects within Sweden, which are shown in Fig. 4.1. More detailed information regarding CCS projects within Sweden can be seen in Appendix A.

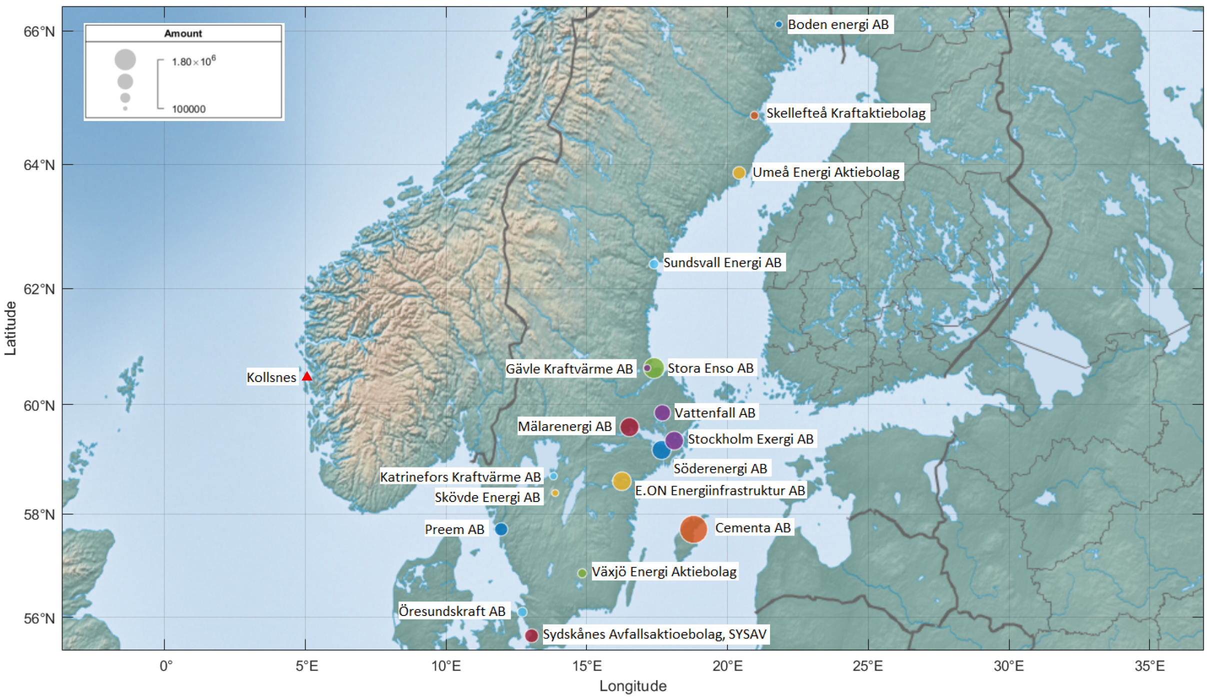


Figure 4.1: CCS projects in Sweden. Data data provided by IVL and Energimyndighetens (2022).

Therefore, the location of the hubs should be chosen in such a way that it can be gather as much CO_2 as possible reducing the costs (investment in new infrastructure, logistic transport chain, etc) of centralising it in these hubs. At the view of the results, it is decided to set 2 main hubs:

- Gothenburg: It is the second biggest city in Sweden, many industry nearby and its unique location in the west cost makes it a suitable spot.
- Nynäshamn/Oxelösund: Largest CO_2 emissions are around Stockholm. Nevertheless, it is considered some challenges to overcome in terms of marine traffic and

vessel size restriction within the archipelago. Furthermore, restrictions in manoeuvrability and speed are a big drawback since it will take more time than in open sea. Therefore, a hub outside the archipelago is considered.

The validation of these selected locations can be found by comparing the potential transport hubs considered in Karlsson et al. (2023).

It is worth of mention that, according to literature, this new market it is foreseen to follow a growing rate, as different companies, industries and public infrastructure must adapt to cope with future national and international emissions regulations in order to be able to maintain their normal industrial activity. Therefore, based on Karlsson et al. (2023) the selected hubs (Gothenburg and Nynäshamn) can be considered a valid selection from both present and future perspective. Scenarios for 2030 and 2045 are shown in Fig. 4.2.

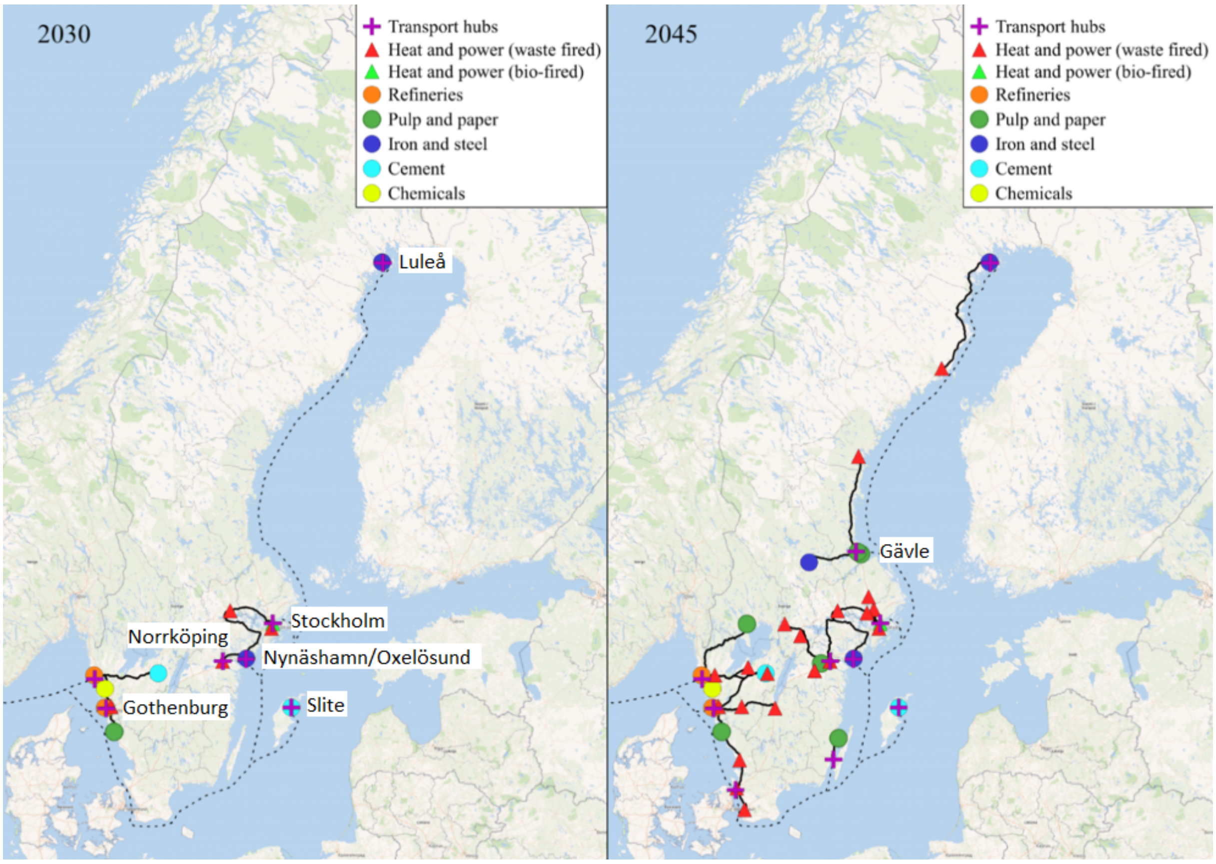


Figure 4.2: Potential hubs. (Adopted from Karlsson et al., 2023).

Often there are different possible options to solve certain situation. The optimal solution requires to know which case is the most cost-efficient. Hence, the model is tested to confirm its practicality in a real case giving an answer to this question by means of the scenarios presented in Tab. 4.2 below.

Table 4.2: Studied scenarios

Scenario	Source	Intermediate stop	Sink
1	Gothenburg	-	Kollsnes
2	Stockholm	-	Kollsnes
	Västerås	-	Kollsnes
	Södertälje	-	Kollsnes
3	Stockholm Västerås Södertälje	Nynäshamn (hub)	Kollsnes

The selected scenarios are carefully chosen in order to be able to cover the widest possible range of possibilities. By means of these specific situations, several valuable comparisons and results can be shown in following sections. For instance, whether is more cost-efficient or not to join a cluster in order to use an intermediate storage, also known as hub, and how the total costs of the operation for an specific case could change. Moreover, it can be thus seen what other advantages could be triggered by this decision, e.g., smaller ship size (which, as explained in Chapter 3 means less CAPEX), more versatile fleet, etc. The answer to this question is provided in a case-by-case basis.

4.3 Scenarios prerequisites

Before show the applicability of the model in the propose scenarios, is of major importance to highlight that in some of the following scenarios, results with and without vessel size limitation are shown. These are the cases where it is considered that an improvement of the ports involved can be driven in the near future regarding the maximum ships size allowances. The optimum fleet differ from each other when applying such constraint. The purpose of showing both scenarios, is to compare how much could the process be optimised economically if investment in the infrastructure of the ports is made in order to be able to receive bigger vessels.

Additionally, it must be emphasised that, currently, costs with port limitation are more approximate to reality, as such large ships are yet to be proven to be technologically feasible. Hence, vessel size will be within the range of 2,500 to 12,500 tonnes of cargo capacity for the near future. Cases without port limitation, can be considered as absolute optimums or as a benchmark to guide what it will be needed in terms of port infrastructure in the next following years.

Furthermore, for Scenario 2 (Section 4.5) and Scenario 3 (Section 4.6), see Tab. 4.2, the comparison with and without vessel size limitation is only applied for Stockholm case. For the other two emitters considered, these constraints are a consequence of restrictions along the sailing routes[1], and thus, maximum length, beam and/or draft are defined by a geographical boundary, which, in this study, it is considered as permanent over time, i.e., no development can be achieved to be able to handle bigger ships, as it can be assumed

[1]Within Mälaren lake and along Södertälje channel.

for port infrastructures.

Note that distances for each required route considered in the further below discussed scenarios are given by Searoutes (2023). Such scenarios cover all kind of possible situations that can be found:

- Straight journey from emitter to receiver dealing with big volumes of CO_2 to be transported considering with and without vessel size limitations (Scenario 1).
- Straight journey from emitter to receiver dealing with small volumes of CO_2 to be transported considering with and without vessel size limitations (Scenario 2).
- Emitters gathering their respective CO_2 volumes in a hub by means of smaller shuttle ships and considering a bigger vessel to transport the total amount from the hub to the receiver (Scenario 3).

Similarly, required calculations for other specific cases to the ones presented are achieved by changing the main inputs to the model known as the CO_2 amount to be transported and the distance between ends.

It must me taken into account that the main particulars for the vessels are calculated according to empirical formulas with respect to ship Deadweight Tonnage (DWT) and speed according to (*Empirical ship formula*, 2023). Therefore, in the following scenarios when calculating the fleet arrangement when vessel size limitations are applied, the solution is directly linked to these forms. In a sensitivity study could be researched in detail the optimum ships size for an specific situation, as it can be optimised by, for instance, increasing the beam to save some meters in the draft and thus be able to sail through a more straightforward route with a bigger cargo capacity vessel in order to reach a more cost-efficient solution. This analysis is not conducted in this thesis as it is found outside the scope boundaries.

It shall be reminded that maximum cargo capacity for medium pressure vessels considered in this thesis are 10,000 according to the information presented in Section 3.2.3. Therefore, it could be assumed that in future years, if bigger medium pressure LCO_2 carriers are available in the market, the optimum solution could differ to the one reached in the following scenarios, being this a greater cargo capacity vessel option.

Additionally, note that liquefaction cost breakdown and costs related to the used fuel are only shown and explained in Scenario 1 as for Scenario 2 and Scenario 3 it follows the same procedure as the explained in the first case. Additionally, the results follow the same trend and are of the same order of magnitude to those found in Scenario 1.

Finally, it must be recalled the already introduced assumption in Section 3.3.1.1, in which it is stated that the fleet capital expenditures return period is set to ten years. Hence, the results shown in the following described scenarios (Sections 4.4 to 4.6) are the total annual costs during the first ten years. After this period, the total cost differ, as the fleet CAPEX is not considered, since the loan devolution is completed.

Vessel size limitation for every port under consideration can be seen in Tab.4.3:

Table 4.3: Vessel size limitations for considered ports

Location	Main dimension [m]	
	L ≤	T ≤
Kollsnes	130	8.5
Gothenburg	321	19.9
Stockholm	200	11
Västeras	125	6.8
Södertälje	200	6.8
Nynäshamn	326	12.8

4.4 Scenario 1

A common interest within Swedish industry is to know the cost to arrange a marine logistic chain between Gothenburg and Kollsnes. Main reason lies in its optimal location in the west coast of Sweden, allowing to reduce sailing distance considerably as well as avoiding the potential vessel limitations in terms of size and emissions as it has straightforward access to open sea. Therefore, this case is to study, for an assumed CO_2 amount, a potential situation in which several emitters could use Gothenburg as a main hub prior to shipping theirs emissions to the receiver. Notice that such CO_2 could arrive to Gothenburg either by sea or by land since industries located far from the coast could also be considered. Figure 4.3 shows the route from Gothenburg to Kollsnes and has a distance of 386 nautical miles which is equivalent to 715 km.

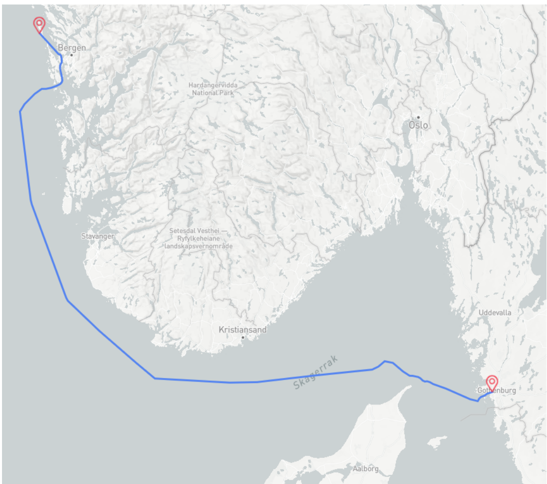


Figure 4.3: Route: Gothenburg - Kollsnes. (Adopted from Searoutes, 2023).

There is an ongoing CCS project in Gothenburg called CinfraCap (Nordion Energi, 2022) which studies a large-scale CO_2 hub in the Port of Gothenburg. For this scenario it is assumed that all CO_2 is liquefied at the same site and 1.865 million tons of CO_2 per year will be transported, according to Energimyndighetens (2022). Table 4.4 shows the most cost-efficient option for this case for both low pressure and medium pressure transport option with and without vessel size limitation. Moreover, Fig. 4.4 show the cost breakdown for both transport condition. Notice that, the fleet cost shown in Fig.4.4

and Table 4.4 for both transport conditions is calculated on the assumption that the vessel operates on VSLFO.

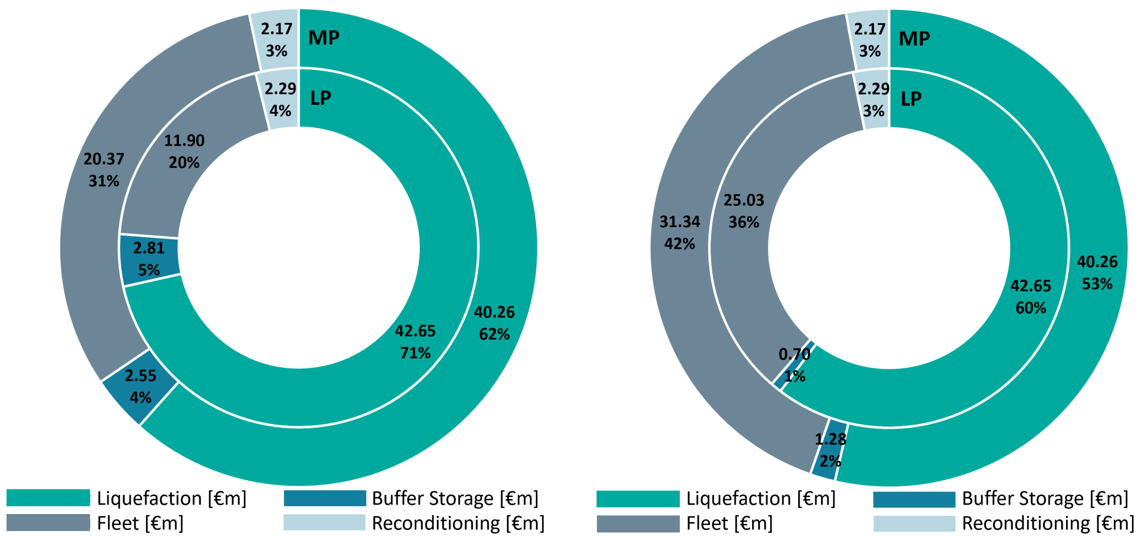
Table 4.4: Fleet costs and logistics Gothenburg - Kollsnes

Scenario 1	**Gothenburg - Kollsnes**			
Input				
Flow rate [tCO2/y]	1,865,000			
Distance [km]	715			
Type of fuel	VLSFO			
Vessel size limitations	Kollsnes: L $\leq$ 130 m, T $\leq$ 8.5 m			
	Not considered		**Considered**	
Output	**LP**	**MP**	**LP**	**MP**
Ship cargo capacity [t]	20,000	10,000	5,000	5,000
Speed [kn]	14	14	14	14
No. of ships	1	2	4	4
Total time roundtrip [h]	85	85	85	85
Fleet total roundtrips	93	187	373	373
Cost [€m]	**LP**	**MP**	**LP**	**MP**
Liquefaction	42.65	40.26	42.65	40.26
Buffer storage	2.81	2.55	0.70	1.28
Fleet	11.90	20.37	25.03	31.34
Reconditioning	2.29	2.17	2.29	2.17
Total	59.65	65.36	70.67	75.06

Table 4.4 show the fleet costs and logistics taken into account a vessel size limitation and without it. This limitation arises from the most restrictive admissible ship size in both ports, which in this case is found in Kollsnes, with a maximum length of 130 meters and a draft of 8.5 meters.

Without vessel size limitation the optimum ship cargo capacity are 20,000 and 10,000 tonnes for low and medium pressure respectively, and, as expected, when constraints in size are applied, the optimum ship cargo capacity is reduced to 5,000 tonnes for both pressures. In the later case, the total cost of the logistic operation increase considerably, i.e., 18.5% for low pressure and 14.8% for medium pressure. This arise from the requirement of using a suitable vessel for the designated ports. Hence, by investing in harbour infrastructure[2] to increase the ship size threshold, 11.02 €m and 9.7 €m can be saved for low and medium pressure annually.

[2]How much such investment could cost are not considered in this thesis, as it is outside the defined scope.



(a) Without vessel size limitation. **(b)** With vessel size limitation.

Figure 4.4: Gothenburg - Kollsens breakdown of total cost.

In both transport conditions, the main cost is the liquefaction process, which accounts for a large percentage of the entire CCS chain considered with a percentage of 71% and 62% for low pressure and medium pressure condition, respectively when vessel size limitation is disregarded. Applying ship size constraints, the percentage for liquefaction respect to the total cost decrease to 60% and 53% for low and medium pressure respectively. This is due to the higher fleet cost, mainly caused by the greater number of required ships, when the size limitation is consider, as smaller vessels are chosen in order to comply with the maximum L and T, and, therefore, increasing both, capital and operational expenses.

While the fleet cost is divided in CAPEX and OPEX of the industrial activity of the shipping transport activity (explained in detail previously in Section 3.3), in Fig.4.5 is depicted the breakdown for the biggest cost of the logistic chain: Liquefaction.

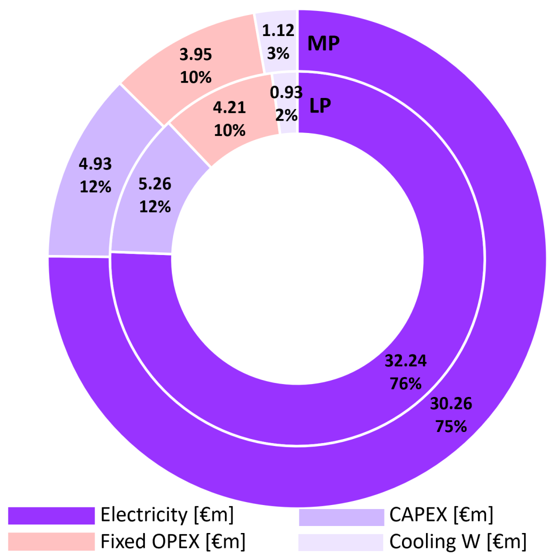
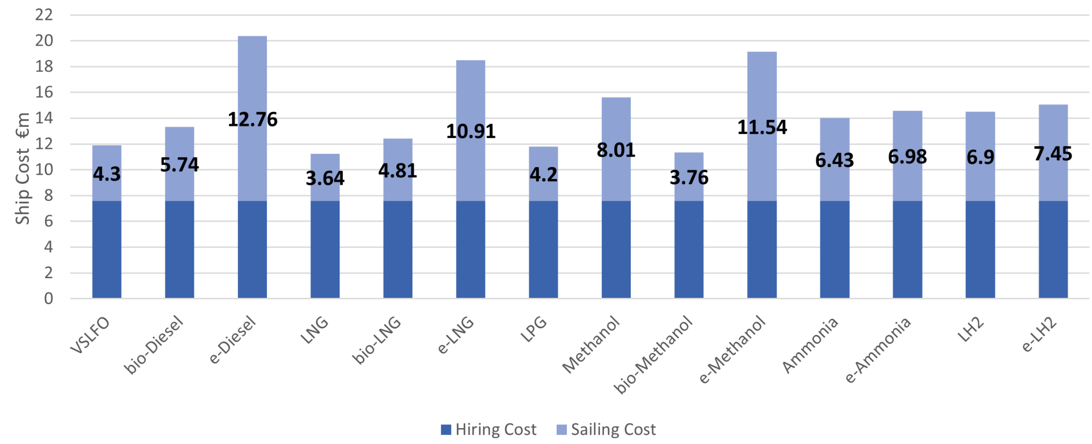


Figure 4.5: Gothenburg - Kollsnes breakdown liquefaction cost.

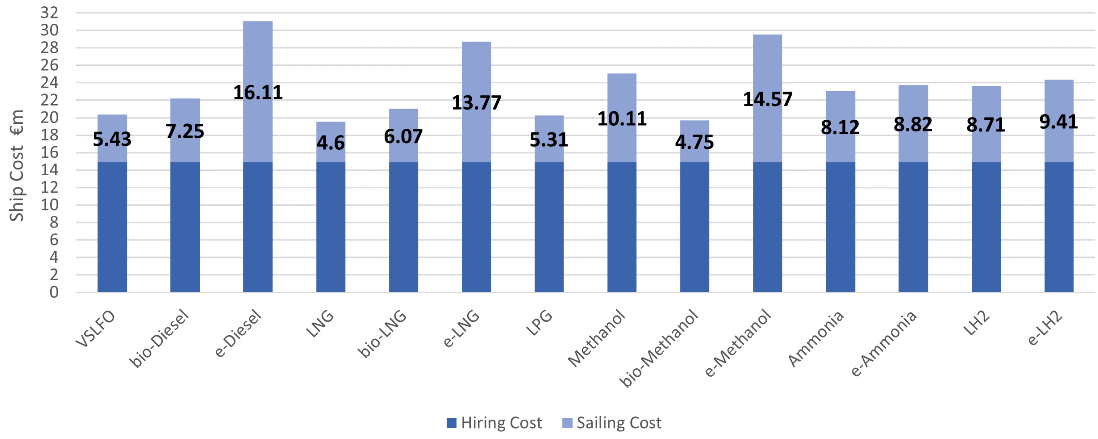
The major cost of liquefaction is due to its close dependency on the electricity price, which, as mentioned in Section 3.3.3, has been assumed to be 179.50 €/MWh compared to 80 €/MWh found in the literature. CAPEX cost is associated with the initial investment of the required infrastructure. Fixed OPEX is the cost caused by the required means to maintain the unit in operational conditions. Finally, the cooling water cost is determined by the total amount of cubic metres required. Therefore, liquefaction price is strongly linked to electricity price fluctuations.

As explained in Section 3.3.1 and as it can be seen in Equation 3.12, ship cost is the sum of hiring and sailing costs. The hiring costs depend on the investment fleet cost as well as on the fixed operational costs. The sailing costs depend on the fuel consumption and thus on the fuel used. And both are shown in Fig.4.6.

For this scenario, despite VLSFO is chosen as fuel for the fleet costs and logistic calculations, Fig.4.6 presents the hiring costs and sailing costs in €m for every fuel under consideration in this thesis.



(a) Low Pressure condition



(b) Medium Pressure condition

Figure 4.6: Gothenburg - Kollsnes breakdown of ship cost by fuel type.

The hiring cost remains constant as it does not depend on the fuel used, whereas the sailing costs varies. The hiring costs for VLSFO are 7.60 €m and 14.94 €m for low pressure and medium pressure condition, respectively. While the sailing cost of every fuel can be seen in Fig. 4.6. LNG is the most economical fuel and e-Diesel the most costly, for both pressure transport conditions. It must be mentioned the fact that the fuel cost is linked to carbon tax prices, which will increase in the future. Hence, it shall be expected the raise of price for fuels that emit CO_2, while the non-carbon based fuels will remain the same or even decrease their costs when infrastructure for handling such fuels reach a more mature level in the following years.

Notice that, as explained in Section 3.3.1.2, fuel costs are linked to a margin or error, as the selected value for the calculations in this research is the average cost between the upper and lower bounds.

4.5 Scenario 2

For this scenario, it is assumed that each of the considered emitters, despite their vicinity, have their own fleet sailing the required route from the source to the receiver port in Kollsnes. The annual flow rates of each emitter are based on Energimyndighetens (2022) and can be seen in Table 4.5. The main purpose of this analysis is to run a comparison between this situation and the scenario in which these emitters gather their emissions in a common hub (Section 4.6)

Table 4.5: Scenario 2: Emitter's flow rate.

Emitter (location)	**Flow rate [tCO_2/y]**
Stockholm Exergi AB (Stockholm)	800,000
Mälerenergi AB (Västerås)	820,000
Söderenergi AB (Södertälje)	835,000

Clarification about each emitter particular situation and boundaries must be presented. As in any other case, all of them present a size limitation of the vessels willing to docked due to their port infrastructure. Nevertheless, it shall be taken into account the geographical location in which these industries are located. Lake Mälaren forces a restriction on the size of vessels sailing along it, which in most cases is more restrictive than the constraints imposed by the harbours found on the lake. Similarly, this applies to the Södertälje channel.

As mentioned in page 45, there is a comparative study with and without vessel size restrictions only for the Stockholm case. For Västerås and Södertälje, due to the geographical boundaries (not provoked by port infrastructure) such comparison is not carried out, as its improvement is not considered.

Table 4.6 shows the values obtained by means of the model for the first emitter located in Stockholm, which flow rate is set to 800,000 tCO_2 (Stockholm Exergi, 2023) and the distance to Kollsnes for vessels with draft above[3] 6.5 meters is 2115 km (Searoutes, 2023) (see Fig.4.7).

[3]For ships with smaller draft an alternative route can be taken through Södertälje channel

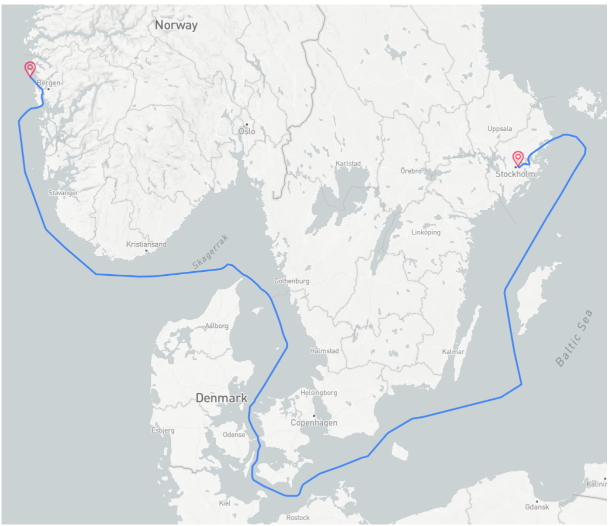


Figure 4.7: Route: Stockholm - Kollsnes. (Adopted from Searoutes, 2023).

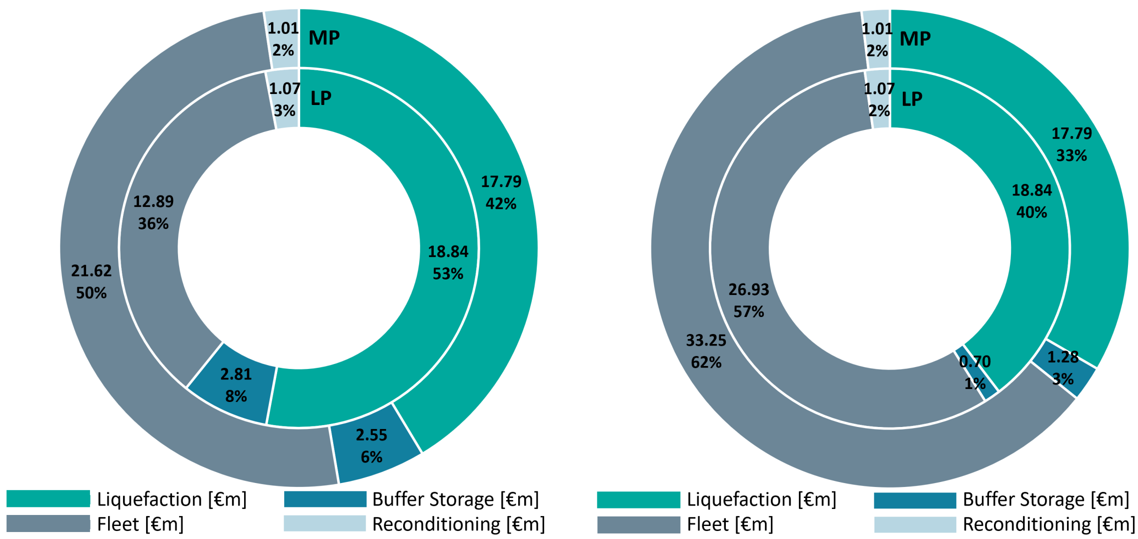
4.5.1 Stockholm - Kollsnes

Similarly to previous case (Scenario 1), results for the fleet cost and logistics are tabulated in Tab.4.6 and, as explained, with and without vessel size limitation, where the most restrictive dimensions at this time are found in Kollsnes.

Table 4.6: Fleet costs and logistics Stockholm - Kollsnes

Scenario 2	**Stockholm - Kollsnes**			
Input				
Flow rate [tCO2/y]	800,000			
Distance [km]	2115			
Type of fuel	VLSFO			
Vessel size limitation	Kollsnes: L ≤ 130 m, T ≤ 8.5 m			
	Not considered		**Considered**	
Output	**LP**	**MP**	**LP**	**MP**
Ship cargo capacity [t]	20,000	10,000	5,000	5,000
Speed [kn]	14	14	14	14
No. of ships	1	2	4	4
Total time roundtrip [h]	193	193	193	193
Fleet total roundtrips	40	80	160	160
Cost [€m]	LP	MP	LP	MP
Liquefaction	18.84	17.79	18.84	17.79
Buffer storage	2.81	2.55	0.70	1.28
Fleet	12.89	21.62	26.93	33.25
Reconditioning	1.07	1.01	1.07	1.01
Total	35.61	42.98	47.55	53.32

Results are similar to those find in Scenario 1, Tab.4.4, without constraints optimum solution are one vessel of 20,000 t cargo capactiy at 14 kn for low pressure and 2 vessels of 10,000 tonnes at 14 kn. Buffer storage cost decrease when vessel size limitation is applied, since smaller carriers are used, and thus, smaller storage volumes are needed. Nevertheless, as it can be seen, liquefaction and reconditioning remain unchange, as this is linked to the amount of CO_2 to be transported regardless of the fleet arrangement. Total costs increase in this scenario a value of 33.5% and 24% for low and medium pressure respectively. These higher growths compare to Scenario 1 are due to the longer sailing distance.



(a) Without vessel size limitation. **(b)** With vessel size limitation.

Figure 4.8: Stockholm - Kollsnes breakdown total cost.

4.5.2 Västerås - Kollsnes

The route for the current case it can be seen in Fig.4.9. Such route is bound to the draft restriction of 6.8 m due to inner waters sailing in Västerås are previously mentioned in Section 4.3. It also can be highlighted an advantage of this constraint in vessel size, since considering such draft limitation, the Södertälje channel can be used reducing in this way the distance from the emitter to the receiver port in Kollsnes.

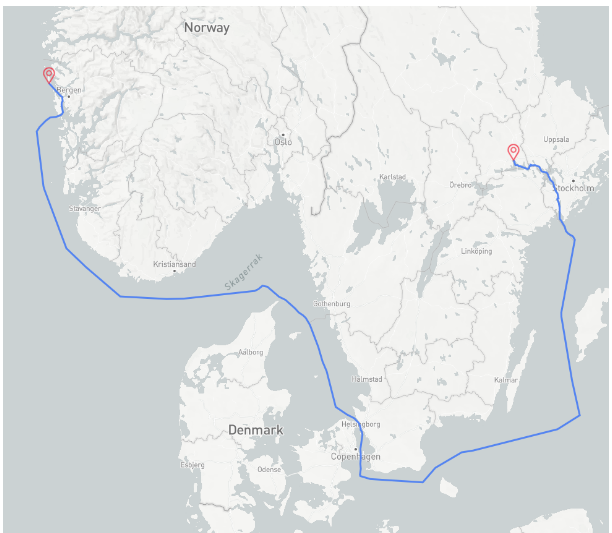


Figure 4.9: Route: Västerås - Kollsnes. (Adopted from Searoutes, 2023).

Following the same procedure followed in the previous cases, the optimum solution for the fleet logistic and its associated costs are shown in Tab.4.7. Note that only results accounting for vessel size limitation is presented, following the argument previously explained in Section 4.3. The most restrictive limitations are found in Västerås area, where maximum vessel length ever registered to have entered the port is 125 m (MarineTraffic, 2023).

Table 4.7: Fleet costs and logistics Västerås - Kollsnes

Scenario 2	**Västerås - Kollsnes**	
Input		
Flow rate [tCO_2/y]	820,000	
Distance [km]	1780	
Type of fuel	VLSFO	
Vessel size limitation	Västerås: L $\leq$ 125 m, T $\leq$ 6.8 m	
	Considered	
Output	**LP**	**MP**
Ship cargo capacity [t]	2,500	2,500
Speed [kn]	16	16
No. of ships	6	6
Total time roundtrip [h]	150	150
Fleet total roundtrips	328	328
Cost [€m]	**LP**	**MP**
Liquefaction	19.30	18.22
Buffer storage	0.35	0.64
Fleet	30.96	38.62
Reconditioning	1.09	1.04
Total	51.70	58.52

Table 4.7 shows that the smaller cargo capacity vessel considered in this thesis (2,500 tonnes) is the optimum option for both cases. This is directly linked to the draft limitation. Since the maximum draft allowance is 6.8 m, the only available options within the considered ships in the current research are 2,500 tonnes at 10, 14 and 16 kn and 5,000 tonnes at 10 kn[4] (see Tab. A.3 in Appendix A). Results are graphically presented in Fig.4.10.

[4]Vessel size is a function of the DWT and speed, as argued in Section 4.3

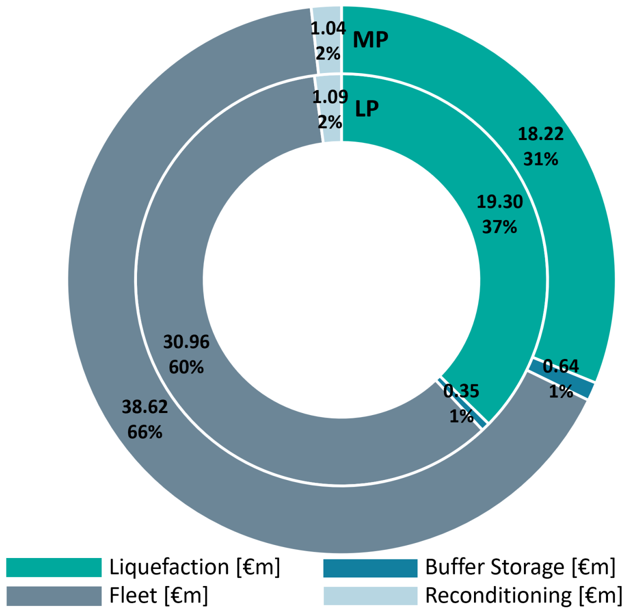


Figure 4.10: Västerås - Kollsnes breakdown total cost with vessel size limitation.

At the view of the results shown in Tab. 4.7 and Fig. 4.10, it is interesting to remark the largest number of vessels which compose the fleet that are required in order to cope with the amount of CO_2 to be transported. Such quantity could be considered relatively small, as future amounts are expected to grow when maturity of the market is at an advanced stage. This is evidence that the total cost would increase greatly with the growth of CO_2, since the total number of (small) vessels will increase accordingly, and therefore multiplying CAPEX and OPEX of the fleet.

4.5.3 Södertälje - Kollsnes

Last case of current scenario is presented below. As for Västerås case, maximum draft is limited to 6.8 m due to the Södertälje channel. Thus, small vessels are expected once more time to carry out the logistic job of LCO_2 transportation. Achieved results values are shown in Tab. 4.8:

Table 4.8: Fleet costs and logistics Södertälje - Kollsnes.

Scenario 2	**Södertälje - Kollsnes**	
Input		
Flow rate [tCO_2/y]	835,000	
Distance [km]	1685	
Type of fuel	VLSFO	
Vessel size limitation	Kollsnes: L $\leq$ 130 m	
	Södertälje: T $\leq$ 6.8 m	
	Considered	
Output	**LP**	**MP**
Ship cargo capacity [t]	2,500	2,500
Speed [kn]	16	16
No. of ships	6	6
Total time roundtrip [h]	144	144
Fleet total roundtrips	334	334
Cost [€m]	**LP**	**MP**
Liquefaction	19.64	18.54
Buffer storage	0.35	0.64
Fleet	30.92	38.59
Reconditioning	1.11	1.05
Total	52.02	58.82

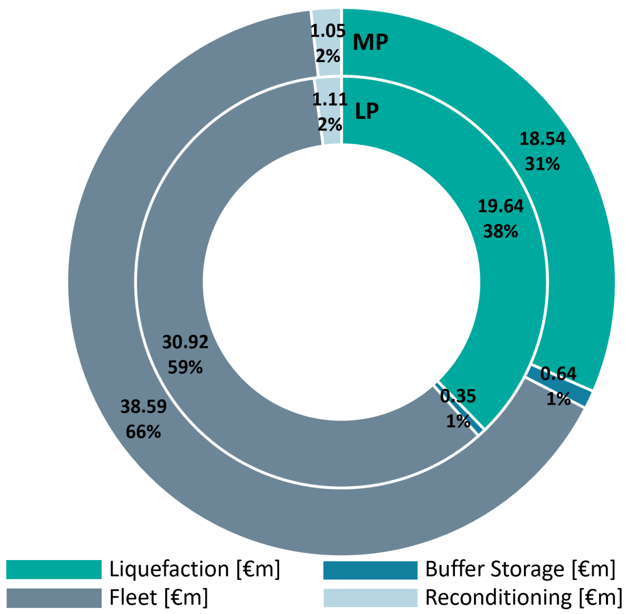


Figure 4.11: Södertälje - Kollsnes breakdown total cost with vessel size limitation.

Similarly to Stockholm - Kollsnes case, maximum length is set to 130 m due to Kollsnes port vessel size limitation, which is more restrictive than the one found in Södertälje area. Additionally, trend in the costs are similar, the fleet cost being greater than the liquefaction, as distance is relatively high, limitations are quite restrictive and amount of CO_2 can be considered relatively small.

For the Scenario 2 (considering the three presented cases), the fleet costs raise up from 59% to 66% of the total cost when vessel size limitation is applied[5], deviating from the trend in Scenario 1 where fleet costs percentage of total cost were found around half, suggesting that another more cost-effective approach could be found. Therefore, Scenario 3 is hereafter presented in order to analysed an alternative solution.

4.6 Scenario 3

In this situation, same sources as in Section 4.6 are analysed with the distinction that now, the singular CO_2 amounts of each industry it is gathered by means of a shuttle vessel traffic that connects them with the hub placed in Nynäshamn. Therefore, the hub capacity must be able to handle the summation of the amounts of each source. This implies several factors to have into account:

- Hub buffer storage capacity bigger since CO_2 amount is considerably higher than the sources on their own.
- Coordination between arrival rates to both source and hub in order to fulfill the docking time without delaying other vessels.
- Small vessels for restricted sailing conditions waters since the amount to transport is lower, and thus easier to comply with ship size limitations in terms of L, B and T.
- Bigger vessel from hub to sink in order to be able to cope with the total amount of CO_2 of all emitters.

Figure 4.12 shows a sketch of Scenario 3. The amounts of CO_2 transported from the emitting source to the intermediate storage (point B in Fig.4.12) are the same as those considered in Scenario 2 (Table 4.5). Moreover, the distances considered between the emitters and the intermediate storage, situated in Nynäshamn, are shown in Table 4.9.

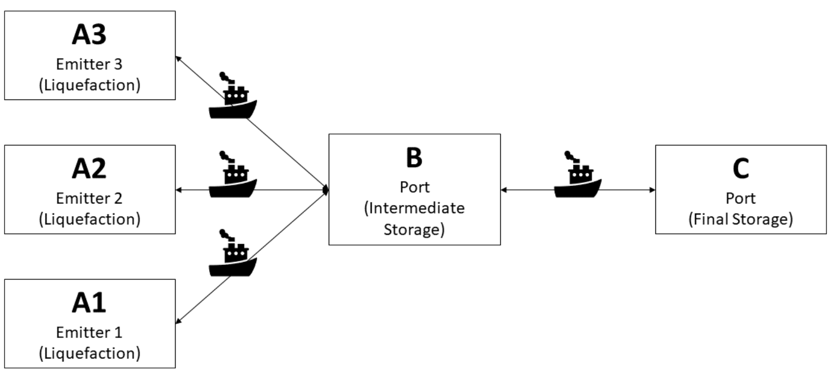


Figure 4.12: Scenario 3

[5]Such limitation, once more remarked, cannot be avoided in the future since it is due to the geographical conditions of the area not to the port infrastructure (see Section 4.3 for detailed explanation)

Table 4.9: Scenario 3: Distances between emitter and intermediate storage

Route	Distance [km]
Stockholm - Nynäshamn	311
Västerås - Nynäshamn	174
Södertälje - Nynäshamn	80

To get from Nynäshamn to Kollsnes, two options are considered. The first and fastest option is to pass between Denmark and Sweden. However, on this route there is a restriction on vessel size and some of the vessels considered in the model would not be able to sail this route. The second option is the one shown in Fig.4.13, in which there is no restriction on vessel size. Therefore, it is assumed that all vessels sail the route shown in Fig.4.13 regardless of their size. This route has a distance of 1870.52 km and the amount of CO_2 to be transported is the sum of CO_2 captured in the emitting sources with a total value of 2,455,000 tons of CO_2 per year.

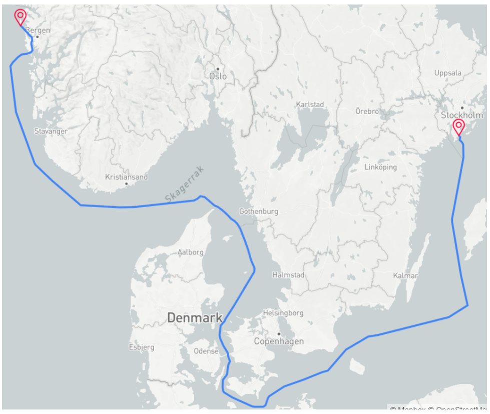


Figure 4.13: Scenario 3: Nynäshamn - Kollsnes Route

The different logistics profiles and CCS chain cost for the different cases are shown below. First, the output of the model from Nynäshamn to Kollsnes is presented in Section 4.6.1 and then the different logistic profiles from the emitters to Nynäshamn are explained in Sections 4.6.2 to 4.6.4, as well as the CCS chain cost.

4.6.1 Nynäshamn - Kollsnes

This part of the chain is taking into consideration the CO_2 produced at three different emitters. In order to obtain the cost of the entire CCS under consideration in Sections 4.6.2 to 4.6.4, i.e. from emitter to final storage via hub, and thus be able to compare it with the results obtained in Scenario 2, the cost for the second leg (Nynäshamn - Kollsnes) is presented in €/tCO_2 and can be seen in Table 4.10. This way it is possible to know how much it cost to transport one ton of CO_2 from the hub (point B) to the final destination (point C). Figure 4.12 can be observed to better comprehension of the described situation. This mentioned cost measure in €/tCO_2 is scaled with the flow rate of the emitter and added to the CCS chain cost between emitter and intermediate storage. Table 4.10 shows the most cost-efficient logistic option for both pressure transport conditions for this scenario.

Table 4.10: Fleet costs and logistics Nynäshamn - Kollsnes (second leg)

Scenario 3	**Nynäshamn (hub) - Kollsnes**			
Input				
Flow rate [tCO2/y]	2,455,000			
Distance [km]	1871			
Type of fuel	VLSFO			
Vessel size limitation	Kollsnes: L $\leq$ 130 m, T $\leq$ 8.5 m			
	Not considered		**Considered**	
Output	**LP**	**MP**	**LP**	**MP**
Ship cargo capacity [t]	50,000	10,000	5,000	5,000
Speed [kn]	16	16	16	16
No. of ships	1	5	10	10
Total time roundtrip [h]	157	157	157	157
Fleet total roundtrips	50	246	491	491
Cost [€/tCO$_2$]	**LP**	**MP**	**LP**	**MP**
Liquefaction	-	-	-	-
Buffer storage	2.86	1.04	0.29	0.52
Fleet	9.80	25.60	27.83	34.26
Reconditioning	1.20	1.13	1.20	1.13
Total	13.86	27.78	29.31	35.91

For low-pressure transport without vessel size limitation, the most optimum solution is to transport CO_2 at 16 knot with a vessel of 50,000 tCO_2 capacity with a cost of 13.86 €/tCO_2 and for medium-pressure transport with five ships at 16 knots each and a vessel capacity of 10,000 tCO_2, which is the maximum considered in the model for this transport condition, resulting in a cost of 27.78 €/tCO_2. Notice that, as in previous scenarios, the fuel type input is VSLFO.

When limitations in ship size is imposed, the fleet for low and medium pressure consist on ten vessels of 5,000 tonnes of cargo capacity at 16 kn. Thus, cost are affected, increasing a 111.5% for low pressure and 29% for medium pressure. Such a big increase in costs for the low pressure option arises from the fact that the fleet consists in ten times more ships, while when it comes to medium pressure option, the raise is more modest since this increase in number of vessels in the fleet is only two times more. Nevertheless, it can be once again seen how an increase in the vessel size allowance at Kollsnes port infrastructure could favour the market by reducing considerably the total costs.

4.6.2 Stockholm - Nynäshamn - Kollsnes

First emitter to be analysed is Stockholm. As can be seen in Table 4.11, the optimal logistics profile to transport the CO_2 captured in Stockholm Exergi AB to Nynäshamn (hub) is one vessel of 5,000 tCO_2 capacity at 16 kn regardless the pressure transport condition. Moreover, each round trip takes 51 hours and the vessel makes 160 round trips at the end of the year.

Table 4.11: Fleet cost and logistics Stockholm - Nynäshamn (first leg)

Scenario 3	**Stockholm - Nynäshamn (hub)**			
Input (First leg)				
Flow rate [tCO_2/y]	800,000			
Distance [km]	311			
Type of fuel	VLSFO			
Vessel size limitation	Stockholm: L $\leq$ 200 m, T $\leq$ 11 m			
	Not considered		**Considered**	
Output (First leg)	**LP**	**MP**	**LP**	**MP**
Ship cargo capacity [t]	5,000	5,000	5,000	5,000
Speed [kn]	16	16	16	16
No. of ships	1	1	1	1
Total time roundtrip [h]	51	51	51	51
Fleet total roundtrips	160	160	160	160
Cost (First leg) [€m]	**LP**	**MP**	**LP**	**MP**
Liquefaction	18.84	17.79	18.84	17.79
Buffer storage	0.35	0.64	0.35	0.64
Fleet	5.79	7.37	5.79	7.37
Reconditioning	-	-	-	-
Total	24.99	25.79	24.99	25.79

As it can be seen, values are the same for both situations, with and without restrictions. This is due to the small amount considered to be transported in the first stages of this new market. As the CO_2 flow rate increases, for instance, by adding emissions from different new sources in Stockholm, bigger vessels would be a more cost-effective option. Therefore, port size limitation could potentially impose a constraint in the allowance of such vessels, leading to the need of operating with smaller vessels than what would optimum.

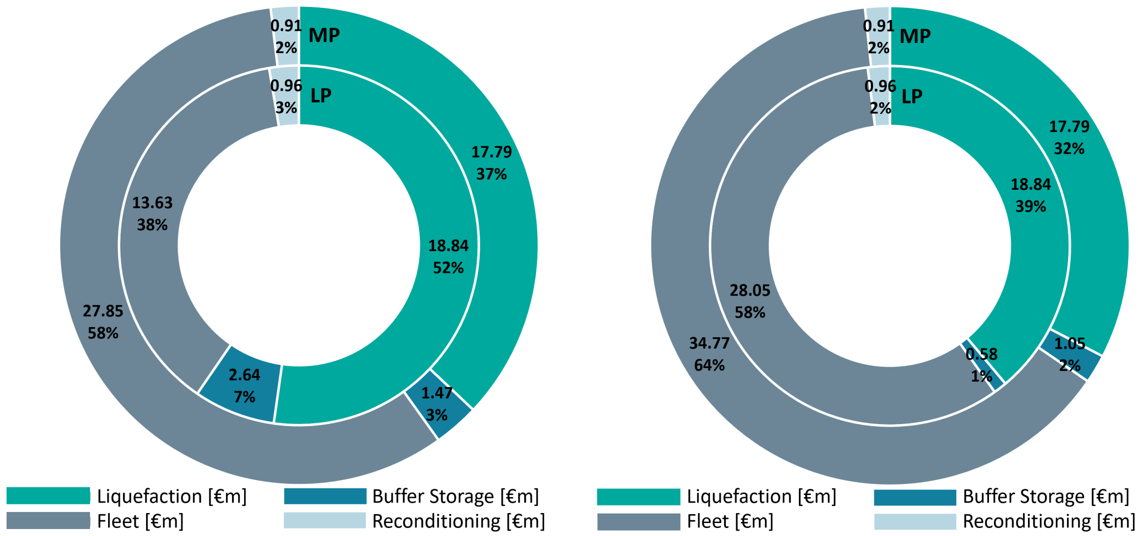
The values presented in Tab. 4.12 stands for the total cost of the activity taking into account the first leg (Stockholm - Nynäshamn) and the second leg (Nynäshamn - Kollsnes).

Table 4.12: Fleet cost and logistics Stockholm - Nynäshamn - Kollsnes

Scenario 3	**Stockholm - Nynäshamn (hub) - Kollsnes**			
Vessel size limitation	**Not considered**		**Considered (Kollsnes)**	
Cost (first + second leg) [€m]	**LP**	**MP**	**LP**	**MP**
Liquefaction	18.84	17.79	18.84	17.79
Buffer storage	2.64	1.47	0.58	1.05
Fleet	13.63	27.85	28.05	34.77
Reconditioning	0.96	0.91	0.96	0.91
Total	36.07	48.02	48.43	54.52

Following the same trend, performing the route without vessel size limitation in low pressure condition results in lower cost, with a value of 36.07 €m, than at medium pressure, which has a cost of 48.02 €m. Similarly with ship size limitations applied, cheapest option is lower pressure with 48.43 €m. Medium pressure option cost is 54.52 €m. Although the cost of the liquefaction process from the assumed condition to the transport condition at low pressure is higher than at the medium pressure, the ship cost for the medium pressure condition is significantly higher than for the low pressure condition resulting in a more expensive overall option.

For a transport condition at low pressure without vessel size limitation, the cost of the liquefaction process represents about half of the cost of the CCS chain considered with a value of 52%, however, for medium-pressure transport the major contributor to the total cost is the fleet cost. This is mainly due to the fact that the ship cost for medium pressure transport from Nynäshamn to Kollsnes is high since five vessels are needed (see Tab. 4.10 and Fig. 4.14). This increases the hiring costs considerably, as it is assumed to be linear in the model. The same trend is followed in Sections 4.6.3 and 4.6.4.



(a) Without vessel size limitation. **(b)** With vessel size limitation.

Figure 4.14: Stockholm - Nynäshamn (hub) - Kollsnes breakdown total cost.

It can be observed from Fig. 4.14 how important is to reduce the fleet size as much as possible in order to avoid increasing costs rapidly due to the investment and operational expenses of every ship in operation. This fact can be notice by comparing low pressure option in both conditions, with and without vessel size limitation, where total fleet cost grow from a 38% to a 58% of the total cost.

4.6.3 Västerås - Nynäshamn - Kollsnes

Table 4.13 shows the optimum ship logistics to transport 820,000 tCO_2 over a year from Västerås to Nynäshamn. Since the CO_2 throughput and distances are similar to those in Section 4.6.2, the logistics output in terms of ship capacity, number of vessels and speed, is the same. The roundtrip takes 6 hours more with a total of 49 hours as the distance is bigger and the vessel does a total of 164 roundtrips per year.

Table 4.13: Fleet cost and logistics Västerås - Nynäshamn (first leg)

Scenario 3	**Västerås - Nynäshamn (hub)**	
Input (First leg)		
Flow rate [tCO_2/y]	820,000	
Distance [km]	174	
Type of fuel	VLSFO	
Vessel size limitation	Västerås: L ≤ 125 m, T ≤ 6.8 m	
	Considered	
Output (First leg)	**LP**	**MP**
Ship cargo capacity [t]	5,000	5,000
Speed [kn]	10	10
No. of ships	1	1
Total time roundtrip [h]	49	49
Fleet total roundtrips	164	164
Cost (First leg) [€m]	**LP**	**MP**
Liquefaction	19.30	18.22
Buffer storage	0.35	0.64
Fleet	5.48	7.06
Reconditioning	-	-
Total	25.13	25.91

Moreover, the total cost remains in the same order of magnitude as in Section 4.6.2, since, although the amount of CO_2 to transport is higher, in this case the sailing distance is lower. It can be seen in Table 4.14 that once again, low pressure transport is the cheapest option.

Table 4.14: Fleet cost and logistics Västerås - Nynäshamn - Kollsnes

Scenario 3	**Västerås - Nynäshamn (hub) - Kollsnes**	
Vessel size limitation	**Considered (Västerås and Kollsnes)**	
Cost (first + second leg) [€m]	**LP**	**MP**
Liquefaction	19.30	18.22
Buffer storage	0.59	1.07
Fleet	28.30	35.10
Reconditioning	0.98	0.90
Total	49.16	55.36

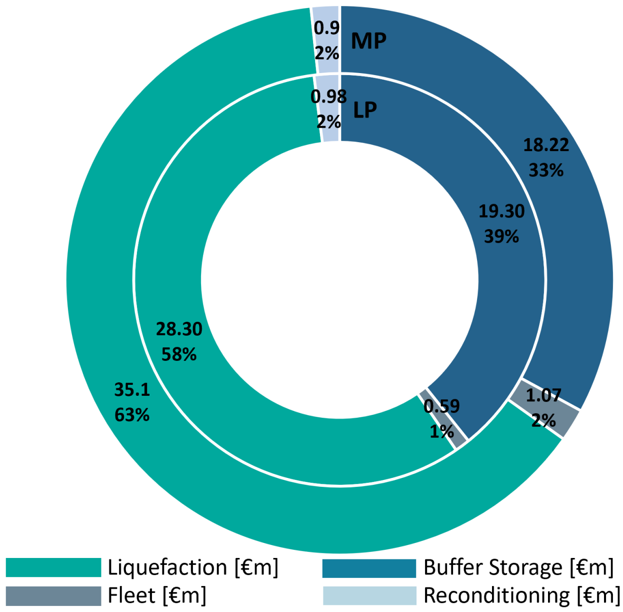


Figure 4.15: Västerås - Nynäshamn (hub) - Kollsnes breakdown total cost with vessel size limitation.

This case, is very similar in terms of costs and percentages when comparing it with the previous one (for the vessel size restriction option, see Fig.4.14(b)). This lies in the fact that, although Västerås have a bigger CO_2 flow rate, is also further away than Stockholm. Hence distance and amount of CO_2, which is recalled once more time that are the most relevant parameters, balance each other in terms of costs.

4.6.4 Södertälje - Nynäshamn - Kollsnes

As in Sections 4.6.2 and 4.6.3, for both transport conditions a 5,000 tCO_2 capacity ship is the most cost-efficient option. This is closely related to the vessel size limitation constraints. As the distance is shorter the total roundtrip for this case is 39 hours.

Table 4.15: Fleet cost and logistics Södertälje - Nynäshamn (first leg)

Scenario 3	**Södertälje - Nynäshamn (hub)**	
Input (First leg)		
Flow rate [tCO_2/y]	835,000	
Distance [km]	80	
Type of fuel	VLSFO	
Vessel size limitation	Södertälje: L $\leq$ 200 m, T $\leq$ 6.8 m	
	Considered	
Output (First leg)	**LP**	**MP**
Ship cargo capacity [t]	5,000	5,000
Speed [kn]	10	10
No. of ships	1	1
Total time roundtrip [h]	39	39
Fleet total roundtrips	167	167
Cost (First leg) [€m]	**LP**	**MP**
Liquefaction	19.64	18.54
Buffer storage	0.35	0.64
Fleet	5.46	7.03
Reconditioning	-	-
Total	25.44	26.21

As explained in Section 4.6.1, the cost calculation is firstly carried out for the first leg (see results in Tab.4.10), which is independently from the rest of emitters using the hub. Then, the transportation cost for the second leg is distributed proportionally to each of the emitters involve[6]. Thus, the total costs for Södertälje - Nynäshamn - Kollsnes case is presented below in Tab.4.16.

Table 4.16: Fleet cost and logistics Södertälje - Nynäshamn - Kollsnes

Scenario 3	**Södertälje - Nynäshamn (hub) - Kollsnes**	
Vessel size limitation	**Considered (Södertälje and Kollsnes)**	
Cost (first + second leg) [€m]	**LP**	**MP**
Liquefaction	19.64	18.54
Buffer storage	0.59	1.07
Fleet	28.69	35.64
Reconditioning	1.00	0.95
Total	49.92	56.19

In addition, the total cost of the CCS chain considered from the CO_2 source to the final storage is 49.92 €m considering a low-pressure transport and 56.19 €m considering a medium-pressure transport. Following the trend established by the previous cases, low pressure is the most cost-effective option. The cost breakdown is depicted below in Fig. 4.16.

[6]In terms of the CO_2 volume contributed by each emitter.

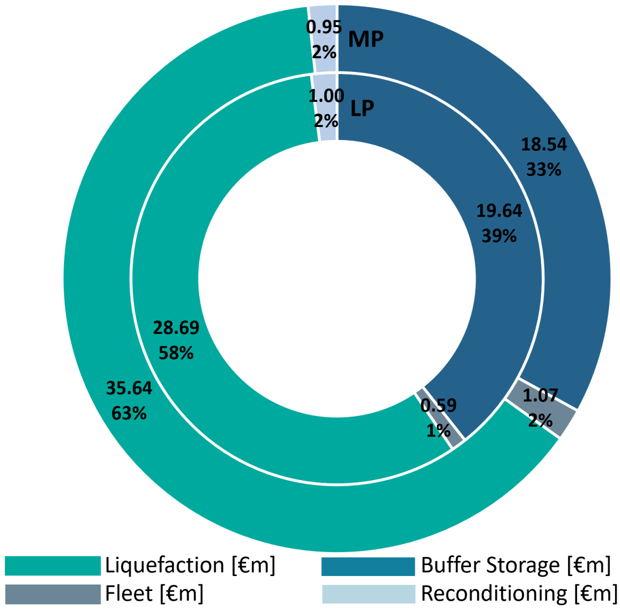


Figure 4.16: Södertälje - Nynäshamn (hub) - Kollsnes breakdown total cost.

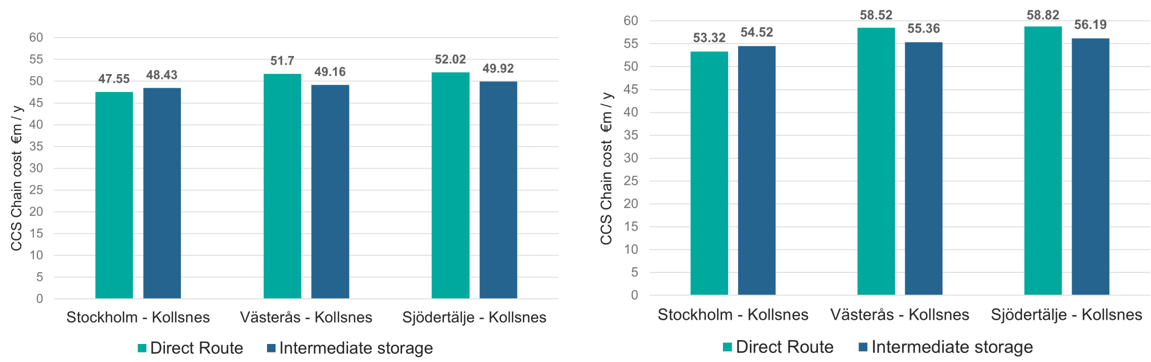
The above figure support the same line of reasoning as the one explained at the end of Västerås - Nynäshamn - Kollsnes scenario. Which, as it can be seen comparing the cost breakdown of the three studied cases, costs and their respective percentages are considerably similar. In this particular case, Södertälje is the closest emitter of the three considered, but also the one with larger amount of CO_2. Hence, once again, distance and CO_2 volume are balanced achieving similar results as previous cases, which are more distant emitters but with less amount of cargo.

4.7 Comparison between Scenario 2 and 3

Scenario 2, Section 4.6, takes into consideration the same emitters with the same quantities as in Scenario 3, Section 4.6, but without taking into account intermediate storage, i.e. the route is direct from the emitting source to the final storage.

The comparison between these two scenarios is made to see whether it is more cost-efficient to consider an intermediate storage in Nynäshamn or to go directly from the CO_2 emitting source to the port where the injection of CO_2 into the seabed takes place.

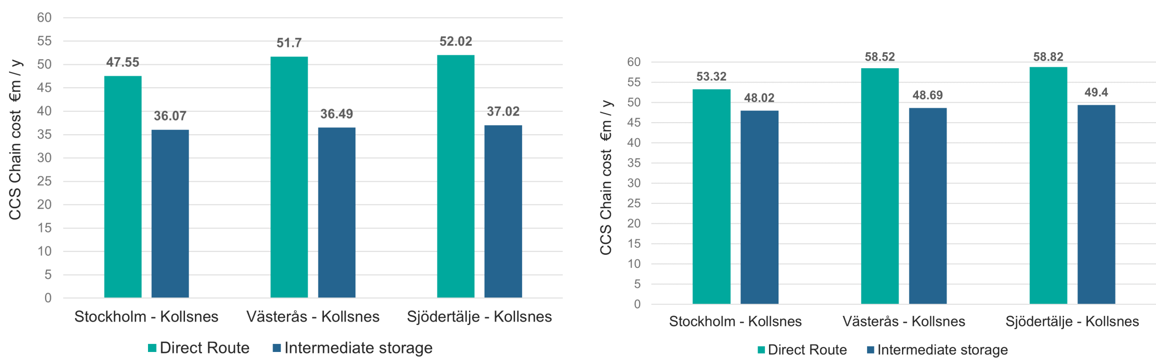
Figure 4.17 shows the total cost of the CCS chain for both transport conditions (low and medium pressure), for both routes (with and without intermediate storage) using VLSFO and considering the vessel size restrictions on the route. On the one hand, from Stockholm to Kollsnes, port restrictions at Kollsnes apply for both routes (as they are the most restrictive ones) and these restrictions are a length limitation of 130 m and a draft limitation of 8.5 m. This results in a vessel capacity limit of 5,000 tonnes of CO_2 (as it can be seen in Table 4.6 and Table 4.11), taking into account the estimated dimensions which can be seen in Appendix A. In addition, considering intermediate storage implies more distance in the total route. Therefore, for this case, a direct route results in a more cost-efficient option with a cost reduction of about 2% compared to an intermediate storage in Nynäshamn. One the other hand, from Västerås and Södertälje to Kollsnes a draft restriction of 6.8 m applies, whereas considering an intermediate storage this draft restriction only applies from Västerås and Södertälje to Nynäshamn. From Nynäshamn to Kollsnes only the port of Kollsnes shall be imposed. Although the option considering intermediate storage implies a longer distance, for these cases it implies a cost reduction of between 4.5% and 5.5%. This is due to the fact that the ship capacity that can be used between Nynäshamn to Kollsnes is larger than the capacity that can be used between Västerås and Södertälje to Kollsnes (direct route).



(a) Low pressure condition. **(b)** Medium pressure condition.

Figure 4.17: Comparison of costs in relation to the route (direct route or via intermediate storage) considering vessel size restrictions.

Disregarding the vessel size limitations forced by the current infrastructure, i.e. the port vessel size limitations, it can be seen in Fig. 4.18, how the results differ considerably to the ones reached when size constraints are applied.



(a) Low pressure condition. **(b)** Medium pressure condition.

Figure 4.18: Comparison of costs in relation to the route (direct route or via intermediate storage) without considering infrastructure vessel size restrictions.

As shown in Table 4.10, if vessel size restrictions are not considered, the optimal maritime logistics output is one vessel of 50,000 tonnes capacity at 16 knots for low-pressure transport option and five vessels of 10,000 tonnes capacity at 16 knots for the medium-pressure transport option, these being the maximum capacities considered. Moreover, if one looks at the same table, taking into account the vessel size limitations, the vessel capacity is limited to 5,000 tonnes capacity for both pressure transport condition. This is the reason why the blue bars in Fig. 4.18 show a lower cost than in Fig. 4.17, especially for low-pressure transport option, since the maritime logistics is shifted from considering a 5,000 tonne capacity to 50,000 tonne capacity.

5

Discussion

The purpose of this work is to develop a model to determine the most optimal maritime logistics solution for transport of CO_2 between two harbours. The results indicate that the optimal maritime logistics is linked with distance and flow rate. This can be seen in the results where vessel size restrictions are not considered in Table 4.4, which corresponds to Scenario 1 from Gothenburg to Kollsnes (Section 4.4), and Table 4.6, which corresponds to Scenario 2 from Stockholm to Kollsnes (Section 4.5.1). Both scenarios present the same optimal transport logistics, however, the quantity of CO_2 to be transported in Scenario 1 is twice as much as in Scenario 2, while the distance of Scenario 2 from Stockholm to Kollsnes is more than twice as much as in Scenario 1.

Figure 5.1 shows the relationship between ship capacity and the number of vessels with the flow rate for low pressure shipping as more capacities are considered.

- Gray colour corresponds to a distance of 715 km which belongs to Scenario 1.
- Light blue colour corresponds to the aforementioned Scenario 2 with a distance of 2115 km.
- Turquoise blue colour corresponds to an example distance of 3000 km.

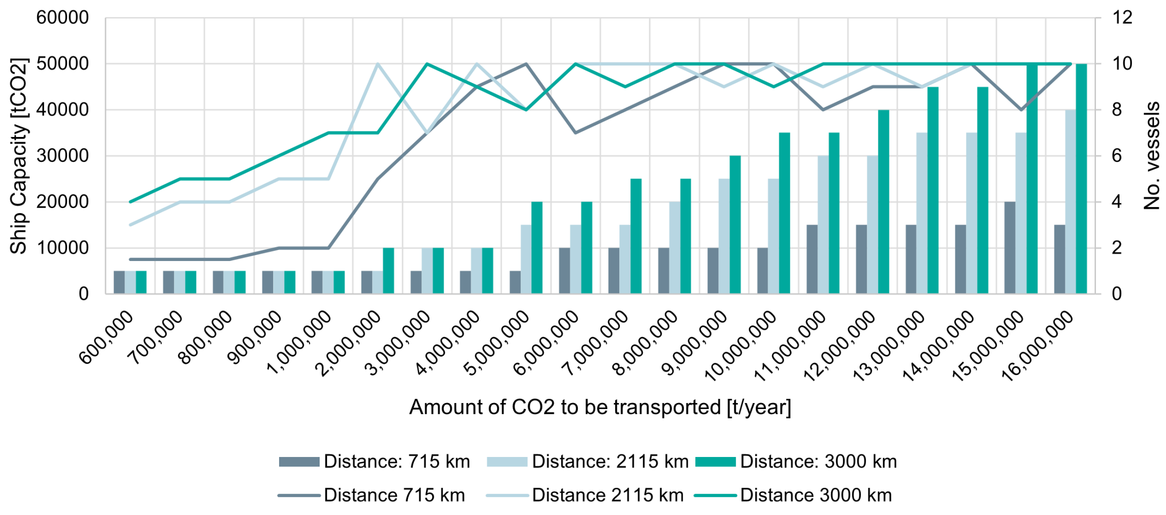


Figure 5.1: Ship capacity and number of vessels vs flow rate. The lines correspond to the ship capacity axis and the bars to the number of vessels axis.

For smaller quantities of CO_2 flow rate and longer distances, a bigger vessel capacity is more optimal since only one vessel is needed to transport this amount. As quantities increase, more vessels are needed.

Generally, when the flow rate increases and more vessels are required, it is more cost-efficient to reduce the vessel capacity than to keep the same capacity and increase the speed.

Moreover, Fig. 5.2 considers the distances of Scenario 1 (Section 4.4) and Scenario 2 from Stockholm to Kollsnes (Section 4.5.1) without vessel size restrictions and with vessel size restrictions. It can be seen, the greater the distance, the higher the cost to transport a ton of CO_2. In addition, for all cases, the greater the quantity to be transported, the lower the cost.

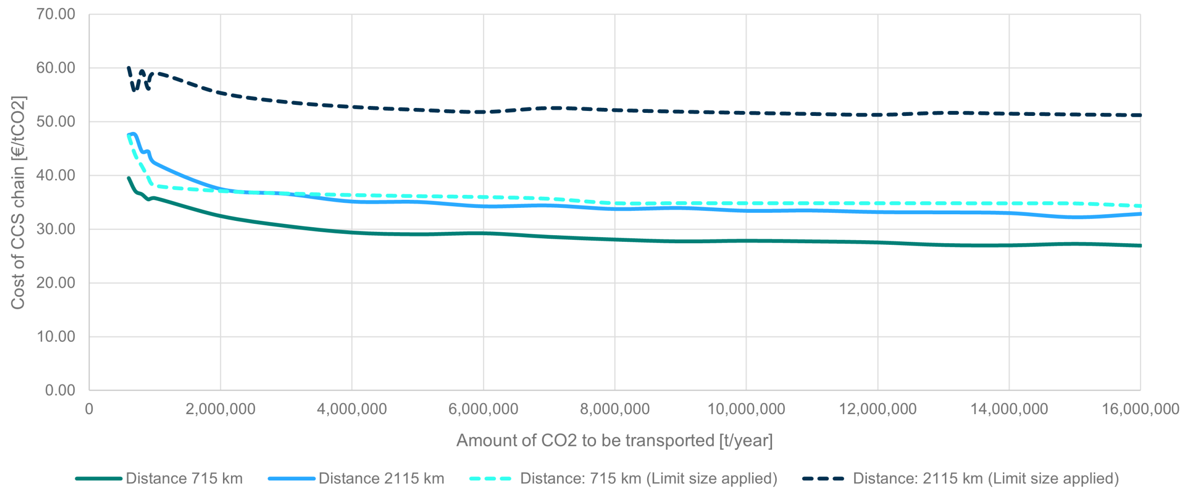


Figure 5.2: Cost of the CCS chain as a function of flow rate for low pressure transport considering two distances and with and without vessel size restrictions.

Continuing with Fig. 5.2, the unit cost of the CCS chain is lower when no vessel size restrictions are applied, especially for longer distances. This is due to the fact that when no size restriction is applied, the most optimal solution, as seen in Chapter 4, tends to be larger capacities. In contrast, when restrictions on vessel size are applied, the CO_2 capacity carried by a vessel is limited and therefore the number of vessels must be increased considerably. This is in line with the question raised in Chapter 2 on whether it is more cost efficient to have a fleet of larger capacity vessels or a larger number of smaller capacity vessels. Bjerketvedt et al. (2020) states that the variation in CO_2 emissions due to the change of seasons lead to the option of larger ship as smaller ships would need to increase their power and speed to comply with the larger CO_2 volumes during peak seasons leading to a higher fuel consumption. Moreover, taking into account weather conditions, smaller vessels are more susceptible to weather conditions than larger vessels (Bjerketvedt et al., 2020). The same conclusion can be drawn from the results obtained in the different scenarios. With this in mind, it is deduced that in the future, if the CCS industry grows and low-pressure transport with these vessel capacities is considered, more infrastructure will be needed.

Furthermore, one of the current uncertainties is if it is better to consider a direct route or to consider intermediate storage. Taking a look at Scenario 2 (Section 4.5) and Scenario

3 (Section 4.6), it can be seen that this depends on the emitter and the vessel size restrictions. In addition, in Appendix B can be seen these scenarios considering different annual flow rates. From Stockholm to Kollsnes with the size restrictions expose in Chapter 4, a direct route is always more cost-effective than considering intermediate storage. However, from Västerås to Kollsnes and from Södertälje to Kollsnes is more cost-effective consider a intermediate storage, specially from Västerås. It is worth mentioning that this conclusion is made on the basis of the current vessel size estimation.

Another uncertainty is the pressure at which CO_2 should be transported by ship. Current projects, such as Northern Lights project (Northern Lights, 2023), focus on medium-pressure shipping as the technology is more mature. Nevertheless, literature (Chapter 2) shows low-pressure shipping is more cost-effective than medium-pressure shipping. The model developed is consistent with that statement, as for all the scenarios studied in Chapter 4, the low pressure condition results in a lower cost. This is because although liquefaction and reconditioning is more economical if a medium-pressure shipping is considered, the cost of liquefied CO_2 tankers at medium pressure are much higher than in the case of low-pressure.

The outcome of this work gives an insight of what a maritime CCS logistics looks like for different distances and different amounts of CO_2. Furthermore, it provides a prediction of the CCS market, as well as the infrastructures that may be needed in the future if this market grows.

Nonetheless, it is worth mentioning that the model has some limitations:

The liquefaction process takes place in the emitter facility and therefore the CO_2 needs to be transported to the port terminal in liquid form. This transport, if needed, it is not considered in the chain. Furthermore, the costs of the CCS chain under consideration, taking into account the vessel size restrictions outlined in Chapter 4, depend primarily on the fleet cost, which in turn depends on the shipping logistic profiles. Hence, the vessel capacities considered in the shipping logistic profiles are linked to the vessel sizes estimated through empirical equations shown in Appendix A. For example, a ship sailing at 14 knots with a capacity of 7500 tonnes of CO_2 is estimated to be 139.5 m in length, however, the ship considered in Northern Lights (2023) has this conditions and has a length of 130 m. Moreover, the M/T Ulle Clover designed in Argyros et al. (2023), sails at 10 knots with capacity to transport 7500 tonnes of CO_2, has a length of 124.2 m and a draft of 6.7 m, while the one under consideration has a length of 126.5 m and a draft of 7.5 m. This has an impact on the outcomes of the model when size restrictions are apply.

6
Conclusion

The aim of this project is to establish a model for the logistics of LCO_2 in Sweden and based on this give recomendations on design parameters for the vessels involved. While building up the model, it can be seen the close relationship between all parameters that involve the logistic structure, such as vessel dimensions and speeds, CAPEX and OPEX, liquefaction and reconditioning operations, buffer storage capacity, sailing routes, ports locations and ships dimensions constraints linked to it, etc. The desire goal is to verify the viability of a logistic operation by means of calculating costs, times and optimum fleet performance configuration. The model is subsequently applied to transport cases in Sweden, from which the following conclusions are reached:

- Weather to use a hub or not it cannot be predicted in a general way. Therefore, a case-by-case approach is required to predict the most cost-efficient solution.
- Despite medium pressure technology can be considered in a more mature stage than low pressure option due to its long term usage in food and oil and gas industries, when it comes to LCO_2 tranportation have major drawbacks that make this option a less efficient one in general terms. This is caused by its more expensive construction methods and its limited cargo capacity due to the required tank thicknesses and thus greater weight and size.
- Medium pressure transportation is always the most expensive option. This is due to the need for more ships per fleet, as the capacities cannot be as higher as they are for low pressure option. Hence, if technically it could be possible to create lighter medium pressure tanks in order to increase the cargo capacity, and to use the same cargo capacity as with low pressure vessels, it would make the solution cheaper, as all other costs (especially liquefaction) are cheaper for medium pressure vessels than for low pressure ships.
- Although low pressure technology is not as mature as medium pressure, is on the regular basis, the most cost-effective solution. Nevertheless, a great challenge needs to be overcome for this technology to start being a real option in the market. Such challenge is no other than the, so far, mistrust triggered by uncertainties which may discourage early movers from investing in this new market. Therefore, more extent research and risk analyses studying this technology is required to bring some light on the subject and thus pave the way for early investors.
- Generally, the option of larger vessels is more cost-effective. However, for some particular cases, the most economical option is to increase the number of vessels and decrease their capacity. Therefore, a case-by-case study is recommended, for

which the introduced model has been developed. It is worth mentioning that this study has not carried out any technical study on the feasibility of the vessels under consideration.

- Using the largest ship possible is almost always more economical, as the increase in the cost of buffer storage is not as great as the increase in the number of ships per fleet, so if you take smaller ships, the buffer decreases, and the price of the buffer decreases, but the price of the fleet increases to a much greater extent. Thus, if smaller vessels are taken, the buffer decreases, and so does the price, but the fleet price increases to a much greater extent, with the end result being more expensive. Liquefaction and reconditioning does not change, as the CO_2 volume is constant, regardless of the fleet arrangement.

- On what the logistical solution depends the most is the sailing distance and the CO_2 amount to be transported. Other constraints such as vessel size limitation are obviously of major important, as such constraint may cause it to diverge from the optimal solution thus making the activity much more expensive because as the optimum size vessel cannot be eligible as a feasible solution.

- The major importance potential cost save for the logistic activity is found in the liquefaction. By achieving a more efficient liquefaction in order to consume less energy, would be the best option to reduce the cost of the operation.

Having explained the procedure followed, it is concluded that the studies realised are conceptually accurate. Nevertheless, in order to perform a more realistic model, it shall be necessary to take more information into account by means of further research.

7

Further work

The research conducted for this thesis highlights a number of matters on which further investigation would be constructive. These include the following.

A sensitivity study could research in detail the optimal vessels size for a specific situation, as it can be optimised, for instance, by increasing the beam to save a few meters in draft and thus be able to sail a more straightforward route with a vessel of a bigger cargo capacity in order to save time and fuel.

This research highlights that bigger vessels could be a more cost-effective option and therefore a change in port infrastructures would be necessary. Nonetheless, this topic requires further development in terms of looking at how much investment would be required to upgrade port infrastructure to accept bigger vessels and whether this construction would be economically worthwhile compared to the cost of a fleet of smaller vessels.

Furthermore, the research considers, for simplicity, pure CO_2 along the chain, however, impurities in the CO_2 have an impact on the process, such as liquefaction cost. Therefore, a sensitivity analysis of how CO_2 impurities affect the CCS chain and transport logistics would be necessary.

The model does not consider transport, if any, between the liquefaction plant and the port terminal. Research to add transport logistics and cost between these two points would be of interest and would make the model more accurate and the overall performance of the model would be improved.

The costs associated with each process in the CCS chain are estimations obtained from the literature review and have a level of uncertainty, as the operational cost generally assumed to be linearised with investment costs. Further investigation of each process would provide more accurate data.

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A

Tables

Table A.1: System boundaries and methodology from the literature review

Source	System boundaries	Excluded from the system	Methodology
Aspelund et al. (2006)	- Liquefaction phase - Intermediate storage - Loading system - Ship design - Offshore loading system	- CO_2 capture - Storage of CO_2 in the emitter source	- Techno-economic assessment
Decarre et al. (2010)	- From the capture outlet to the injection in an offshore aquifer	-	- Economic model by French Environment and Energy Management Agency.
d'Amore et al. (2018)	-	-	- Spatially explicit mixed integer linear programming approach
Coussy et al. (2013)	-	-	- Economic model based on a dynamic liner programming system developed with GAMS®
Mathisen et al. (2013)	-	-	- Flexible cost-efficient model using the factor estimation method based on data from Eurostat.
Yoo et al. (2013)	- Initial Compression - Liquefaction - Temporary storage as CO_2 export terminal - CO_2 carrier - CO_2 Offloading and CO_2 temporary storage as an import terminal - CO_2 pipeline	- CO_2 capture	- Techno-economic model developed by shipping company.
Roussanaly et al. (2013)	-	-	- Technical, economic and environmental assessment through iCCS. Simulations in Aspen HYSYS® and literature.
Kjärstad et al. (2016)	-	-	- Cost assessment as a function of volume and distance
Element Energy (2018)	- Liquefaction - Loading and unloading - Temporary storage - Ships - Gasification equipment	- CO_2 capture in the emitter source - Onshore transport	- Identification of key infrastructure elements for CO_2 shipping through literature review and interview with interested stakeholders. - Development of an interactive and flexible CO_2 shipping cost model - Identification of key opportunities and barriers
Bjerketvedt et al. (2020)	-	-	- Single-source single-sink model based on a two-stage stochastic investment model
Roussanaly et al. (2021)	- Liquefaction process - Buffer storage and loading - Shipping - Unloading and buffer storage - Reconditioning	- CO_2 capture	- Liquefaction based and its cost based on Deng et al. (2019) - Techno-economic assessment for the supply chain based on CCS tool developed by BIGCCS (iCCS).
Nam et al. (2013)	-	-	- Mixed Integer Lineal Programming
Bennæs et al. (2022)	-	-	- Mixed Integer Programming (MIP).

Table A.2: CCS Projects in Sweden. Adopted from IVL (2023) and Energimyndighetens (2022).

Company	Type of facility	Amount of $CO2$
Stora Enso	Pulp and Paper: Sulfate pulp mill. Coastal	Approx. 1 million tons of biogenic CO2/y
Söderenergi	Heating plant and bio power plant Close to the port	A total of 835 000 tons of biogenic CO2/y, of which 650 000 tCO2/y come from the heat and power plant and 185 000 tCO2/y from the heating plant
Vattenfall	KVV (waste & biofuel) + (HVC) Inland	A total of approx. 600 000 tons of biogenic and fossil CO2/y of which HVC: 49 000 tCO2/y (bio), Carpe Futurum: 141 000 tCO2/y (bio), waste KVV: 411 000 tCO2/y (of which 240 000 tons are biogenic CO2).
Mäkarenergi	Biopower heating Close to the port	A total of approx. 820 000 tons of CO2/y, of which 460 000 tons are biogenic. - Block 6: approx. 360 000 tons of fossil CO2/y and 200 000 tons of biogenic CO2/y - Block 7: 260 000 tons of biogenic CO2/y
Bodens Energis	Waste Inland	Possible detachment: 112 000 - 144 000 tons of CO2 per year of which 77 000 - 105 000 tons are biogenic
Sysav	Waste Coastal	Possible separation (fossil + biogenic). Approx. 430 000 tons of CO2/y from existing boilers and further approx. 200 000 tons of CO2/y from new boilers
Sundsvall Energi	Waste Coastal Close to the port	120 000 tons of biogenic CO2/y and 80 000 tons of fossil Co2/y
Växjö Energi	Biopower heating Inland	180 000 tons biogenic CO2/y
Helsingborg HICAS	Biopower plant Coastal Close to the port	Full-scale plant: 210 000 tons of CO2/y of which 120 000 tons are biogenic.
Skellefteå	Bio power plant Coastal	Long-term 150 000 tons of biogenic CO2 per year
Umeå Energi	Bio power plant and waste Coastal Close to the port	Potential approx. 300 000 tons of biogenic CO2/y. Plus approx. 60 000 tons of fossil CO2/y
Skövde Energi	Bio power plant and waste Inland	Potential approx. 100 000 tons of biogenic CO2/y.
Katrinefors Kraftvärme	Biopower heating	Potential after expansion of production capacity approx. 120 000 tons of biogenic CO2/y
E.ON Energiinfrastruktur	Bio power plant and waste	Up to 800 000 tons of CO2/y.
Stockholm Exergi		Approximately 0.8 Mton of biogenic CO2/y
CinfraCap (project)	CO2 from two refineries and two cogeneration plants	The amount of CO2 is expected to be ramped up, from an initial 400 000 tCO2/y in 2025 to 1 856 000 tCO2/y in 2040 (a portion of this will be biogenic).
Cementa AB	Cement	1.8 Mton CO2/y

Table A.3: Ships main dimensions relation

Speed [kn]	Cargo capacity [t]	L [m]	B [m]	D [m]	T [m]
10	2500	90.1	13.9	7.8	5.2
14	2500	99.3	15.3	8.6	5.8
16	2500	102.5	15.8	8.9	6.0
10	5000	113.5	17.5	9.9	6.7
14	5000	125.1	19.3	10.9	7.5
16	5000	129.1	19.9	11.2	7.7
10	7500	126.5	19.5	11.0	7.5
14	7500	139.5	21.5	12.1	8.4
16	7500	143.9	22.1	12.5	8.7
10	10000	131.3	20.2	11.4	7.9
14	10000	144.8	22.3	12.6	8.7
16	10000	149.4	23.0	13.0	9.0
10	12500	144.6	22.3	12.6	8.7
14	12500	159.5	24.5	13.9	9.7
16	12500	164.6	25.3	14.3	10.0
10	15000	153.7	23.6	13.4	9.3
14	15000	169.4	26.1	14.7	10.3
16	15000	174.9	26.9	15.2	10.7
10	20000	157.5	24.2	13.7	9.6
14	20000	173.6	26.7	15.1	10.6
16	20000	179.2	27.6	15.6	11.0
10	25000	172.8	26.6	15.0	10.6
14	25000	190.5	29.3	16.6	11.7
16	25000	196.6	30.3	17.1	12.1
10	30000	183.6	28.3	16.0	11.3
14	30000	202.5	31.1	17.6	12.5
16	30000	208.9	32.1	18.2	12.9
10	35000	199.4	30.7	17.3	12.3
14	35000	219.8	33.8	19.1	13.6
16	35000	226.8	34.9	19.7	14.1
10	40000	208.4	32.1	18.1	12.9
14	40000	229.8	35.4	20.0	14.3
16	40000	237.2	36.5	20.6	14.7
10	45000	210.2	32.3	18.3	13.0
14	45000	231.8	35.7	20.2	14.4
16	45000	239.2	36.8	20.8	14.9
10	50000	217.7	33.5	18.9	13.5
14	50000	240.1	36.9	20.9	14.9
16	50000	247.7	38.1	21.6	15.4

B
Figures

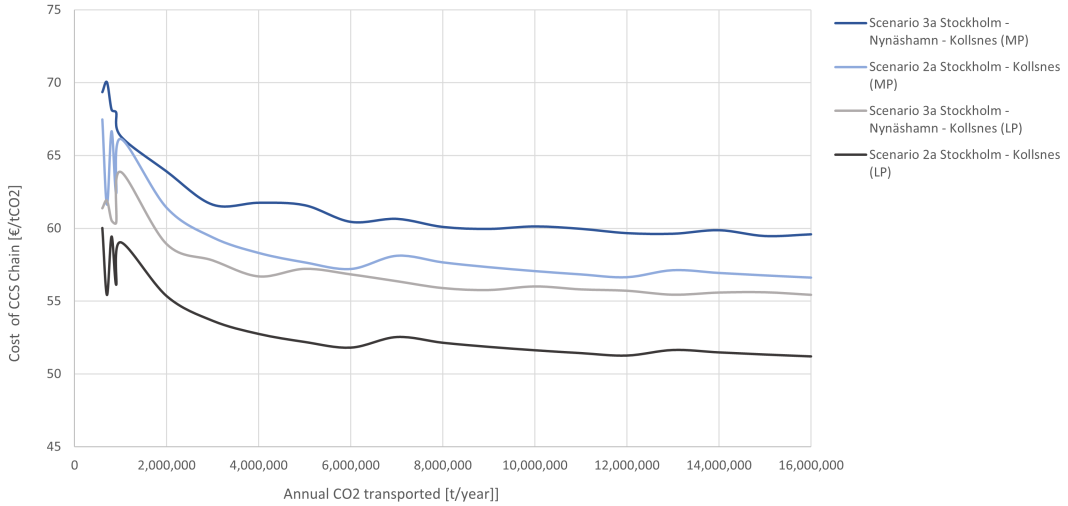

Figure B.1: Cost of the CCS chain as a function of flow rate for both transport pressure considering two routes from Stockholm to Kollsnes.

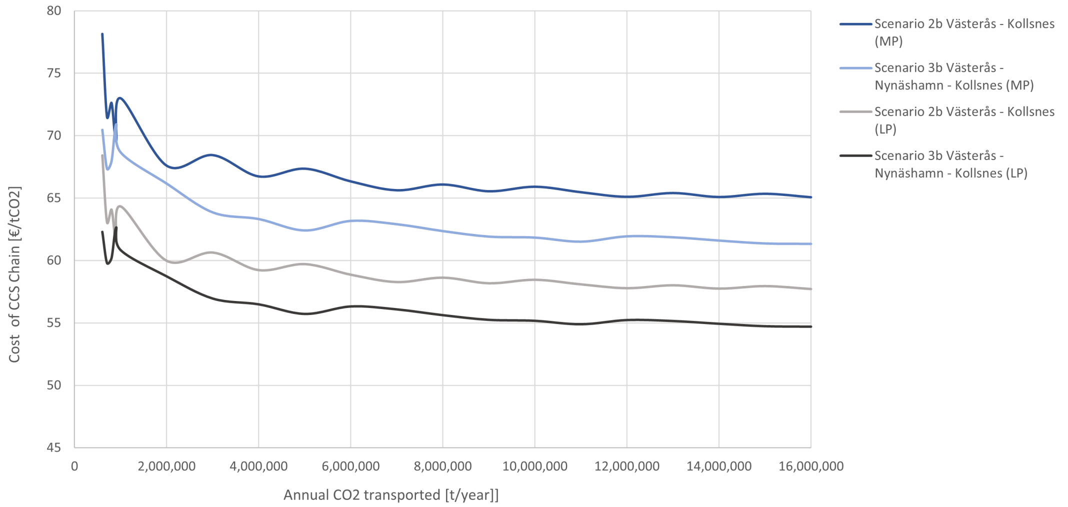

Figure B.2: Cost of the CCS chain as a function of flow rate for both transport pressure considering two routes from Västerås to Kollsnes.

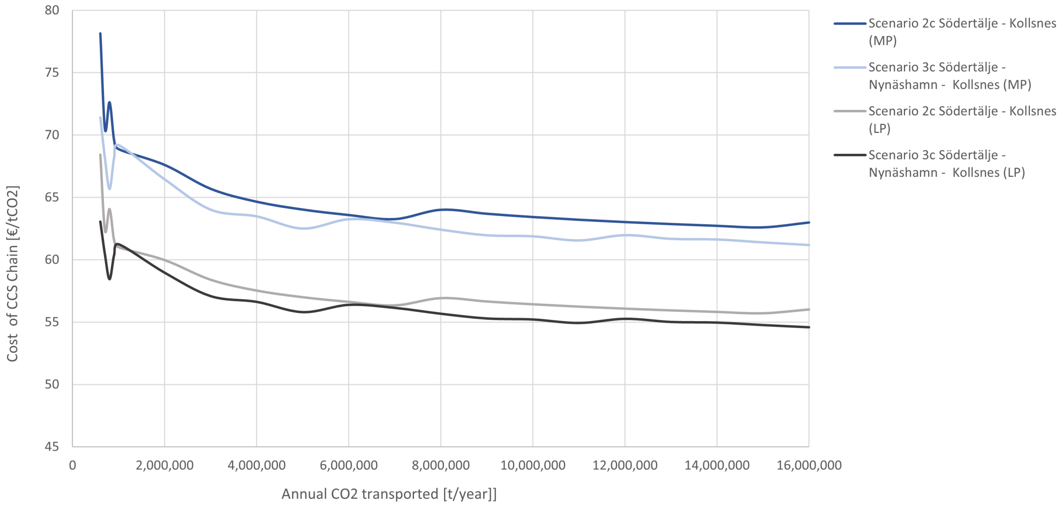

Figure B.3: Cost of the CCS chain as a function of flow rate for both transport pressure considering two routes from Södertälje to Kollsnes.

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