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Cost-optimal CO_2 transport systems for carbon capture and storage deployment

The impact of CO_2 conditioning standards, transport fleets and CO_2 volume captured in Sweden

Master's thesis in Sustainable Energy Systems

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Abstract

This thesis investigates the cost and composition of a Swedish system with large-scale implementation of CCS and how the implementation is affected by condition standards, route-flexible vehicle deployment and volume of CO_2 captured.

A mixed integer linear programming model that considers the cost of emitted CO_2 and each step in the CCS chain. The CCS chain in the model contains the capture and liquefaction processes, intermediate storage at sites and transportation hubs, transportation of captured CO_2, and the storage sites. The transportation modes considered in the model are ships, trains, trucks and pipelines. There are 3 conditions considered in the model, which are combinations of pressure and temperature during transportation. This model is applied to a case study where Swedish industrial plants with more than 100 kt annual CO_2 emissions are included. The model adds flexible deployment of vehicles . The system and how it is affected are investigated by constructing and comparing scenarios.

The modeling result shows that transportation is a relatively small part of the CCS cost, but this part can increase if there are limited transportation options. The model also shows that there are multiple ways to set up the system for similar specific chain costs when the base case and scenarios are compared. Systems with one condition are likely better than systems with multiple conditions. That a system with only pipelines is not viable in Sweden. The only difference between route-flexible and route-specific vehicles is the system composition. Higher volume of captured CO_2 have a small decrease in the specific cost. The preferred transportation mode in the model is ships with large capacity for long distances and trains for shorter distances. Trucks are also used for shorter distances due to locations missing the required infrastructure for trains.

Keywords: CCS, BECCS, CO_2 transportation, Cost minimization , Mixed integer linear programming

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Fredrik Gunnarsson, Gothenburg, June 2024

List of Acronyms

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

BECCS	Bioenergy Carbon Capture and Storage
C	Chemical plant
CCS	Carbon Capture and Storage
Ce	Cement and limestone plant
CHP	Heat and power plant
CLC	Chemical looping combustion
CO2	Carbon Dioxide
EA	Energy agency
EU	European Union
GAMS	General Algebraic Modeling System
GHG	Greenhouse gases
HP	High pressure
IOGP	International Association of Oil & Gas Producers
IS	Iron and steel plant
LNG	Liquefied natural gas
LP	Low pressure
MEA	Monothanolamine
MILP	Mixed integer linear programming
MP	Medium pressure
PP	Pulp and paper plant
R	Refinery

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1

Introduction

In 2015 most of the world agreed to limit the global average temperature increase to well below 2 °C and ideally under 1.5 °C compared to pre-industrial levels, in the Paris Agreement. The agreement also states that developed countries should lead the effort to achieve the targets [1]. To be able to follow the goals of the Paris Agreement other regulatory bodies have introduced their own laws and goals. The European Union (EU) has in the Green New Deal and the European Climate Law committed to having net zero emissions of greenhouse gas (GHG) by 2050. As a step on the way towards zero the net emissions of GHG should be reduced by at least 55% when compared to the level of 1990 by 2030 [2]. Sweden has adopted a climate policy framework with the goal of net zero GHG emissions by 2045 and negative net emissions after that [3].

A large reduction of net emissions of CO_2 is needed to reach the goal of net zero emissions. One way to reduce emissions is electrification of industry and transportation with emission-free electricity production. Another way is to substitute fossil feedstock with bio-based alternatives. A third way is the use of carbon capture and storage (CCS) for industries with otherwise unavoidable emissions like cement production. However, some emissions are hard to avoid and/or very costly to reduce. To compensate for these emissions, supplementary measures are needed to reach the targets. One of the measures is bioenergy CCS (BECCS) where biogenic CO_2 is captured and stored. The potential of BECSS is good in Sweden since there are around 70 plants with annual biogenic CO_2 emissions above 100 kt and the total emissions from these plants are above 30 Mt CO_2 annually. Most of these plants are found in either the pulp and paper industry or electricity and district heating production [3]. There are currently no incentives for CCS in Sweden. For fossil emissions, the EU ETS allowance price is currently lower than the cost of CCS. For biogenic emissions, there are no incentives but there are suggested incentives. One of these incentives is a reform of the EU ETS to include biogenic emissions. Another alternative is a government-run reverse auction where the government buys carbon removal from sellers [4]. The goal of BECCS incentives is to reach the proposed capture targets of biogenic CO_2, which is 1.8 Mtpa by 2030 and 3-10 Mtpa by 2045 [3].

The implementation of CCS needs to start soon in order to meet the targets set up for 2030. When a CCS system is implemented, many decisions are considered to get a cost-effective system, most of them are either technical or geographical. Two of these decisions are where the CO_2 is captured and where it is stored, which require knowledge about available capture and storage sites. Another decision is which transportation mode to use and how that decision is affected by the volume of CO_2, transportation distance and the choice of the condition of CO_2, i.e., the pressure and temperature of the CO_2 during transportation.

To investigate the implementation of a CCS system, mixed integer linear programming (MILP) models can be developed and applied to different countries or regions. One example is Becattini et al. [5], where a MILP model is used for the implementation of CCS at waste-to-energy plants in Switzerland with storage in Norway and includes the option of a national storage site in the future. The model shows that the most cost-effective mode of transportation is pipelines for cases with large CO_2 volumes (1.5 Mtpa) and longer planning time. Ships and barges are a cost-competitive alternative to pipelines. Trucks and trains are only viable options for low volumes of CO_2 or shorter planning times. Another example is d'Amore et al. [6], where the implementation of a CO_2 transport network for captured CO_2 at significant industrial sources in sectors like cement, steel and oil refining in the EU. The study shows that pipelines have a higher general importance to the transportation network than ships, but ships can be essential locally. The capture cost is the largest part of the system cost in the study. A third example is Bennaes et al. [7], where the implementation of a transport network from industrial plants in Germany to Norway for storage via a coastal CO_2 hub in Germany. The study includes different scenarios where between 5 and 100 Mt of CO_2 are captured and transported annually. The study shows that cost decreases when the CO_2 volume increases and that CCS could soon be an alternative due to the cost being similar to the EU ETS price. There is also an example for Sweden, Karlsson et al. [8], where CO_2 can be captured from point sources like industry and energy plants with emissions above 100 kt annually, liquefied on site, transported to transportation hubs by truck and from there transported by ship to a storage site in Norway. The incentive for CCS in this study is an annual BECCS target and a cost for fossil CO_2 emissions. Due to these incentives, the value for CCS from waste-fired CHP plants is higher than the value of capture from pulp mills, even if pulp mills have a lower specific CCS cost. This is caused by the mix of biogenic and fossil emissions from waste-based plants, which helps the system with both incentives. The study also shows that capture and liquefaction are the biggest costs, but the distances between capture site, transportation hub and storage site are also important for the cost.

In European systems pipelines are determined to be the preferred transportation mode, but there are possibilities for other transportation modes. In the Swedish system, only trucks and ships have been considered. More transportation modes are added in this thesis to see if they can have an impact on the Swedish system, which has longer distances and lower CO_2 flows compared to other systems in Europe. There is more than one possible condition of CO_2 during transportation and different transportation modes are available for each condition. Systems with one condition are compared to systems with multiple conditions to investigate the impact of the conditions in the Swedish system. Most transportation modes are vehicles, which can be flexibly deployed for transportation. In previous models in the Swedish system, vehicles have been route-specific investments and not utilized the vehicles' flexibility. To better showcase the flexibility, a vehicle fleet is introduced, which owns all vehicles and can route-flexibly deploy them. Sweden has a large potential for BECCS and if other countries were allowed to buy negative emissions from Sweden, more CO_2 would be captured in Sweden. To consider this possibility, systems with more CO_2 capture are also investigated in the thesis.

1.1 Aim

The overall aim of this work is to develop a model that design cost-optimal transportation systems for a broad implementation of CO_2 capture in Sweden. The model should consider where and when CO_2 is captured, CO_2 transportation mode, pressure and temperature the CO_2 has during transportation and which storage site the CO_2 is delivered to. The model should also consider the impact of the system composition of utilized transportation modes and locations.

The following questions are investigated:

- How the system composition and cost are affected by limitations regarding the mode of transportation and the condition of transported CO_2?
- How does the system composition and cost change in a system where vehicle investments are made for specific routes instead of being deployed flexibly for the whole system?
- How the system composition and cost are affected by different volumes of CO_2 captured and transported?

2

Theory

To implement CCS and prevent or reduce CO_2 in the atmosphere, a CCS supply chain is required, this chain is made up of five parts. An overview of the CCS chain and its parts is shown in Figure 2.1. The first part is to capture the CO_2. The second part is liquefaction and conditioning of captured CO_2. The third part is transportation of CO_2 from the place of capture to a storage site. The fourth part is intermediate storage that is used in combination with the transportation modes during transportation of CO_2. The last part is to permanently store the CO_2 at storage sites.

2.1 Capture of CO_2

There are many technologies with different technical readiness levels that can be used for the capture of CO_2 from point sources. Most of these can be categorized as pre-combustion or post-combustion technologies. All technologies have some kind of cost penalty for equipment, energy and/or materials. Pre-combustion technologies are upstream solutions that produce flue gas with mainly CO_2 and water vapor, which make CO_2 separation relatively easy and low-cost, through condensation of water vapor from flue gases. Examples of technologies are oxy-combustion, chemical looping combustion (CLC) and gasification or reforming of fuels. Both oxy-combustion and CLC separate oxygen from air before combustion. Oxy-combustion utilizes an air separation unit to separate oxygen from air. CLC utilizes oxygen carriers, which is a metal oxide that is reduced in a fuel reactor and then recycled and re-oxidized in an air reactor [9].

Post-combustion technologies separate CO_2 from nitrogen-rich flue gases after air combustion. There are a variety of mechanisms used to separate CO_2 from flue gas. Some of the most common mechanisms are absorption, adsorption, membrane and

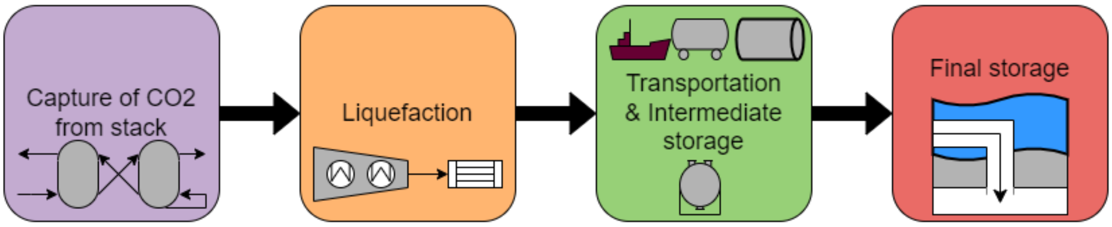


Figure 2.1: An overview of the CCS supply chain and the order of its parts.

cryogenic separation. Most post-combustion technologies can also be retrofitted to existing plants without impacting the process too much. The most commercially available mechanism is chemical absorption by amine-based solutions as it has been commercially used for over 50 years in the gas industry [9]. The steam demand for the reboiler in an amine-based system depends on the amine solution but it is typically between 0.7-1 MWh per ton CO_2 captured [10]. There are many solvents available for amine-based chemical absorption, but monoethanolamine (MEA) is the most common solvent [9] and is often used as the benchmark technology when comparing solvents [11].

The first step of chemical absorption is that cleaned flue gas enters the absorber where CO_2 is separated by reacting with the solvent. The next step is the stripper, where the CO_2-rich solvent is regenerated by steam and the captured CO_2 desorbed. After the stripper, the regenerated solvent is reused in the absorber and the desorbed CO_2 is cooled to remove water vapor before conditioning and transportation [12].

2.2 Liquefaction

Liquefaction is used to increase the density of CO_2 which improves the efficiency of transportation and storage of CO_2 [10]. A process overview for liquefaction is presented in Figure 2.2. The liquefaction process utilizes an intercooled compression train to pressurize the captured CO_2 from 1 bar and 40 °C before the train to the desired pressure after. Each compression stage of the train consists of a compressor, cooler and a flash separator to remove condensed water. Impurities are removed from the CO_2 stream after the compression train before being cooled. The CO_2 is first pre-cooled to 25 °C and then condensed by an ammonia refrigeration cycle-based liquefier. The next step in the process after the liquefier is a flash tank that separates uncondensed gas containing impurities and some CO_2. The last step in the process is a second flash tank where the liquid stream goes through a valve before the tank to reduce the pressure to the desired delivery pressure. After the second flash tank, the liquid stream is ready for transport which is stored in an intermediate storage. The gas stream is recirculated and mixed before the pre-cooler, but before mixing a compressor is needed to increase the pressure of the gas stream to the liquefaction pressure [13].

The power and cooling demand of the liquefaction process is modeled in Deng et al. [13] for delivery pressures within the pressure range of 7-70 bar. The flow of CO_2 for all pressures is 37.31 kg/s in the study. The power demand for the compressors is around 12-13 MW for all pressures considered. The cooling demand is above 40 MW for the lowest pressures and decreases when the delivery pressure and temperature are increased. The cooling demand is for all cooling in the process that is not done by the ammonia refrigeration cycle and is satisfied by utilizing cooling water.

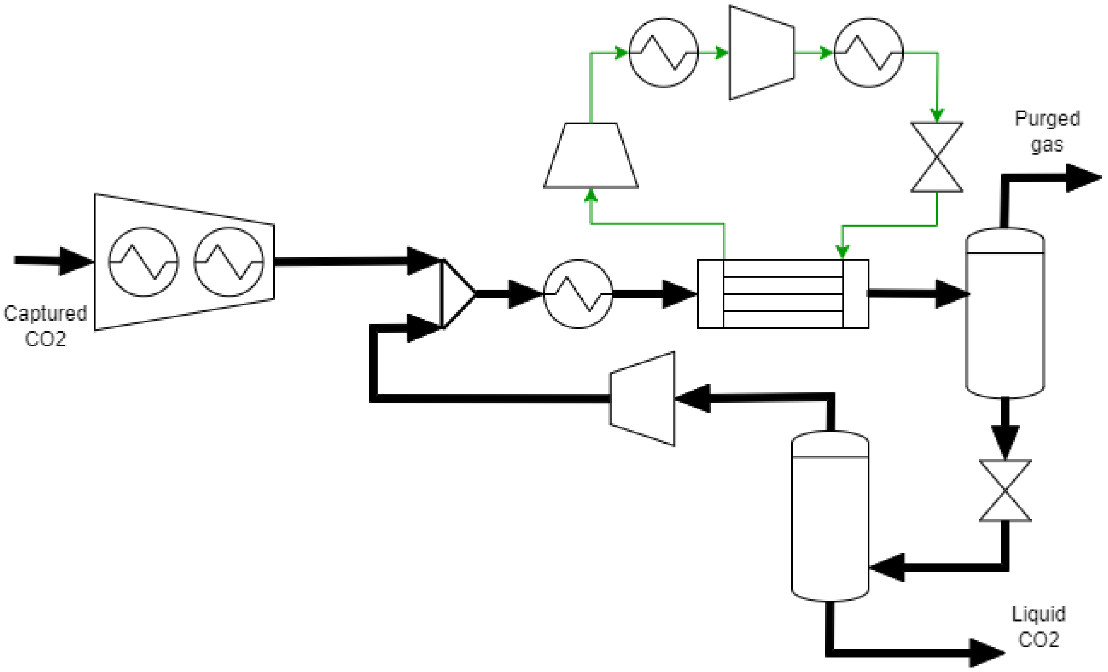


Figure 2.2: A overview of the liquefaction process. Black arrows are CO_2 streams and green arrows are part of the ammonia refrigeration cycle. Inspiered by Deng et al. [13].

2.3 Transportation modes

In literature, up to 4 different transportation modes are mostly considered for the transportation of CO_2. These are trucks, ships, trains and pipelines [9], [10], [14].

2.3.1 Truck

Transportation of liquid CO_2 from distribution hubs to industrial consumers is commonly done by tanker trucks today. The industry standard conditions for the transportation of liquid CO_2 is 15-18 bar and between -25 and -30 °C. To keep the low temperatures, the tanks on the trucks are isolated by vacuum or polyurethane foam. Truck transport is mostly relevant for small to medium volumes of CO_2 [10]. It is assumed in the ZEROC project [14] that truck transportation has the same conditions as the rest of the transport chain, which was 7 bar and -50 °C in that project. Parameters from different sources are presented in Table 2.1 for comparison.

2.3.2 Ship

Transportation of liquid CO_2 by ship has been done for over 3 decades for the food and beverage industry. But both the annual flow and the capacity of the ships are smaller than the scale required for CCS projects. The ships used for the food and beverage industry are mostly operated under the conditions of the medium pressure level, which is one of three possible conditions that are discussed for CO_2 transport

Table 2.1: Values of relevant parameters about truck transportation from literature.

	References		
Parameter	Danish EA [10]	ZEROC [14]	Oeuvray [15]
Capacity [t_{CO_2}]	30	50	26
Speed [km/h]	50	60	-
Loading/Unloading time [h]	0.75/0.75	-	0.75/1
Pressure [bar]	15	7	16
Temperature [°C]	-28	-50	-27
Operating time [h]	7760[a]	7300[b]	8500
Annual salary per truck [k€]	365[c]	-	186[d]
CAPEX truck [k€]	660	-	-
Fuel consumption [l/km]	0.5	-	-

[a] 1000 h maintenance per year.

[b] The vehicle is utilized 20 h per day.

[c] Calculate from operating time and an hourly salary of 47 €/h.

[d] Calculate from operating time and an hourly salary of 21.9 €/h.

by ship. For all three conditions, the temperature of the liquid CO_2 is similar to the temperature of saturated liquid at these pressure levels. The low pressure (LP) level has a pressure in the range of 5.5-9.8 bar and -55 to -41 °C is the temperature range. The already mentioned medium pressure level has a temperature between -30 and -19.5 °C and the pressure range is 14-20 bar. The high pressure (HP) level has a pressure between 45-72 bar and the temperature is between 10-30 °C [16]. However, in literature are mostly LP and/or MP considered [10], [15], [17], [18] , which can be seen in Table 2.2 where an overview of parameters from different literature regarding ship transportation are presented.

Table 2.2: Values of relevant parameters about ship transportation from different literature.

Parameter	ZEROC [14]	Danish EA [10]	Oeuvray [15]	Kjärstad [19]	Element Energy[16]	Bjerketvedt [18]
Included conditions	LP	MP	LP,MP	LP	LP,MP,HP	LP,MP
Speed [knots]/[km/h]	12/22	15/28	-	12/22	15/28	
Loading/Unloading time [h]	-/-	12/12	-/-	16/54[a]	15/36[a]	
Capacity interval LP [kt$_{CO2}$]	12-42	-	2.5-50	-40	2-50	2.5-45
Capacity interval MP [kt$_{CO2}$]	-	4-10	2.5-10	-	2-10	2.5-10
Capacity interval HP [kt$_{CO2}$]	-	-	-	-	2-10	-
CAPEX LP[b] [M€]	-	-	-	31[c]	14.4-83.0[d]	16.2-80.9
CAPEX MP[b] [M€]	-	40.0- 60	-	-	31.3-69.8[d]	34.0-67.8
CAPEX HP[b] [M€]	-	-	-	-	62.6-140.7[d]	-
Fuel consump. [t/h]	-	90-180	-	1.05[c,e]	233-415	-
Operating time [h]	-	7884[f]	8400	8400	8322	-
Lifetime [years]	-	40	-	-	-	-
Harbor costs [€/trip]	-	-	-	2.33 C[g]	5559.3 + 0.4635 C[g]	-

[a] Time for offshore unloading, for onshore is the time similar to loading.

[b] Presents the lowest and highest CAPEX for the condition category.

[c] Values for 11.5 kt capacity ship (10 000 m^3 and 1.15 t/m^3).

[d] Converted costs from £ to €.

[e] The value has another unit (t/h) instead of MWh/day.

[f] 90 % availability due to weather and maintenance.

[g] C is the capacity of the ship in t$_{CO2}$.

One of the advantages of LP conditions is that the density of the liquid CO_2 increases with decreasing pressure [20]. Another advantage is the thinner thickness of the storage tank walls. The wall thickness increases to withstand the pressure when the pressure is increased. Increased wall thickness decreases the maximum size of the tanks, which means that more tanks are required, which leads to a lower utilization rate of the ship's cargo volume as the tanks must have a certain distance between them [16]. However, with lower pressure, there is less margin to the triple point, increasing the risk of liquid CO_2 becoming solid in the tank, which should be avoided [20]. In Roussanaly et al. [17] the cost of the LP condition with an operating pressure of 7 bar and the MP condition with an operating pressure of 15 bar are compared. The main result of this study is that 7 bar ships are the better option as it has a lower cost per ton of CO_2 transported. This is explained by the larger ship capacities available for the 7 bar option and that CAPEX of a 15 bar ship is doubled compared to a 7 bar ship with the same capacity. However, there are currently no ships for the transport of CO_2 at LP conditions and further development is required. Another possible problem with LP conditions is that the temperature of the CO_2 is around -50 °C, which could limit the choice of material. The ships ordered for the first stage of the Northern Light project are all operating within the MP condition [20].

2.3.3 Train

Transportation of CO_2 by train is done batch-wise where liquid CO_2 is transported by cryogenic tanks on rail cars. There are higher uncertainties with CO_2 transport by train due to a low amount of data in the literature [21] and trains not being considered an option in a CCS chain due to relevant locations, e.g. emission sources, not being connected to the railway network in some countries [10]. The uncertainty is shown in Table 2.3 where different literature values are presented for some parameters.

2.3.4 Pipeline

Transporting CO_2 by pipeline has been done globally for decades and is a mature technology. In the United States there were over 8000 km of CO_2 pipelines in 2017, where they are primarily used for enhanced oil recovery [22].

The phase of the CO_2 transported by pipeline is either gas or dense phase with ambient temperatures [15]. The CO_2 is considered to be in the dense phase when the operating pressure is above critical pressure and the temperature is below the critical temperature, which is 73.8 barg and 31 °C for CO_2. The dense phase is desirable in pipelines as there are small thermal losses due to the ambient temperatures of the transported CO_2 and it avoids phase shifts, which are not wanted when transporting CO_2 in pipelines.

Table 2.3: Values of relevant parameters about train transportation from different literature.

	References		
Parameter	ZEROC [14]	Oeuvray [15]	Roussanaly [21]
Wagon capacity [t]	60-70	50	240[a]
Number of wagons per train	30	20	20
Speed [km/h]	-	18	60
Loading/Unloading time [h]	-	-/18	5/5
Operating time [h]	-	8760	-
Investment cost wagon [k€]	-[b]	-[b]	936[c]
Investment cost locomotive [M€]	-[b]	-[b]	11.08[d]

[a] Capacity based on volume of certain wagon model.

[b] Unitary costs presented, but not part specific.

[c] Based on wagon capacity that a costs 3.9 k€/t_{CO_2}.

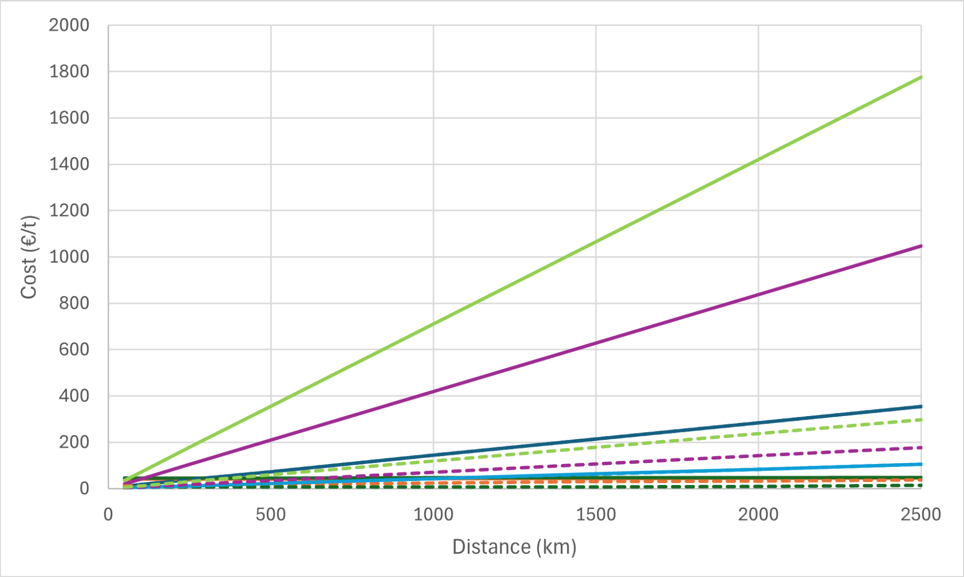
[d] Based on max train capacity and calculated by an equation in the source.

The dense phase is the standard condition for transportation distances longer than 400 km. The operation is usually between 80-150 bar, which is a compromise between operating range to allow for pressure drops and increased cost from thicker pipe walls to be able to handle higher pressure [10].

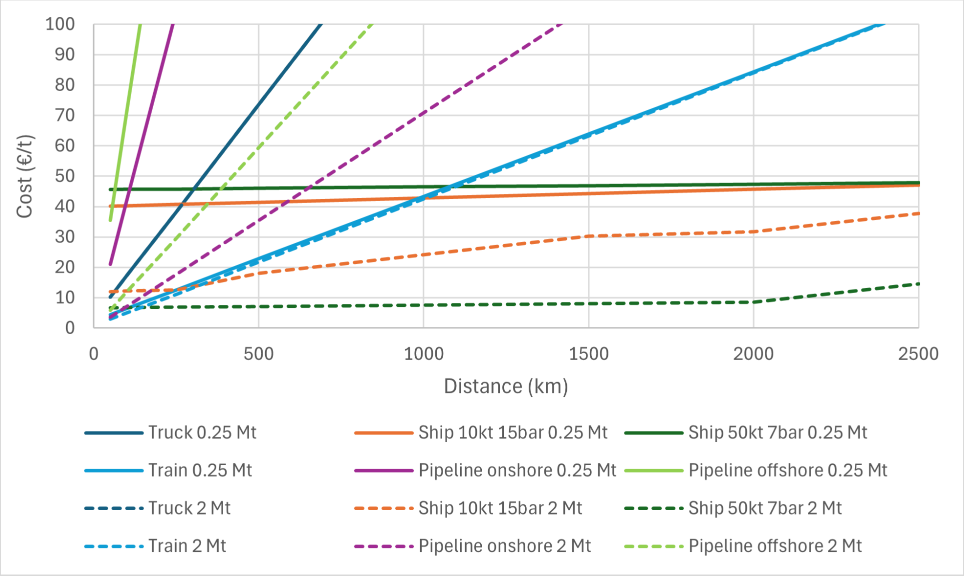
2.3.5 Comparison of transportation modes

To compare the cost of the transportation modes presented, example graphs were produced. These graphs are based on data and equations presented in the method. The cost of transportation is calculated by dividing the sum of annualized CAPEX and OPEX for the transportation mode by the amount of CO_2 transported that year.

Figure 2.3 presents the cost of transporting 0.25 Mtpa and 2 Mtpa of CO_2 over different distances. The trend in the figure is that the cost of transport by truck, train and pipeline has a linear increase corresponding to the transportation distance. The costs for ships are basically constant when the same number of ships are required for transportation, but the cost increases when more ships are needed to cover the distance.



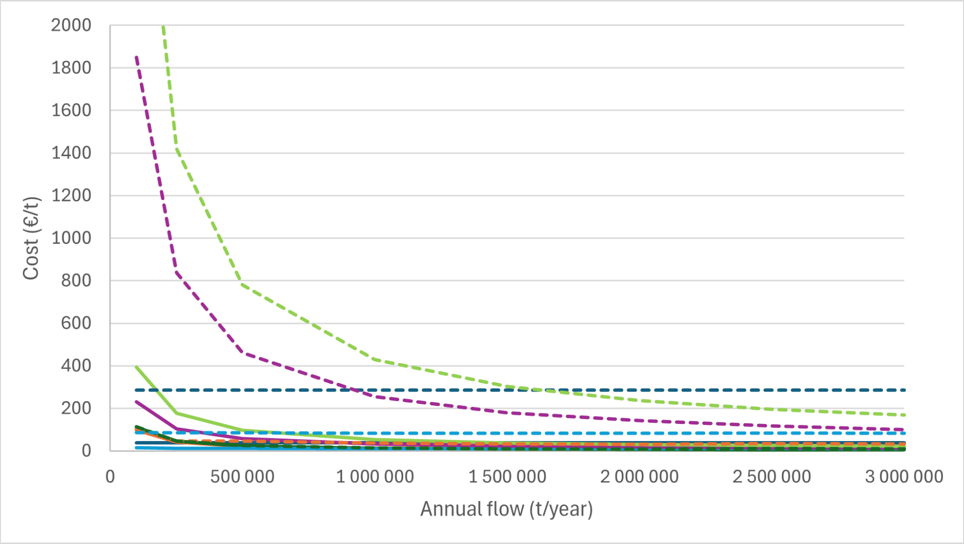
(a)



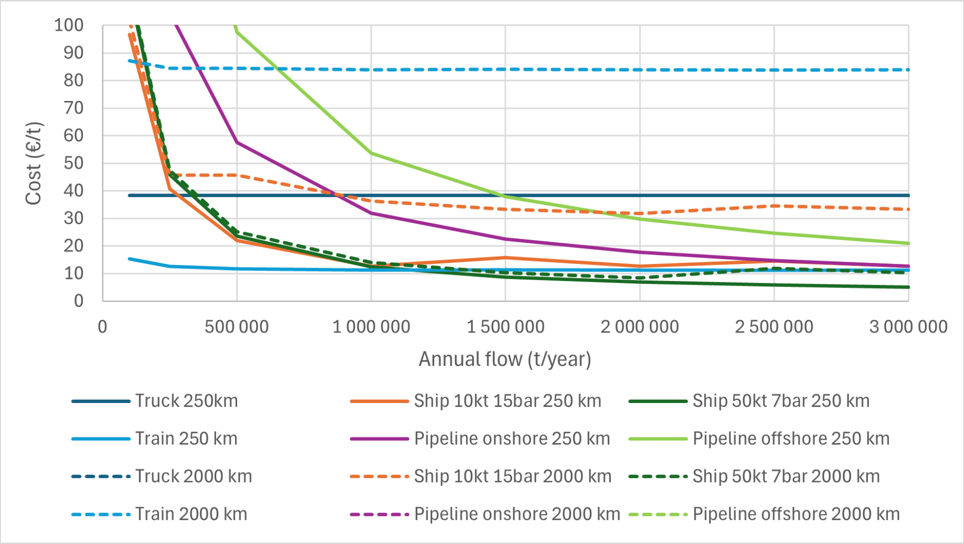
(b)

Figure 2.3: The cost of transporting CO_2 as a function of distances when the annual flow of CO_2 are 0.25 Mt (full lines) and 2 Mt (dashed lines) are presented in **(a)** and **(b)**, but **(b)** cut the y-axis a 100 €/t.

Figure 2.4 presents the cost of transporting different flows of CO_2 when the transportation distances are 250 km and 2000 km. The trend for trucks and trains is that the cost is almost constant regarding the annual flow transported. For ships and pipelines, the trend is that cost exponentially decreases and stabilizes for higher flows. Pipelines stabilize slower than ships. When the cost of ships has stabilized, small waves can be seen, which are caused by more ships being needed to handle higher flows.



(a)



(b)

Figure 2.4: The cost of transporting CO_2 as a function of CO_2 flows when the transportation distances are 250 km (full lines) and 2000 km (dashed lines) are presented in **(a)** and **(b)**, but **(b)** cut the y-axis a 100 €/t.

2.4 Intermediate storage

When transportation is done by truck, train or ship, intermediate storage is required [14] due to the liquefaction process being continuous while transportation by vehicles is a batch process. To enable fast loading, the storage capacity of the intermediate storage should at least have the same capacity as the vehicle. But there should also be extra capacity so that the capture and liquefaction process can avoid stops due to a full storage tank caused by unexpected delays. But there is no need for sizing storage for extraordinary cases as CO_2 can be released into the air if delays occur.

Table 2.4: Values of relevant parameters about intermediate storage from different literature.

	References			
Parameter	Danish EA [10]	Bjerketvedt [18]	Element Energy [16]	ZEROC [14]
CAPEX 7 bar [k€/t_{CO_2}]	-	478	580[a]	3484[b]
CAPEX 15 bar [k€/t_{CO_2}]	3800	867	956[a]	-
OPEX 7 bar [k€/t_{CO_2}]	-	26	29[a,c]	140[b,d]
OPEX 15 bar [k€/t_{CO_2}]	114	48	48[a,c]	-
Buffer capacity[e]	-	-	0-50%	25%
Lifetime [years]	25	-	-	-

[a] Converted from £ to €.
[b] Converted from SEK to € and assumed density of 1.15 t/m^3.
[c] Determined as 5 % of CAPEX.
[d] Determined as 4 % of CAPEX.
[e] Extra capacity for unforeseen situations.

There is no consensus in the literature on how large the buffer capacity should be [16]. In Table 2.4 the buffer capacity and other parameters with uncertainty, like costs, are presented for comparison.

The material used for the storage tanks depends on the conditions of the stored CO_2. For MP conditions carbon steel is used for the walls and polyurethane or vacuum for insulation. Proposed materials to use for LP in literature are carbon manganese steel, stainless steel and low temperature steel [10], [16].

2.5 Final storage

Most sites that are considered currently for final storage are different kinds of geological structures or formations deep below the ground. These sites can be found both on land and offshore under the sea. The most important characteristic of the storage site is that it can store the CO_2 for a long time with negligible leakages [9]. In a Norwegian cost estimation tool for CCS, pressure and temperature at the wellhead is set to 80 bar and 5 °C, but the wanted pressure range in the future is 80-200 bar [20].

The first commercial storage for climate mitigation was the Sleipner CCS project, where CO_2 has been stored in a saline formation under the sea bed of the North Sea 250 km off the shore of Norway since the middle of the 1990s. There have been earlier projects since the 1970s, but they did not target climate mitigation even if they captured and stored CO_2. In 2020 there were 26 storage facilities in operation and they had together an annual storage capacity of around 40 Mt CO_2, almost a factor of 1000 smaller than 37 Gt CO_2, which is the annual emissions globally. Suitable storage sites are not available everywhere in the world, but there is a good overlap between the locations of large emissions sources and potential storage sites [9].

There is potential for Swedish storage sites but the knowledge about these sites is poor. Therefore, using storage sites in other North Sea countries is a more realistic alternative for the storage of CO_2 captured in Sweden [3]. There are multiple projects developing storage sites in Norway and Denmark that can be potential storage sites for Swedish CO_2. The total projected capacity of all projects in Norway and Denmark is presented in Figure 2.5 based on data from the International Association of Oil & Gas Producers (IOGP) [23]. Most of these projects are located in the North Sea, which is an area with the potential for even more storage sites in the future[24].

One of the projects presented is Northern Lights where CO_2 is received at an onshore terminal near Kollsnes on the Norwegian west coast and then transported by pipeline to an offshore saline aquifer. The project will start operation in 2024 with an annual storage capacity of 1.5 Mt [25]. Another project is Greensand which utilizes depleted oil fields in the Danish part of the North Sea, the planned full-scale capacity of the project is 1.5 Mt per year by 2025/2026 and 8 Mt by 2030. In March 2023 was the world's first cross-border offshore CO_2 storage made under the project when CO_2 captured in Antwerp, Belgium, was transported to and stored in Denmark [26].

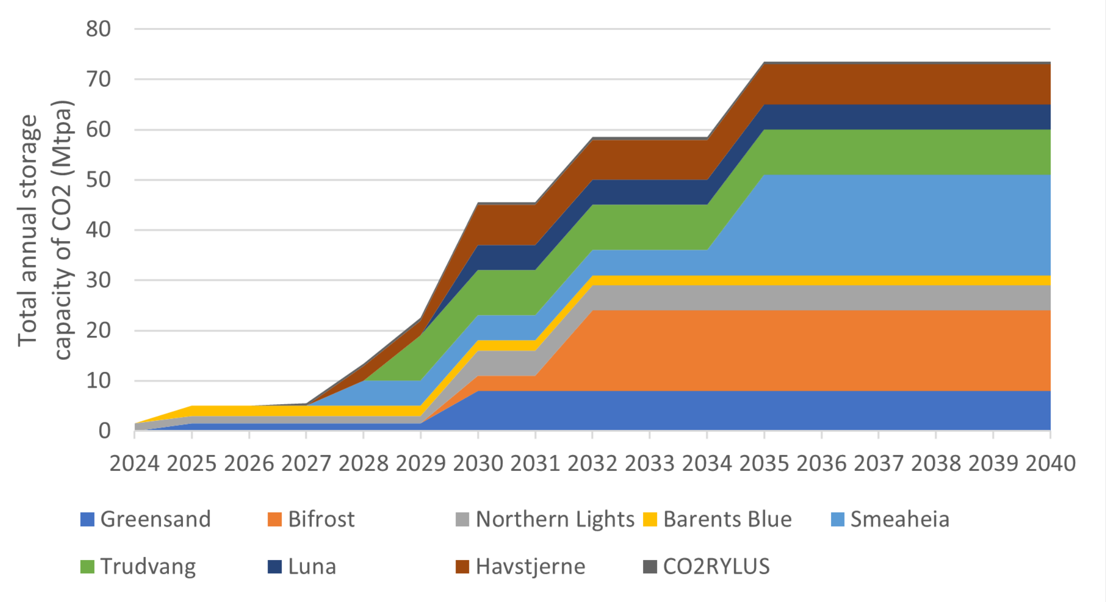


Figure 2.5: Total projected storage capacity in Norway and Denmark between 2024-2040 based on data from IOGP [23].

3

Methods

The method consists data collection, construction and development of the model, creation of different scenarios and analysis of the obtained results. A flowsheet of how these parts produce results is presented in Figure 3.1. The data collected is used as parameters in the model and is split into two categories, techno-economic data, where costs and capacities of technologies are included, and case-specific data, which includes the location of plants, the emissions of each plant, distance between different locations and infrastructure for different transportation modes. The model utilizes the data to find a cost-optimal solution based on the variables and constraints set. Scenarios are used to vary some parameters, variables or constraints that could impact the results of the model. The results from the model are analyzed and then compared to the results from other scenarios to understand the impact of the change between the scenarios.

3.1 Modeling

To find the cost-optimal implementation of a CCS chain in Sweden, a model is developed by expanding an existing model presented in Karlsson et al. [8]. The model is implemented in version 44 of the General Algebraic Modeling System (GAMS) where the net present value of the system cost is minimized by MILP optimization. An overview of the model is shown in Figure 3.2. In the model, multiple sites are

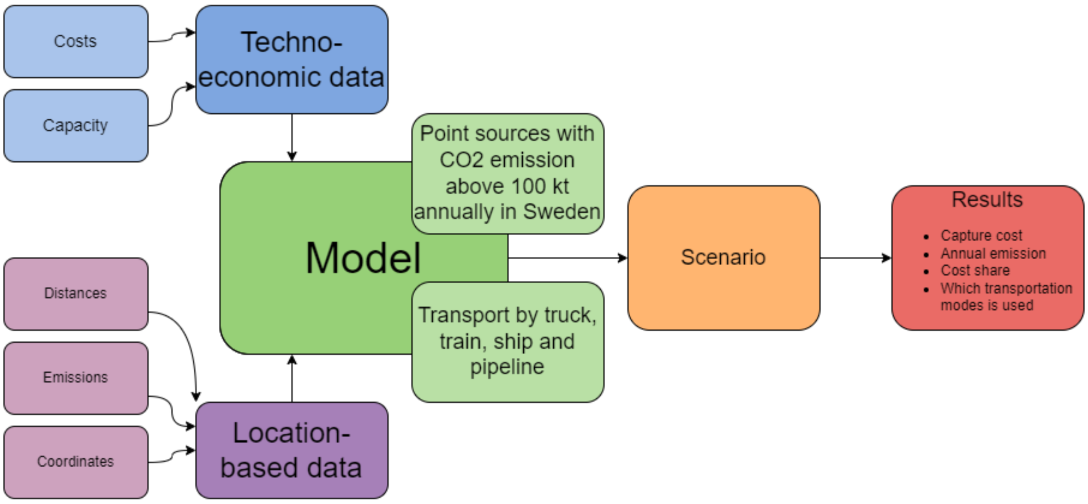


Figure 3.1: Overview of the methodology used in the project.

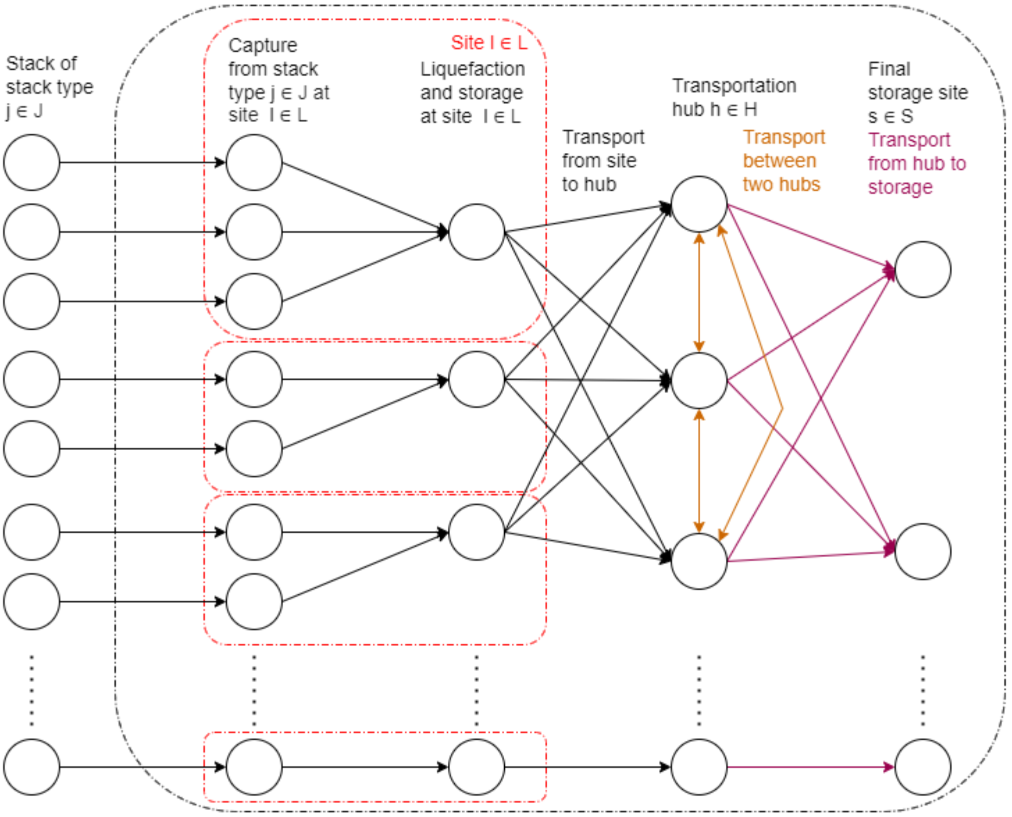


Figure 3.2: An overview of the system included in the model. The black dashed line indicates the parts that are considered for the objective function. The red dashed line shows parts located at site l L.

included. At each site, there is at least one stack where CO_2 can be captured. The liquefaction process changes the pressure and temperature of the captured CO_2 from all stacks at that site to prepare for the transportation of the CO_2. The CO_2 is first transported by land-based transportation modes from the site to a transportation hub. From the transportation hub, the CO_2 is either transported to a storage site for permanent storage or to another hub for continued transportation, with the possibility to use both land- and water-based transportation modes. A list of all nomenclature used in the model and their unit can be found in Appendix B.

Costs in the model are given in € from 2020. Other currencies are converted to € based on the exchange rate of that year from the European Central Bank [27]. Costs from other years than 2020 are adjusted with CEPCI [28].

The objective function of the model is presented in Equation 3.1

$$\min c^{tot,NPV} \geq \sum_{y \quad Y} \frac{c_y^{annual}}{(1+r)^{y-2025}} \tag{3.1}$$

where $c^{tot,NPV}$ is the net present value of the total system cost of CCS implementation between 2025-2050, and r is the discount rate, which is set to 8 % in the model. The time steps used in the model are 1 year long and indicated by index y. The annual system cost in year y, c_y^{annual} is the combined cost of all installed infrastructure, vehicles and CO_2 emitted, which is calculated by Equation 3.2

$$\begin{aligned}
c_y^{annual} \geq & \sum_{l \in L}\sum_{j \in J}\left(c_{l,j,y}^{CAPEX,capture} + c_{l,j,y}^{OPEX,capture}\right) + \sum_{l \in L}\sum_{i \in I}\left(c_{l,i,y}^{CAPEX,liq}\right. \\
& \left. + c_{l,i,y}^{OPEX,liq} + c_{l,i,y}^{CAPEX,storage-liq} + c_{l,i,y}^{OPEX,storage-liq}\right) \\
& + \sum_{h \in H}\left(c_{h,y}^{CAPEX,storage-hub} + c_{h,y}^{OPEX,storage-hub}\right) \\
& + \sum_{l \in L}\sum_{h \in H}\sum_{k \in K}\sum_{i \in I}\left(c_{l,h,k,i,y}^{CAPEX,transport-liq} + c_{l,h,k,i,y}^{OPEX,transport-liq}\right) \\
& + \sum_{h \in H}\sum_{h' \in H}\sum_{k \in K}\sum_{i \in I}\left(c_{h,h',k,i,y}^{CAPEX,transport-hub} + c_{h,h',k,i,y}^{OPEX,transport-hub}\right) \\
& + \sum_{h \in H}\sum_{s \in S}\sum_{k \in K}\sum_{i \in I}\left(c_{h,s,k,i,y}^{CAPEX,transport-storage} + c_{h,s,k,i,y}^{OPEX,transport-storage}\right) \\
& + \sum_{et \in ET} c_{et,y}^{emission} + \sum_{k \in K} c_{k,y}^{fleet,unused} + \sum_{s \in S} c_{s,y}^{storage} \quad \forall y \in Y
\end{aligned} \tag{3.2}$$

where most terms are the annualized CAPEX, $c_y^{CAPEX,\cdot}$, and OPEX, $c_y^{OPEX,\cdot}$, of year y for different parts of the CCS chain. The annual cost of fossil emissions and earnings of capturing biogenic emissions during the year y is represented by $c_{et,y}^{emission}$. To include the costs of annualized CAPEX and maintenance for unused vehicles in the fleet of transportation mode k during year y is the unused fleet cost, $c_{k,y}^{fleet,unused}$, added to the annual cost of the system as they would be missed in model otherwise. The cost of permanently storing CO_2 at storage site s in year y, $c_{s,y}^{storage}$, is calculated by Equation 3.3.

$$c_{s,y}^{storage} \geq z_{s,y} \cdot SC_s \quad \forall s \in S \quad \forall y \in Y \tag{3.3}$$

In the equation, $z_{s,y}$ is the amount of CO_2 stored at storage site s during year y and SC_s is the specific cost of storing CO_2 at storage site s.

Annuity factors, α, are used to spread the investment cost of infrastructure over its lifetime, LT, and are calculated as shown in Equation 3.4.

$$\alpha = \frac{r}{1-(1+r)^{-LT}} \tag{3.4}$$

The installed capacity of one type of equipment each year is determined by an equation that considers already existing capacity, capacity added from new investments and lost capacity due to equipment exceeding its technical lifetime. The installed capacity is the equipment capacity available for use, most equipment capacity is specific for each location. A general version of this equation is presented in Equation 3.5

$$b_y = b_{y-1} - a_{y-LT} + a_y \quad \forall y \in Y \tag{3.5}$$

where b_y is the installed capacity during year y, b_{y-1} is the installed capacity during the year before year y, a_y is the added capacity due to new investments during year

y and a_{y-LT} is capacity have exceeding its technical lifetime, LT, and can no longer be used. This equation is applied to all capacities included in the model. The cost of annualized CAPEX during year y, c_y^{CAPEX}, is calculated by the general equation that is presented in Equation 3.6 and is used for all equipment in the model.

$$c_y^{CAPEX} \geq b_y \, \beta \, \alpha \quad y \quad Y \tag{3.6}$$

In the equation, β is the CAPEX of the equipment considered. The fixed OPEX for year y, c_y^{fixed}, is applied for all equipment and is calculated by the general equation presented in Equation 3.7.

$$c_y^{\text{fixed}} \geq b_y \, \beta \, \theta \quad y \quad Y \tag{3.7}$$

In the equation, θ is a term that can contain the cost of operation and/or maintenance of the equipment , which is defined as a percentage of the CAPEX.

3.1.1 Capture and liquefaction

The assumed capture technology in the model is MEA-based absorption with 90 % capture rate. The liquefaction process is used to change the pressure and temperature of the CO_2 to one of the 3 conditions included in the model. The first condition is "7 bar" and is an LP option with a pressure and temperature around 7 bar and -48 °C. The second condition is "15 bar", which is an MP option with a pressure around 15 bar and -28 °C as the temperature. The last condition is "110 bar", which is an option where the CO_2 is conditioned for pipeline transportation.

The cost of capture and liquefaction in the model is made up of two parts each, annualized CAPEX, which is determined by Equation 3.6, and OPEX. The OPEX for capturing process is determined by Equation 3.8

$$c_{l,y}^{OPEX,capture} \geq \sum_{j \quad J} \left(c_{l,j,y}^{fixed,capture} + x_{l,j,y}^{stack} q^{reboiler} f^{steam} \right) \quad y \quad Y, \quad l \quad L \tag{3.8}$$

where $x_{l,j,y}^{stack}$ is the CO_2 captured and liquefied at site l from stack j in year y, $q^{reboiler}$ is the steam demand for the capture process and f^{steam} is the cost of producing steam for the process. The OPEX of the liquefaction process is calculated by Equation 3.9

$$c_{l,i,y}^{OPEX,liq} \geq c_{l,i,y}^{fixed,liq} + b_{l,i,y}^{liq} \text{OPEX}_i^{liq} \quad y \quad Y, \quad l \quad L, \quad i \quad I \tag{3.9}$$

where $b_{l,i,y}^{liq}$ is the installed capacity for liquefaction to condition i at site l in year y and OPEX_i^{liq} is the operational cost for liquefaction to condition i. In Table 3.1 is all economic data regarding capture and liquefaction presented, except specific CAPEX for capture, which is different for each stack due to different CO_2 concentrations in the flue gas which affects the cost of capture. The values for CAPEX of capture are based on the method from Johnsson et al. [29].

The captured CO_2 flow, installed capture capacity and installed liquefaction capacity are limited by Equations 3.10, 3.11 and 3.12, respectively

Table 3.1: Economic data for capture and liquefaction processes.

Parameter	**Value**	**Unit**	**Reference**
Lifetime of equipment	25	years	[10]
Annual operational time for plants and liquefaction	7980	h	Assumed
Fixed OPEX capture	3	% of CAPEX	[10]
Fixed OPEX liquefaction	6	% of CAPEX	[13]
Steam demand for reboiler	1	$\frac{\text{MWh}}{\text{t}_{\text{CO}_2}}$	[10]
Cost of steam	20	$\frac{€}{\text{MWh}}$	Assumed[a]
CAPEX of liquefaction (7 bar)	50.5	$\frac{€}{\text{t}_{\text{CO}_2}}$	[13]
CAPEX of liquefaction (15 bar)	47.3	$\frac{€}{\text{t}_{\text{CO}_2}}$	[13]
CAPEX of liquefaction (110 bar)	53.5	$\frac{€}{\text{t}_{\text{CO}_2}}$	[29][b]
OPEX of liquefaction (7 bar)	7.3	$\frac{€}{\text{t}_{\text{CO}_2}}$	[13]
OPEX of liquefaction (15 bar)	6.7	$\frac{€}{\text{t}_{\text{CO}_2}}$	[13]
OPEX of liquefaction (110 bar)	9.7	$\frac{€}{\text{t}_{\text{CO}_2}}$	[29][b]

[a] 1/3 of the assumed electricity price, which is 60 €/MWh.

[b] Based on the method from the article.

$$x^{stack}_{l,j,y} \leq \mathrm{CO2}^{capture,max}_{l,j} \qquad l \quad L \quad j \quad J \quad y \quad Y \tag{3.10}$$

$$x^{stack}_{l,j,y} \leq b^{capture}_{l,j,y} \qquad l \quad L \quad j \quad J \quad y \quad Y \tag{3.11}$$

$$\sum_{h \quad H} \sum_{k \quad K} x^{liq}_{l,h,k,i,y} \leq b^{liq}_{l,i,y} \qquad l \quad L \quad i \quad I \quad y \quad Y \tag{3.12}$$

where $\mathrm{CO2}^{capture,max}_{l,j}$ is the maximum amount of capturable $\mathrm{CO_2}$ from stack j at site l . $x^{liq}_{l,h,k,i,y}$ is the $\mathrm{CO_2}$ flow from the liquefaction at site l to transportation hub h with transportation mode k under condition i during year y. The maximum amount of capturable $\mathrm{CO_2}$ is equal to 90 % of the total $\mathrm{CO_2}$ emission of the stack.

3.1.2 Intermediate storage

There is a need for intermediate storage both after the liquefaction process and at the transportation hubs. For both locations, the annualized CAPEX is determined by Equation 3.6 and the OPEX is only a fixed cost and therefore calculated by Equation 3.7.

After the liquefaction process, intermediate storage tanks are built for specific conditions before transportation by batch-wise transportation modes, which are all modes except pipelines. Pipelines do not need intermediate storage as the transportation is continuous. At the transportation hubs, it is assumed that the intermediate storage tank only has one condition that can be utilized for storage of all incoming $\mathrm{CO_2}$, regardless of the condition of the incoming $\mathrm{CO_2}$. This is due to the cost of changing

Table 3.2: Economic data for intermediate storage after liquefaction and at transportation hubs.

Parameter	Value	Unit	Reference
Lifetime of equipment	25	years	[10]
Operation and maintenance cost	5	% of CAPEX	[16]
CAPEX for liquefaction storage (7 bar)	580	$\frac{\text{€}}{\mathrm{t}_{\mathrm{CO}_2}}$	[16]
CAPEX for liquefaction storage(15 bar)	956	$\frac{\text{€}}{\mathrm{t}_{\mathrm{CO}_2}}$	[16]
CAPEX for hub storage	956	$\frac{\text{€}}{\mathrm{t}_{\mathrm{CO}_2}}$	Assumed

from one condition to another is not available in literature and therefore excluded from the model when multiple conditions are available. Economic data for the equations regarding intermediate storage is presented in Table 3.2.

The intermediate storage capacity is sized to include a safety margin in case of an unexpected delay. The installed capacity of intermediate storage after liquefaction should be able to hold 48 hours of CO_2 flow. The capacity of the intermediate storage at the transportation hubs should be 120 % of the capacity of the large ship (50 kt). Both of these limits are represented by Equations 3.13 and 3.14 respectively.

$$b^{storage,liq}_{l,i,y} \geq \sum_{h \quad H} \sum_{k \quad K} \left(\frac{t^{\text{buffer}}_{liq} \quad x^{liq}_{l,h,k,i,y}}{t^{op}_{eq}} \right) \quad l \quad L \quad i \quad I \quad y \quad Y \tag{3.13}$$

$$b^{storage,hub}_{h,y} \geq p^{ship,50kt} 120\% \; \gamma_{h,y} \; h \quad H \quad y \quad Y \tag{3.14}$$

In these equations, t^{eq}_{op} is the annual operational time for equipment and plants, t^{buffer}_{liq} is the buffer for storage after liquefaction (48 h), $p^{ship,50kt}$ is the capacity of the large ship, and $\gamma_{h,y}$ is a binary variable to see if the hub is used or not.

3.1.3 Transportation

Transportation of CO_2 in the model can happen along three different paths, these three are transportation from site to transportation hub, between transportation hubs, and from transportation hub to final storage site. The transportation of CO_2 along these paths is made by at least one of the 6 modes of transportation that are included in the model. These are trucks, ships with either 10 kt or 50 kt capacity, trains, and pipelines built either onshore or offshore. All modes of transportation have their own, mode-specific equations for installed capacity and OPEX. These equations are very similar for all three paths, the difference between the paths are indices on variables for capacity, flow, CAPEX and OPEX in the model.

There are many combinations of CO_2 conditions and transportation modes possible in the model, but only some of them are realistic choices to implement based on their current technical readiness level and cost. Possible combinations are shown in Table 3.3 and the combinations that are marked with an X are combinations the model can invest in.

Table 3.3: Possible combinations of transport mode and CO_2 condition. Realistic combinations are marked with X.

	Ship 10kt	Ship 50kt	Truck	Train	Pipeline onshore	Pipeline offshore
7 bar	X	X	X	X		
15 bar	X		X	X		
110 bar					X	X

The choice of transportation mode also depends on the condition and existing infrastructure at each location, e.g. train transport is possible due to existing railway at the hub. It is assumed in the model that only land-based transport modes are available for transportation from a site to a hub. It is also assumed that land areas separated by water, like islands, are isolated and land-based transportation modes can only be used for transportation to another location within the same land area. Transportation modes are available based on the existing transportation infrastructure at the locations.

The transportation distance between two locations is determined by two parameters, a mode-specific winding factor and the shortest distance. The shortest distance for land-based transportation modes is calculated using the haversine formula [30] based on the coordinates of the locations. For water-based transportation modes, the shortest distance is determined by an approximation of the shortest sea route possible between the two locations. Winding factors are transportation mode-specific and are multiplied by the shortest distance to account for deviations of existing transport infrastructure from the shortest path.

3.1.3.1 Vehicle fleet

Of the 6 possible transportation modes in the model, 4 of them are vehicles, these 4 modes are trucks, trains and ships with either 10 kt or 50 kt as capacity. To represent the flexibility that comes with these transportation modes, the concept of a vehicle fleet is included in the model.

Without the fleet, each route between two locations would have its own vehicles that could only be used on that route in the model. A risk with route-specific capacity is that better routes become available when the CCS system expands and the installed capacity for the first route would be unused until taken out of service at the end of the vehicle's technical lifetime. A vehicle fleet is introduced to reduce the risk of unused vehicles on one specific route by being able to move it to another route. The fleet owns the capacity needed in the system and then dispatches vehicles where they are needed. This adds flexibility and the possibility for an individual vehicle to cover multiple routes during its lifetime. The number of vehicles in the fleet of each transportation mode is determined by the total number of vehicles that are needed in the system, which is calculated by Equation 3.15.

$$b_{i,y}^{fleet,tm} \geq \sum_{l \in L}\sum_{h \in H} b_{l,h,i,y}^{tm,liq} + \sum_{h \in H}\sum_{h' \in H} b_{h,h',i,y}^{tm,hub} + \sum_{h \in H}\sum_{s \in S} b_{h,s,i,y}^{tm,storage} \quad \forall i \in I \quad \forall y \in Y \tag{3.15}$$

In the equation, $b_{i,y}^{fleet,tm}$ is the number of vehicles needed in the fleet of transportation mode tm that transport CO_2 under condition i in year y. $b_{l,h,i,y}^{tm,liq}$, $b_{h,h',i,y}^{tm,hub}$ and $b_{h,s,i,y}^{tm,storage}$ are the number of vehicles needed for a specific route for the three paths considered in the model and all three are determined by Equation 3.16 for vehicles with CO_2 capacity.

$$b^{vehicle,path} \geq \frac{x_{vehicle}^{path} \, t^{rt}}{t_{vehicle}^{op} \, p^{vehicle}} \tag{3.16}$$

In the equation, $x_{vehicle}^{path}$ is the flow of CO_2 transported by a vehicle on a specific route, t^{rt} is the route-specific duration of one round trip, $t_{vehicle}^{op}$ is the annual operating time of the vehicle and $p^{vehicle}$ is the CO_2 capacity of the vehicle. The cost of vehicles deployed for specific routes is calculated as a cost for the path that the route belongs to. It is possible that the fleet can have more vehicles than needed during a year and the excess vehicles are unused that year. These unused vehicles are not deployed to a route in the model and are therefore not included in any other cost equations for that year. These vehicles still have costs regarding annualized investment and maintenance for that year. Therefore, an unused vehicle cost is included in the model, which is determined by Equation 3.17 for each transportation mode tm that is included in the fleet.

$$\begin{aligned} c_{k='tm',y}^{fleet,unused} \geq \sum_{i \in I} \Bigg(& \beta_i^{tm} \left(\theta^{fleet} + \alpha^{tm}\right) \Bigg(b_{i,y}^{fleet,tm} - \Bigg(\\ & \sum_{l \in L}\sum_{h \in H} b_{l,h,i,y}^{tm,liq} + \sum_{h \in H}\sum_{h' \in H} b_{h,h',i,y}^{tm,hub} + \sum_{h \in H}\sum_{s \in S} b_{h,s,i,y}^{tm,storage} \Bigg)\Bigg)\Bigg) \quad \forall y \in Y \end{aligned} \tag{3.17}$$

In the equation, β_i^{tm} is a general CAPEX parameter for transportation of CO_2 by transportation mode tm under condition i, θ^{fleet} is the fixed OPEX cost for maintenance of unused fleet vehicles , which is assumed to be 3 % of CAPEX for all unused vehicles.

3.1.3.2 Truck

Truck transportation is one of the possible options for land-based transportation. The cost for truck transportation is divided into two parts, the annualized CAPEX cost, determined by Equation 3.6, and OPEX, which is determined by Equation 3.18.

$$c_{truck}^{OPEX,path} \geq c_y^{fixed} + \frac{x_{truck}^{path}}{p^{truck}} d^{truck} f_{truck}^{use} f_{truck}^{cost} + b^{truck,path} W^{truck} \tag{3.18}$$

Input data and assumptions used in the model regarding truck transport are presented in Table 3.4.

Table 3.4: Input data and assumptions for truck transport

Parameter	**Value**	**Unit**	**Reference**
Lifetime of truck	10	years	[10]
Capacity	30	t_{CO_2}	[10]
Maintenance cost	4	% of CAPEX	[10]
CAPEX for truck	660	$\frac{k€}{truck}$	[10]
Winding factor	1.3		[8]
Speed	50	$\frac{km}{h}$	[10]
Loading/unloading time	0.75	h	[10]
Annual operating time for truck	7760	h	[10]
Diesel consumption	0.5	$\frac{l}{km}$	[10]
Diesel price	1.7	$\frac{€}{l}$	Assumed
Wage of truck drivers	365	$\frac{k€}{truck}$	[10]

The assumed value is similar to the Swedish diesel prince in April 2024 [31].

3.1.3.3 Ship

For transport by ship, there are two options available, ships with 10 kt capacity and ships with 50 kt capacity, they are also called small and large ships, respectively, in this section. The annualized CAPEX for both ship options are determined by Equation 3.6 and the OPEX is determined by Equation 3.19.

$$c_{ship}^{OPEX,path} \geq c_{y}^{fixed} + \frac{x_{ship}^{path}}{p^{ship}} \left(\left(t_{ship}^{sea} + F_{ship}^{port} t_{ship}^{port} \right) f_{ship}^{use} f_{ship}^{cost} + HC \right) \tag{3.19}$$

The number of ships needed per route is determined by Equation 3.16, which is an integer variable in the model for all ships.

The assumed fuel of the ships is LNG [16]. The fuel consumption is converted to MWh per hour from MWh per day by dividing by the operating hours per day, which is the annual operating time split even over 365 days. Input data and assumptions used in the model regarding transportation by ship are shown in Table 3.5.

3.1.3.4 Train

Trains can be used for the transportation of CO_2 by land if railways are available at considered locations. The train is made up of two parts, a locomotive and wagons. This is to make the model more realistic by being able to invest in the number of wagons that are needed and expand in the future instead of investing in a full train set from the start. However, the pulling capacity of the locomotive is constant and dimensioned for the maximum amount of wagons. Installed train capacity is represented by two separate variables in the model, one for the number of locomotives and one for the number of wagons. But for costs and annual flows of CO_2 transported by train, there is only one variable each for transportation by train. The cost of transporting CO_2 by train is determined by two equations, Equation 3.20 is

Table 3.5: Input data and assumptions for ship transport.

Parameter	Value	Unit	Reference
Shared parameters			
Labor and maintaince cost	5	% of CAPEX	[16]
Fuel price (LNG)	35	$\frac{€}{\text{MWh}}$	[32][a]
Travel speed	28	$\frac{\text{km}}{\text{h}}$	[16]
Lifetime	40	years	[10]
Operating time	8322	h	[16]
Loading time	15	h	[16]
Unloading time	15	h	[16]
Terrain factor	1.1		[19]
Fuel consumption (ports)	10	% of open sea consuption	[19]
Ship 50 kt			
CO_2 capacity	50	kt	[16]
CAPEX (7 bar)	83.0	$\frac{\text{M€}}{\text{ship}}$	[16]
Fuel consumption (open sea)	18.2	$\frac{\text{MWh}}{\text{h}}$	[16][b]
Harbor cost	34.6	$\frac{\text{k€}}{\text{round trip}}$	[16]
Ship 10 kt			
CO_2 capacity	10	kt	[16]
CAPEX (7 bar)	33.7	$\frac{\text{M€}}{\text{ship}}$	[16]
CAPEX (15 bar)	69.8	$\frac{\text{M€}}{\text{ship}}$	[16]
Fuel consumption (open sea)	11.54	$\frac{\text{MWh}}{\text{h}}$	[16][b]
Harbor cost	12.3	$\frac{\text{k€}}{\text{round trip}}$	[16]

[a] The highest price between January and April 2024.

[b] Converted from MWh/day to MWh/h, the length of a day used for the conversion is based on the operating time divided even over 365 days.

used to calculate the annualized CAPEX and Equation 3.21 is used for calculations of OPEX.

$$c_y^{CAPEX,train} \geq c_y^{CAPEX,wagon} + c_y^{CAPEX,locomotive} \tag{3.20}$$

$$c_{train}^{OPEX,path} \geq c_{wagon}^{fixed} + c_{locomotive}^{fixed} + \text{OPEX}^{train} d^{train} p^{wagon} b^{wagon,path} \frac{t_{train}^{op}}{t^{rt}} \tag{3.21}$$

In these equations, OPEX^{train} is the operating cost of the train, which is determined by freight weight and distance traveled. The round-trip distance for the train is represented by d^{train}, p^{wagon} is the capacity of a train wagon, and t_{train}^{op} is the annual operating time of the train. To determine the number of wagons, $b^{wagon,path}$, Equation 3.16 is used. To determine the number of locomotives needed to pull the wagons, $b^{locomotive,path}$, Equation 3.22 is used, which is an integer variable in the model.

$$b^{locomotive,path} \geq \frac{b^{wagon,path}}{p^{locomotive}} \tag{3.22}$$

Table 3.6: Input data and assumptions for train transport of CO$_2$.

Parameter	**Value**	**Unit**	**Reference**
Lifetime of train wagon	26	years	Assumed
Capacity of wagon	60	$t_{\mathrm{CO_2}}$	[14]
Lifetime of train wagon	26	years	Assumed
Capacity of locomotive	30	$\frac{\text{wagons}}{\text{locomotive}}$	[14]
CAPEX wagon	242	$\frac{\text{k€}}{\text{wagon}}$	[14], [21]
CAPEX locomotive	4.98	$\frac{\text{M€}}{\text{locomotive}}$	[14], [21]
Fixed OPEX	4	% of CAPEX	Assumed
Variable OPEX	0.0269	$\frac{\text{€}}{\text{t km}}$	[21]
Winding factor	1.3		Assumed
Annual operating time for train	8760	h	[15]
Travel speed	60	$\frac{\text{km}}{\text{h}}$	[21]
Load/unload time	5	h	[21]

This cost is halved for empty trains.

In the equation, $p^{locomotive}$ is the capacity of the locomotive, which is how many wagons that can be attached to one locomotive. Input data and assumptions used in the model regarding the transport of CO$_2$ by train are presented in Table 3.6.

3.1.3.5 Pipeline

There are two types of pipelines included in the model, onshore and offshore. The cost of transporting CO$_2$ by pipeline is made up of annualized CAPEX and OPEX for both types of pipelines, which are determined by Equations 3.23-3.24.

$$c_y^{CAPEX,pipeline} \geq \beta^{pipeline} b^{pipeline,path} d^{pipeline} \alpha^{pipeline} \tag{3.23}$$

$$c_y^{OPEX,pipeline} \geq \mathrm{OPEX}^{pipeline} b^{pipeline} d^{pipeline} \tag{3.24}$$

In these equations, the CAPEX is based on the length and capacity of the pipeline. $b^{pipeline}$ is the installed capacity of the pipeline, which is determined for each route. The length of the pipeline is represented by $d^{pipeline}$. The annuity factor for pipelines is represented by $\alpha^{pipeline}$. The capacities of the pipelines are determined by Equation 3.25

$$b^{pipeline} \geq x_{pipeline}^{path} \tag{3.25}$$

where $x_{pipeline}^{path}$ is the annual flow of CO$_2$ transported by pipeline. Input data and assumptions used in the model for pipeline transportation of CO$_2$ are presented in Table 3.7.

3.1.4 Mass balance constraints

Constraints are used in the model to to ensure that mass balances are held. The first constraint is used to keep the balance of flows to and from the liquefaction plant at each capture site and is presented in Equation 3.26.

Table 3.7: Input data and assumptions of CO$_2$ transport by pipeline.

Parameter	**Value**	**Unit**	**Reference**
Lifetime of pipelines	50	years	[10]
Annual operating time	365	days	Assumed
CAPEX onshore	20	$\frac{€}{\text{(t/h) m}}$	[10]
CAPEX offshore	34	$\frac{€}{\text{(t/h) m}}$	[10] [33]
OPEX pipeline	20	$\frac{€}{\text{(t/h) year km}}$	[10]
Winding factor onshore	1.2		[19]
Winding factor offshore	1.1		[19]

$$\sum_{j \quad J} x^{stack}_{l,j,y} = \sum_{h \quad H} \sum_{k \quad K} \sum_{i \quad I} x^{liq}_{l,h,k,i,y} \qquad l \quad L \quad y \quad Y \tag{3.26}$$

For the flow balance at the transportation hubs is Equation 3.27 used to make sure that the amount of CO$_2$ coming into the hub from liquefaction sites or other hubs is the same as what is leaving the hub to storage sites or other hubs.

$$\begin{gathered} \sum_{l \quad L} \sum_{k \quad K} \sum_{i \quad I} x^{liq}_{l,h,k,i,y} + \sum_{h' \quad H} \sum_{k \quad K} \sum_{i \quad I} x^{hub}_{h',h,k,i,y} = \\ \sum_{h' \quad H} \sum_{k \quad K} \sum_{i \quad I} x^{hub}_{h,h',k,i,y} + \sum_{s \quad S} \sum_{k \quad K} \sum_{i \quad I} x^{storage}_{h,s,k,i,y} \qquad h \quad H \quad y \quad Y \end{gathered} \tag{3.27}$$

To keep track of which years transportation hubs are used, a constraint around a binary variable, $\gamma_{h,y}$, is constructed. The binary variable is for each hub and each year in the model and the constraint is presented in Equation 3.28.

$$\sum_{l \quad L} \sum_{k \quad K} \sum_{i \quad I} x^{liq}_{l,h,k,i,y} + \sum_{h' \quad H} \sum_{k \quad K} \sum_{i \quad I} x^{hub}_{h',h,k,i,y} \leq p^{hub}_{max} \gamma_{h,y} \qquad h \quad H \quad y \quad Y \tag{3.28}$$

In this equation, p^{hub}_{max} is the maximum annual capacity of a hub, which has a value larger than the total annual amount of capturable CO$_2$ in the model. The annual amount CO$_2$, $z_{s,y}$, that is stored at storage site s in year y is determined by Equation 3.29.

$$z_{s,y} = \sum_{h \quad H} \sum_{k \quad K} \sum_{i \quad I} x^{storage}_{h,s,k,i,y} \qquad s \quad S \quad y \quad Y \tag{3.29}$$

The amount of CO$_2$ stored at one storage site is limited by the upper limits of the storage site, which is based on the site's projected annual storage capacity. This constraint is controlled by Equation 3.30

$$z_{s,y} \leq z^{\mathsf{MAX}}_{s,y} \tag{3.30}$$

where $z^{\mathsf{MAX}}_{s,y}$ is the maximum annual capacity of storage site s for year y.

3.1.5 CO₂ Emissions

The amount of CO_2 captured in the system is determined by Equation 3.31

$$e_{et,y}^{captured,annual} = \sum_{l \in L} \sum_{j \in J} \left(x_{l,j,y}^{stack} m_{l,j,et} \right) \quad et \in ET \quad y \in Y \tag{3.31}$$

where $e_{et,y}^{captured,annual}$ the CO_2 captured of emission type et (biogenic or fossil) from all stacks and sites in year y and $m_{l,j,et}$ is the share of emission type et from stack j at site l. The total amount of CO_2 of emission type et captured over the considered time period, $e_{et}^{captured,total}$, is defined by equation 3.32.

$$e_{et}^{captured,total} = \sum_{y \in Y} e_{et,y}^{captured,annual} \quad et \in ET \tag{3.32}$$

To follow capture goals in the model is Equation 3.33 applied

$$e_{et,y}^{captured,annual} \geq e_{et,y}^{target} \quad et \in ET \quad y \in Y \tag{3.33}$$

where $e_{et,y}^{target}$ is the minimum amount of CO_2 of emission type et that should be captured in year y. Equation 3.34 is used to calculate the emissions released to the atmosphere

$$e_{et,y}^{emission,annual} = \sum_{l \in L} e_{l,et}^{CO_2} - e_{et,y}^{captured,annual} \quad et \in ET \quad y \in Y \tag{3.34}$$

where $e_{et,y}^{emission,annual}$ is the released CO_2 emissions of emission type et in year y and $e_{l,et}^{CO_2}$ is the annual CO_2 emission of emission type et from all stacks at site l. The total amount of emissions, $e_{et}^{emission,total}$, of emission type et that are released to the atmosphere during the considered time period are determined by Equation 3.35.

$$e_{et}^{emission,total} = \sum_{y \in Y} e_{et,y}^{emission,annual} \quad et \in ET \tag{3.35}$$

The annual cost of emissions is determined by Equations 3.36 for fossil emissions and by Equation 3.37 for negative biogenic emissions.

$$c_{et='\text{fossil}',y}^{emission} \geq e_{et='\text{fossil}',y}^{emission,annual} c_{et='\text{fossil}',y}^{CO_2} \quad y \in Y \tag{3.36}$$

$$c_{et='\text{bio}',y}^{emission} \geq e_{et='\text{bio}',y}^{captured,annual} c_{et='\text{bio}',y}^{CO_2} \quad y \in Y \tag{3.37}$$

In the equations $c_{et,y}^{emission}$ is the annual cost of fossil emissions and the earnings from captured biogenic emission in year y and $c_{et,y}^{CO_2}$ is the CO_2 price of emission type et in year y.

3.2 Case study

The model is applied to a case study of industrial plants in Sweden with annual CO_2 emissions above 100 kt in 2022 based on data from Naturvårdsverket [34]. For the modeled time period 2025-2050, it is assumed that no new plants are added, no existing plants are decommissioned and the emissions from each plant are constant over time.

There are in total 82 plants that are included in the case study: 26 pulp and paper mills (PP), 4 cement or limestone plants (Ce), 3 refineries (R), 3 iron and steel plants (IS), 1 petrochemical industry site (C), and 45 sites producing heat and/or power (CHP). Of these 45 CHP sites, 24 of them only have biomass boilers, 16 have only waste boilers and 5 of them have both types of boilers. There are 18 transportation hubs that can be used. Two of them are located in Norway, the other 16 are located in Sweden and all of them are coastal except one, Hallsberg. There are 5 storage sites available in the case study, these are called Kollsnes, Denmark, Stavanger, Barents and Iceland. The first 3 are combined storage sites, which means that the capacity of multiple storage sites projects in the same area are combined into one storage site in the model. All of these storage sites except Iceland have a limited annual storage capacity, which is based on the projects presented in Figure 2.5. A table of which projects are included in which storage site in the model is presented in Appendix A.3. These limits are based on data about the included projects from IOGP [23]. Iceland is included as a backup option so that storage is always available, but with a longer transportation distance as a trade-off. The full storage capacity at these storage sites can be utilized for CO_2 captured in Sweden.

The capture targets of biogenic CO_2 are set to 1.8 Mtpa from 2030 until 2045 when the target is increased to 8 Mtpa for the remaining years of the considered time period. These targets are based on suggested values from SOU [3] regarding biogenic CCS. The price of fossil CO_2 is determined by Equation 3.38, which is a trend line of the predicted price of fossil CO_2 in the EU ETS system [35]–[37].

$$c^{\mathsf{CO_2}}_{et=\text{'fossil'},y} = 80 \cdot 1.09^{y-\mathsf{2024}} \quad y \quad Y \tag{3.38}$$

The price paid to the system for captured biogenic CO_2 is zero in the base case. The cost of storage at all 5 storage sites in the model is assumed to be 50 €/t.

The location of all plants, hubs and storage sites can be seen in Figure 3.3. The size of the dots corresponds to the annual emissions of the plants. Name, coordinates, emissions and available transportation modes for the locations included in the case study are presented in Appendix A.

3.2.1 Scenarios

All modes of transportation, conditions and route-flexible deployment of vehicles are available in the base case. To investigate the effect of system modifications scenarios are created and compared to the base case. The scenarios considered in this study are standardized CO_2 conditions, route-specific vehicles instead of route-flexible and increased CO_2 volumes due to added BECCS incentive. To compare the cost of the CCS chain in the base case and the scenarios the specific CCS chain cost, $c^{\mathsf{CCS\ chain}}$, is considered. The specific CCS chain cost is the average cost of the CCS chain per ton CO_2 and is calculated by Equation 3.39.

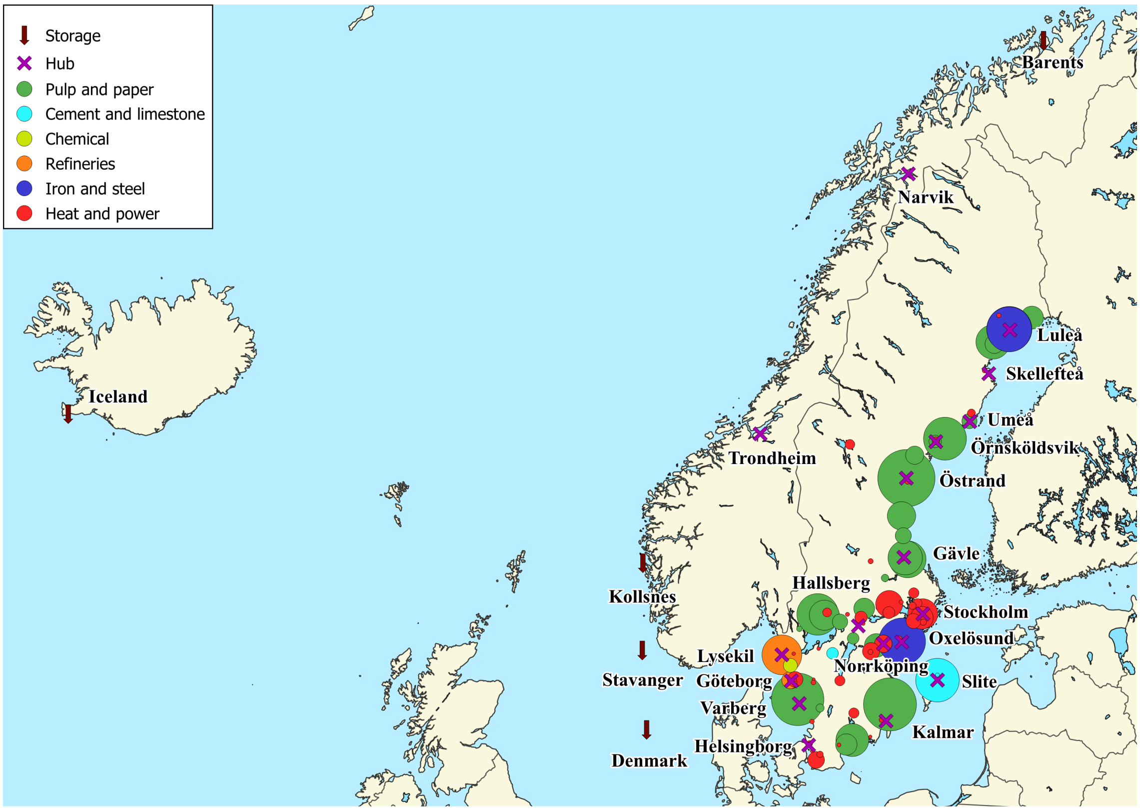


Figure 3.3: Map of all industrial sites, locations for transportation hubs and storage sites included in the model. The names of transportation hubs and storage sites are given in the figure. The size of the dots representing plants corresponds to the annual emissions of the sites.

$$c^{\text{CCS chain}} = \frac{\sum_{y \in Y} \left(c_y^{annual} - \sum_{et \in ET} c_{et,y}^{emission} \right)}{\sum_{et \in ET} e_{et}^{captured,total}} \tag{3.39}$$

Standardized conditions for CO_2 transportation

In these scenarios, only one of the three CO_2 transportation conditions (7 bar, 15 bar, 110 bar) is available and all CO_2 that is transported in that scenario must have that condition. This represents a system with a standardized condition for CCS. This scenario is created to understand the impact of a more locked system regarding the condition of the CO_2 transported. These scenarios are called "7 bar", "15 bar" and "110 bar" in the report.

Route-specific vs route-flexible vehicles

In this scenario, a vehicle investment is made for each specific route rather than investing in a vehicle fleet. The installed capacity for each route will stay there until the end of the technical lifetime of the vehicle is reached. This scenario is closer to a system where individual plant owners invest in and run their own parts of the transportation system. This is a contrast to the system with the fleet, where just one company is in charge of the transportation system and has more flexibility. This scenario is created to understand the impact of less flexibility regarding the deployment of vehicles. This scenario is called "no fleet" in the report.

Increased CO_2 capture from extra BECCS incentive

In this scenario, an extra incentive for BECCS is added to the model by including BECCS in the EU ETS system. This means that captured biogenic CO_2 can be sold as negative emissions. The price of negative emissions is the same as the price of emitted fossil CO_2, which is determined by Equation 3.38. The incentive should increase the annual flow of CO_2 in the CCS chain, which could have an impact on the composition of the system. To reduce the run time of the model, the constraints of the 7 bar scenario are applied for this scenario. It reduces some options but is necessary to get a result. This scenario is called "BECCS" in the report.

4

Results and discussion

In this chapter, the results of the case study are presented and discussed. The chapter starts with general trends from all scenarios and the base case before considering the impact of the modifications considered in each scenario. There are also discussions about the role of transportation modes in the model and some of the uncertainties in the model.

4.1 General trends

The specific CCS chain cost for the base case and all scenarios are presented in Figure 4.1. The contribution of each part of the chain is also shown in the figure. The figure shows that the cost of transportation and storage is relatively small compared to the cost of processes on sites (capture and liquefaction) and final storage. The share of the specific cost from these three parts of the CCS chain is presented in Table 4.1, where transportation and intermediate storage only account for 13-17 % of the specific cost for the base case and the 7 bar, no fleet and BECCS scenarios. The specific cost of the CCS chain of these 4 scenarios is around 125 €/t. For the 15 bar scenario, the share of transportation and intermediate storage is 23 % and for the 110 bar scenario the share is 55 %. These two scenarios have a higher share due to the most cost-effective transportation modes not being available in the scenarios and therefore increasing the transportation cost. The specific cost for the 15 bar scenario is 137 €/t and 244 €/t for the 110 bar scenario.

4.2 Impact of route-flexible vehicles

The specific cost of the base case and the no fleet scenario are very similar and the difference between them is well within the margin of error of the model. The most interesting aspect of the comparison is the difference in hub utilization strategy. The base case has many hubs that are closer to the capture sites but have more ships with a lower average utilization rate per ship. The no fleet scenario has fewer hubs and a higher utilization rate of ships but requires longer transportation between sites and hubs. Despite this difference in strategy, the specific chain cost is similar and it seems like flexibility has a low impact on the specific cost in the model. However, the flexibility increases the total amount of captured of CO_2, especially fossil CO_2, which reduces the total system cost where the cost of emissions is included.

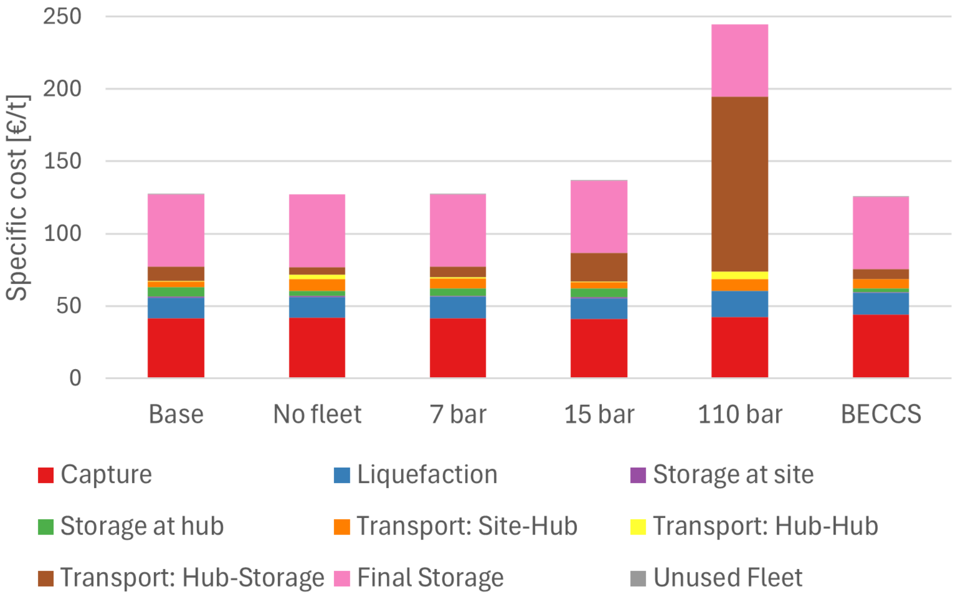
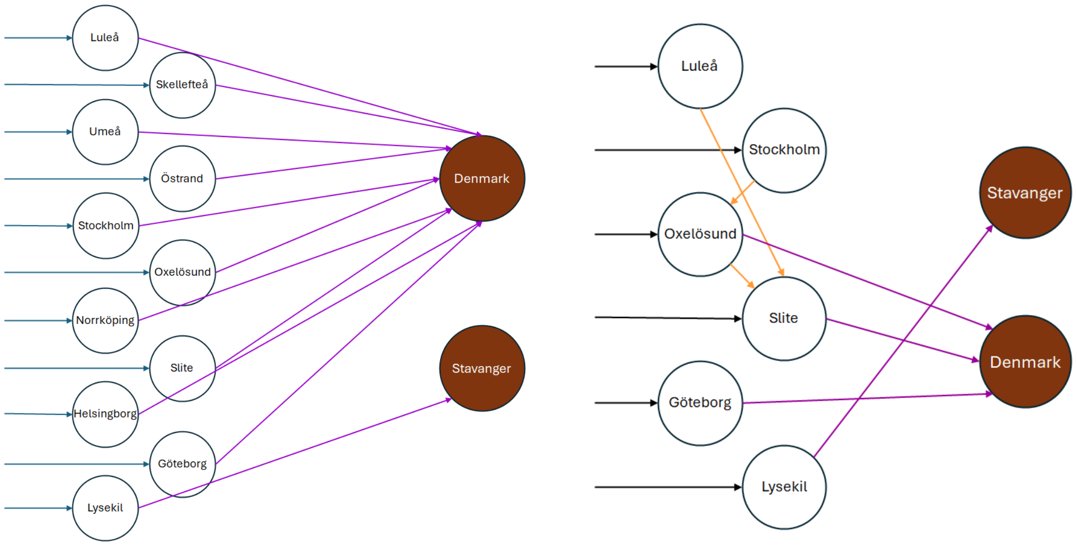


Figure 4.1: The specific CCS chain cost per ton CO_2 captured and stored for the base case and all scenarios.

Table 4.1: Data for the base case and all scenarios. The specific CCS chain cost and the share of the specific cost from site processes (capture and liquefaction), transportation (intermediate storage included) and final storage are presented. Also the total amount CO_2 captured, how much of the captured CO_2 is fossil and biogenic, and the share of captured CO_2 that is transported between two hubs is presented.

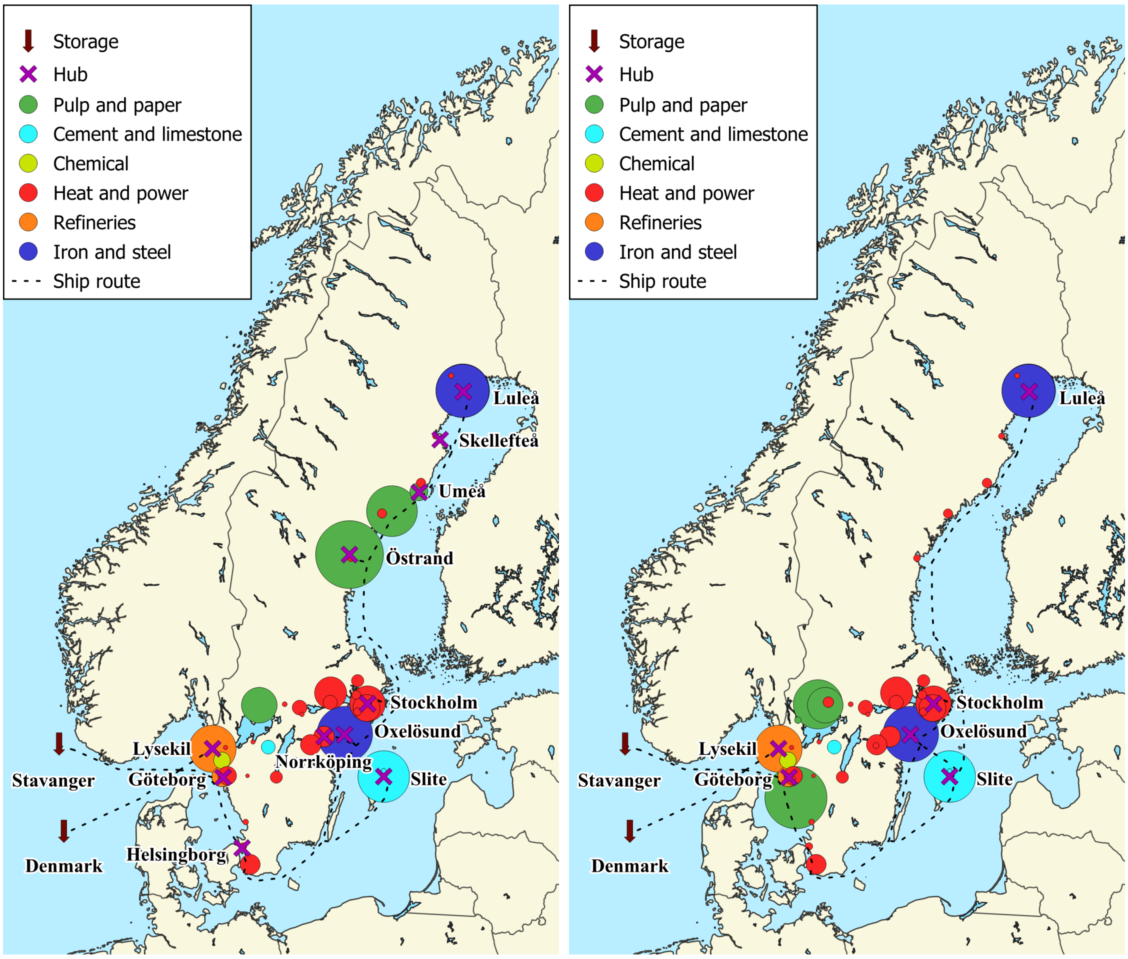
	Base	**7 bar**	**15 bar**	**110 bar**	**No fleet**	**BECCS**
Specific cost [€/t]	127.2	127.8	137.1	244.6	127.0	125.6
Cost share of site processes [%]	43.6	44.4	40.3	24.7	44.1	47.0
Cost share of transportation [%]	17.1	16.5	23.2	54.9	16.5	13.2
Cost share of final storage [%]	39.3	39.1	36.5	20.4	39.4	39.8
Captured CO_2 2025-2050 [Mt]	295.3	292.8	287.1	285.5	290.5	803.6
- Biogenic [Mt]	79.7	79.5	78.0	78.8	83.7	570.1
- Fossil [Mt]	215.6	213.3	209.2	206.7	206.7	233.5
Share of CO_2 transported between two hubs [%]	1.0	9.2	2.3	9.8	38.1	0.0

The difference in specific CCS chain cost between the base case and the no fleet scenario is small, but there are differences in the system competition. One of the largest differences is the share of captured CO_2 that is transported between two hubs. As seen in Table 4.1, the share is only 1 % for the base case and around 38 % for the no fleet scenario. The reasons for the differences can be seen in Figures 4.2 and 4.3. Figure 4.2 presents a simplified version of both systems in 2050 with a focus on transportation routes from active hubs. Figure 4.3 presents an overview of the systems in 2050, the overview shows the number of hubs, which sites have capture, which storage sites are used and where they are located. The base case has 8 active hubs in 2030 which increases over the years up to 11 active hubs by 2045. The no fleet scenario only has 4 active hubs in 2030. During 2031 and 2032 one active hub is added per year, but from 2033 and forward there are no more hubs added. This means that the number of active hubs in the scenario from 2033 and forward is 6. Most of the hubs in the no fleet scenario are near large, mostly fossil point sources. The number of active hubs in the system can be seen in the costs of parts of the CCS chain related to the hubs. These parts are intermediate storage at hubs, transport between sites and hubs, transport between hubs, and transport between hubs and storage sites. A comparison of these 4 costs for the base case and the no fleet scenario is shown in Figure 4.4. The figure shows that transport between sites and hubs and between hubs have a higher specific cost in the no fleet scenario and that intermediate storage at hubs and transport between hubs and storage sites have a higher specific cost in the base case. The main reason behind the extra cost for transportation between sites and hubs is the average transportation distance, which is 50 km for the base case and 100 km for the no fleet. The average distance in the no fleet scenario is longer due to sites being further away from the closest hub since there are fewer active hubs, which can be seen in Figure 4.3, where the systems in 2050 of the base case and no fleet scenario are presented.



(a) **(b)**

Figure 4.2: Simplified version of the transportation system around hubs and storage sites in 2050 for **(a)** the base case and **(b)** the no fleet scenario.



(a) **(b)**

Figure 4.3: The system in 2050 for **(a)** the base case and **(b)** the no fleet scenario.

The reason behind the higher cost of transportation between hubs for the scenario is the higher share of captured CO_2 transported between hubs. It is also the reason transportation from hubs to storage sites is more expensive for the base case. In the no fleet scenario, all CO_2 transported from sites to the Luleå and Stockholm hubs are further transported to another hub before being transported to a storage site, which reduces transportation distance between hubs and storage sites and increases the utilization of large ships. In the base case, each active hub mostly has its own ship to a storage site, which increases the average transportation distance due to more northern hubs with transportation to storage sites. The cost of intermediate storage has a linear correlation to the number of active hubs since the size of the tank at each hub is the same. Therefore, more active hubs give higher specific costs for intermediate storage at hubs.

Figure 4.4 also shows that hub-related specific costs are slightly lower (0.75 €/t) in the no fleet scenario compared to the base case, but the difference over the whole chain is even less (0.2 €/t), mostly due to biogenic CO_2 being captured at different PP and CHP plants. The sites utilized in the no fleet scenario have a higher average

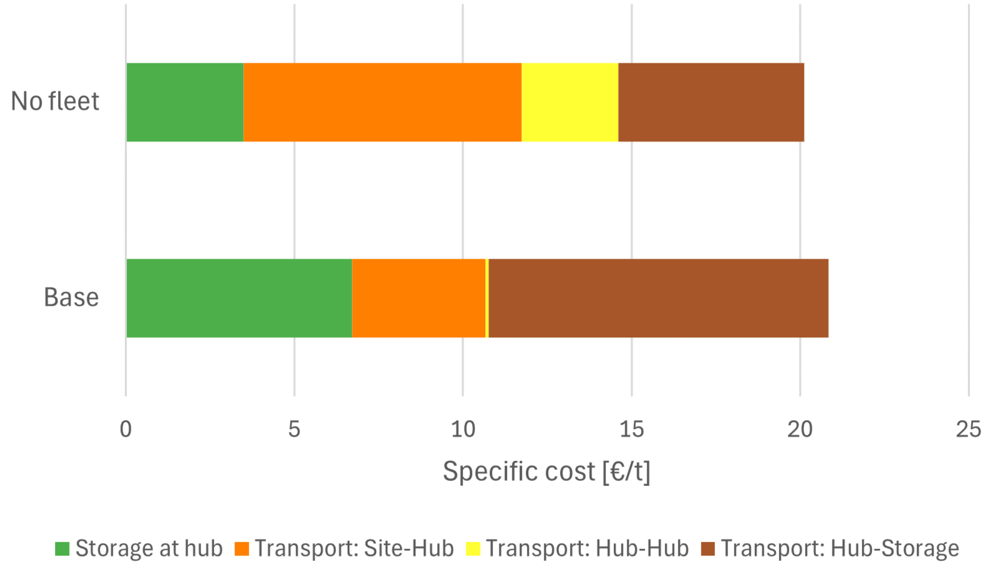


Figure 4.4: Hub-related cost for the base case and the no fleet scenario.

capture cost but are closer to the active hubs in the no fleet scenario and therefore have a lower transportation cost compared to the sites utilized in the base case. The difference in distance is an approximation based on the location of sites with capture in the base case and the no fleet scenario in relation to the active hubs of the scenario in Figure 4.3. The figures also show that the cheaper capture plants in the base case are located near the hubs not used in the scenario.

Another difference between the base case and the no fleet scenario is the total amount of CO_2 captured over the considered time period. The base case captures almost 5 Mt CO_2 more than the scenario. However, the scenario captures 4 Mt of biogenic CO_2 more than the base case, which means that the base case captures more fossil emissions. These differences are relatively small but some of the reasons for the differences are due to the limited flexibility of no fleet scenario. One reason for the difference in total capture is when the first capture is started, the base case starts capturing CO_2 in 2028 while the no fleet scenario starts in 2030. The only sites with capture 2028 in the base case are IS stacks located in Luleå. In the no fleet scenario, these stacks are not captured until 2031 due to transportation from the Luleå hub only going to another hub and not a storage site. But there are other sites with a delay of the first capture in the no fleet scenario compared to the base case. The transportation from these sites is similar in the base case and the no fleet scenario. However, there is no clear indication of why the start year is different in the model results. Therefore, some of the differences are assumed to be caused by the margin of error in the model.

Another reason for the difference in captured emissions is the choice of PP and CHP plants for the capture of biogenic emissions and the biogenic fraction of the captured emission of these plants. The average biogenic fraction of the utilized PP and CHP plants is slightly higher for the no fleet scenario compared to the base case. The higher fraction means that a higher share of the CO_2 captured at these plants is counted as biogenic CO_2. The difference in captured fossil CO_2 also affects the value of the objective function since the cost of fossil emissions is included. Since more fossil emissions are captured in the base case, the value of the objective function is lower than the value of the no fleet scenario.

4.3 Condition standard

The specific cost of the CCS chain for the 7 bar scenario is similar to the cost of the base case. For the 15 bar scenario, the specific cost is around 10 €/t higher than the base case. For the 110 bar scenario, the specific cost is almost doubled compared to the case base due to an increase of 117 €/t. The differences in specific CCS chain cost for the 15 bar and 110 bar scenarios are mostly due to differences in the specific cost of transportation between hubs and storage sites. The large ship not being available in these scenarios is the main reason for transportation between hubs and storage sites being more expensive. The large ship is the most cost-effective mode of transportation for transport between hubs and storage sites since the flow of CO_2 is larger and the distance is longer. Instead, small ships are used in the 15 bar scenario and onshore pipelines in the 110 bar scenario. Both transportation modes have higher specific transportation costs for long distances and larger flows compared to the large ship, which was seen in section 2.3.5.

The large difference in cost of the 110 bar scenario compared to the others shows that large-scale implementation of pipelines is not economically viable in a Swedish CCS system. Pipelines are competitive in systems with large flows and relatively short transportation distances, which is the opposite of the Swedish system, at least in comparison to other systems in Europe. Similar results regarding pipelines in Sweden are found in Kjärstad et al. [19].

The 15 bar scenario is also more expensive than the base case, but the increase is only around 8 % of the specific cost of the base case. The 15 bar scenario is however the system with the highest technical readiness level today and therefore the most likely system in the short term as 15 bar ships and trucks are already in use today on a smaller scale. 15 bar ships are also the choice for the first ships in the Northern Lights project. The 7 bar ships would outcompete 15 bar ships based on the costs in this thesis, even if only small ships are available since the 7 bar ship has half the investment cost of the 15 bar ship. But there are more risks with the 7 bar ship since a ship has not been built yet and therefore less likely short term.

The system of the 7 bar scenario is similar to the system of the no fleet scenario, which can be seen in Figure 4.5 where the systems of both scenarios are presented. The 7 bar scenario has 7 active hubs from 2033, which is one more than the no fleet scenario. The differences in hub-related costs between the base case and the 7 bar scenario have a similar trend as the differences between the base case and the no fleet

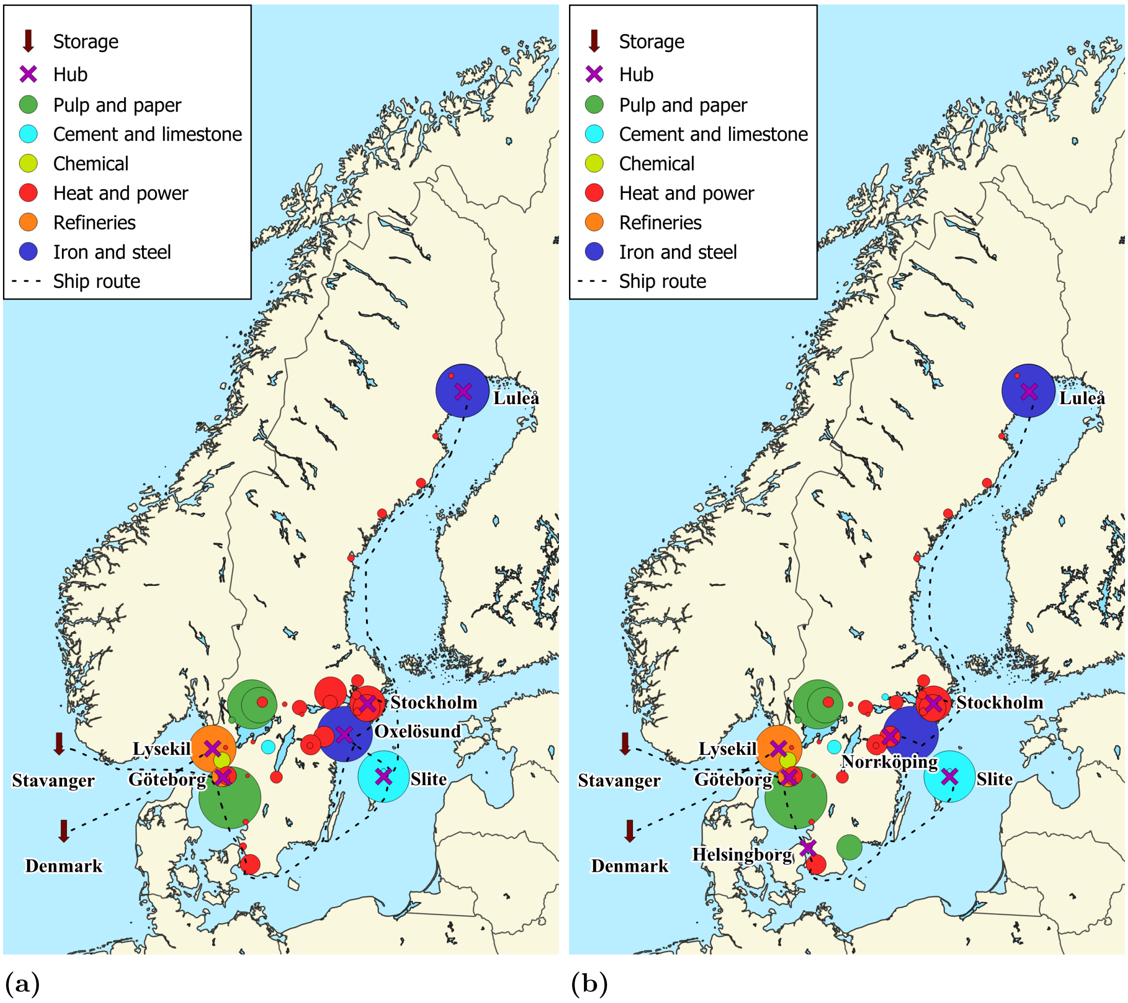


Figure 4.5: The system in 2050 for **(a)** the no fleet scenario and **(b)** the 7 bar scenario.

scenario. Therefore, similar trends for differences in hub-related cost as seen when comparing the base case and the no fleet scenario can be seen when the base case and the 7 bar scenario are compared. However, the differences are smaller between the base case and the 7 bar scenario since there is one more hub compared to the no fleet scenario. The cost for transport between hubs is higher since 9 % of captured CO_2 are transported between hubs in the 7 bar scenario compared to only 1 % in the base case. However, in contrast to the no fleet scenario, there are no constant routes between two hubs in the 7 bar scenario. Instead, there is just transportation between two hubs once in a while and never two years in a row between the same hubs.

One difference between the 3 condition standard scenarios is the specific cost of liquefaction. The scenario with the lowest specific cost is the 15 bar scenario with 14 €/t. The specific cost in the 7 bar scenario is 15 €/t and 18 €/t for the 110 bar scenario. The specific liquefaction cost in the base case is slightly higher than the 15 bar scenario since the 15 bar condition is 90 % of all liquefaction in the base case and the 7 bar condition is the remaining 10 %.

The difference in specific cost of liquefaction between the base case and the 7 bar scenario shows the problem with one of the assumptions made in the model, that the CO_2 condition can change at the hubs. The main reason for the assumption is that the cost of changing conditions regarding both equipment and energy demand is hard to find in literature. Therefore, choosing a cost of changing conditions would also be an assumption and would require more variables and constraints in the model, which could affect the run time of the model. A real implementation of a CCS system that allows for multiple conditions needs to include this cost. Based on this model, the specific cost of changing conditions at hubs can not exceed 0.6 €/t if the base case should be cost-competitive with the 7 bar scenario. This difference is only around 4 % of the average specific liquefaction cost and it is very unlikely that the specific cost of condition changes at hubs is that low. When compared to the 15 bar scenario the difference is 10 €/t, around 68 % of the average liquefaction cost, which would be a more realistic cost. However, it is unlikely that a change of condition from 7 bar to 15 bar would be considered since the CAPEX of 15 bar ship is higher. Therefore, a one-condition system is more likely to be the best choice for implementation of a CO_2 transportation system due to changing conditions at a hub not being needed and the implementation is more similar to the current model. There is a possibility of a two or three-condition system where changing conditions at hubs is not possible and different hubs can have different conditions. However, this option is not likely as the cost of long-distance transportation is higher for the 15 bar condition compared to the 7 bar condition. Having multiple conditions can also affect the cost of the storage site as more equipment, one per condition, could be needed to prepare the CO_2 before being permanently stored.

4.4 Impact of volume of captured CO_2 - BECCS

As seen in Table 4.1, the total amount of captured CO_2 in the BECCS scenario is much larger than the base case and the other scenarios. Despite the large difference in captured CO_2, the specific cost of the BECCS scenario is just slightly lower (1.5 €/t) than the base case.

In the BECCS scenario, the order of implementation of capture at sites is mostly based on the cost of capture at each stack and the cost of transportation from the site of the stack. In the base case and the other scenarios, the order of implementation is based on the fraction of fossil emissions where stacks with a higher share of fossil emissions are more cost-effective for the system. This is due to biogenic emissions not having any value to the system besides reaching the capture targets. Therefore, waste-based CHP stacks implement capture before PP plants, even if PP plants have lower specific capture costs, but stacks at IS, Ce, C and R sites are first in the order of implementation due to lower capture costs and having mostly fossil emissions. Capture is implemented at waste-based CHP stacks before PP stacks in the model due to waste-based CHP stacks helping the system with both reducing the system cost by capturing fossil emissions and capturing biogenic emissions to reach the capture targets. This trend is also described in the conclusion of Karlsson et al. [8]. However, in the BECCS scenario, PP plants in general have jumped in front of CHP plants in the order of implementation since the BECCS scenario adds monetary value to the biogenic CO_2. Since the price for biogenic emissions is the same as the fossil emissions, all captured CO_2 reduce the system cost if the CO_2 price is higher than the chain cost of capture at sites. Most capture equipment is installed between 2029 and 2033 in the BECCS scenario when the CO_2 price is 123-174 €/t. The last installment at a stack is done in 2043 for the most expensive stack, which has a specific capture cost of over 300 €/t, which is more than double the cost of the second most expensive stack. Since CO_2 is captured from all stacks in the BECCS scenario, there is much more CO_2 captured in total, as seen in Table 4.1. But the increase in captured fossil emission is less than 20 Mt more over the whole time period compared to the base case. However, the difference in captured biogenic emissions is very large, almost 500 Mt more in the scenario compared to the base case.

The larger amount of captured CO_2 is also one of the main reasons that the specific chain cost of the BECCS scenario is slightly lower compared to the base case. The scenario and the base case have a similar amount of active hubs in their systems. The total cost of intermediate storage at hubs is similar for the BECCS scenario and the base case since both have similar numbers of active hubs. But the specific cost in the BECCS scenario is 4 €/t less since more CO_2 is captured. However, this difference would be smaller if the intermediate storage capacity at the hubs were sized to be able to handle delays of one or two days. In the current model, the size is instead based on the size of the large ship, which means that delays would have a larger impact for larger flows of CO_2 as the tanks would be filled faster. The specific cost for transportation between hubs and storage sites is also cheaper by around 3.5 €/t for the scenario. The primary reason for the difference in specific costs is the utilization rate of the ships, the average ship transports 1.36 Mtpa in the base case and 2.34 Mtpa in the BECCS scenario. Since more CO_2 is transported per ship the impact of annualized CAPEX and fixed OPEX on the specific cost is lower.

As seen in Table 4.1, there is no transportation between hubs in the BECCS scenario. The reason for no transportation between hubs is the higher flow of CO_2 in the system and the flow to the hubs is large enough for each hub to have its own ship to a storage site. The specific cost of transportation between sites and hubs is higher for the BECCS scenario, around 2.5 €/t, due to transportation from more locations since more sites have capture in the BECCS scenario. The average transportation distance between sites and hubs in the BECCS scenario is around 80 km, which is 30 km longer than the average distance in the base case. The specific capture cost is also higher in the scenario since all stacks are utilized in the BECCS scenario. The reason for the higher specific capture cost is the most expensive stacks in the case study, which are not utilized in the base case and the other scenarios. These stacks have higher CAPEX for capture equipment due to their real operating time only being around 10-20 % of the assumed operation time for all stacks and capture equipment in the model. The lower operating time increases the capacity and

CAPEX of the capture equipment since the flow of flue gas (m^3/s) is higher. A lot of the most expensive stacks are from either bio-based CHP or PP sites. Since they are bio-based stacks, they are not needed in the base case and the other scenario since other stacks can fulfill the biogenic capture target.

The BECCS scenario has the same constraints as the 7 bar scenario to reduce run time since fewer options are available in the model. This means that the specific cost of the BECCS scenario could be even lower in the model due to cheaper liquefaction if the 15 bar condition was an option in the model. However, this is only possible under the assumption of no cost for changing the condition at hubs. Therefore, as previously discussed, a one-condition system is more likely to be the preferred transportation system due to not needing to change the condition at hubs.

4.5 Transportation modes

The large ship is the prioritized mode of transportation over long distances and/or large flows of CO_2 in the model. In the base case and all scenarios where the 7 bar condition was available, the large ship is used for all transportation between hubs and storage sites and most transportation between hubs. The small share of the transportation between hubs that is not transported by the large ship is transported by either the small ship, trains or trucks. These three are also used in the 15 bar scenario for transportation between hubs. The small ship and train transport around 50 % each of all transported CO_2 between hubs in the 15 bar scenario and trucks only have a small share.

For the transportation between sites and hubs, the mode of transportation utilized is split between trains and trucks, except for the 110 bar scenario where only pipelines are available. In all scenarios with trucks and trains, except the BECCS scenario, trucks transport 50-60 % of the captured CO_2, and the rest is transported by trains. However, in the BECCS scenario, over 60 % of the captured CO_2 are transported by trains and the rest by trucks. The specific transportation cost for trains is lower than for trucks, which means trains are the preferred land-based transportation mode. But transport by train requires access to the railway. Railway access is missing for around half of the sites considered in the case study due to no existing railway infrastructure nearby. Half of the sites with access to railway infrastructure are PP plants, which is the plant type that is least utilized for capture in all scenarios except the BECCS scenario. Since access to railway infrastructure is more limited at capture sites utilized in these scenarios, truck transport has a higher presence as it is the second-best land-based transportation mode available. The share of transportation modes is based on the flow of CO_2 transported, which means that trains can handle fewer routes but transport more CO_2.

A possible limitation of train transportation is congestion of the Swedish railway network, especially since certain routes are already busy with little or no capacity for additional trains. Some of the larger sites in the model would need 2-4 round trips per day to transport CO_2 from sites to hubs in the BECCS, which could be a problem if these sites are along busy routes.

Pipelines are only utilized in the 110 bar scenario, where they are the only option. The specific CAPEX (i €/t/km) of pipelines is similar to a function of the volume of CO_2 transported, the function follows the trend of a negative exponential. With this trend, the specific CAPEX is lower for higher volumes. But the cost of pipelines is not modeled like this in the model, they are instead based on a fixed value, which means that the specific CAPEX is the same for all volumes of CO_2 transported. The reason for implementing a fixed value is to avoid binary variables that could be needed to implement the trend in the model. If the specific CAPEX had followed the trend in the model, it is possible that pipelines would be utilized in other scenarios, especially short distances with large flows of CO_2. However, pipelines have a disadvantage since the liquefaction cost for pipelines is higher than for vehicles, which means that the specific cost of transportation would need to be much lower for the pipeline compared to the vehicles.

4.6 Model uncertainties

Interesting parameters to investigate further would have been the cost of final storage, the cost of large ships and the cost of trains. The value of the storage cost is assumed and changing the value would move when CO_2 is captured in the model. In an earlier version of the model, before the storage cost was added to the model, the first capture was often in 2025 or 2026 instead of 2028. However, a large increase would still have captured CO_2 by 2030 due to the biogenic capture target even if the CO2 price is lower than the chain cost. The cost of the large ship and the trains are interesting since both are important transportation modes in the model and have uncertainties regarding them. The large ship is only available for 7 bar condition, which is not in use for transportation of CO_2 currently. The ships are currently just considered the best option in literature and therefore have a risk of being more costly when implemented in the real world. There is limited data about CO_2 transportation by train in literature and the uncertainty of the parameter values used in the model is high.

In this case study all projected storage capacity at the storage sites is available for emissions captured in Sweden, this is unlikely to be the case for the actual implementation. There will be emissions for other countries that also utilize part of the available capacity of the projects, especially the countries where the storage sites are located. The utilization rate of available storage capacity from all storage sites in the model except Iceland is around 25 % in both 2030 and 2045 for the base case and all scenarios except the BECCS scenario. The utilization rate for the BECCS scenario is around 67 % in 2030 and around 50 % in 2045. It is not unreasonable to assume that Swedish emissions could make up 1/4 of the emissions stored at storage sites in the Nordic region. But to increase this share above half of the capacity is unlikely. Especially if governments or companies of other countries have financed the project as they would want some kind of priority as a reward for their investment.

5

Conclusion

This thesis investigates the large-scale implementation of CCS in Sweden with a focus on the transportation system required for the transportation of capture CO_2. This work develops and applies a mixed integer linear programming model to minimize the system cost of the designed transportation system. The results show that transportation has a relatively small impact on the specific cost of the CCS chain, but most of the specific cost is allocated to either the capture process, the liquefaction process or the cost of permanent storage at storage sites. However, if the system is limited to less cost-effective ways to transport CO_2 , transportation can have a large impact on the specific cost of the whole CCS chain.

The model shows that there is more than one way to implement a CCS system in Sweden for similar specific costs. The largest differences in the design of the systems are the number of transportation hubs utilized, how much of capture CO_2 is transported between hubs, and which stacks CO_2 is captured from.

Systems with one standard regarding the pressure and temperature of the transported CO_2 are more likely for real implementation compared to systems with multiple standards. since costs are missing in the systems with multiple standards and the specific cost difference to systems with one standard is very small. However, a system only based on pipelines is not economically viable in Sweden.

Systems with an extra BECCS incentive capture more CO_2 captured due to the incentive and have a slightly lower specific cost compared to systems without the incentive. A major reason for the lower specific cost is the increased amount of CO_2 captured in these systems. The order of capture implementation is different in systems with the incentive compared to systems without due to the monetary value added by the incentive.

The most important transportation mode in the model is the large ship due to a relatively low cost for long-distance transportation. In systems without large ships, the specific cost of the CCS chain is higher due to less cost-effective transportation. Trains are preferred over trucks for land-based transportation over shorter distances, but trains are limited by infrastructure and many of the sites with train infrastructure are bio-based PP or CHP plants, which are not utilized in systems without the additional BECCS incentive due to waste-based CHP plants with a mix of fossil and biogenic emissions providing more value to the system. Therefore, trucks and trains can play an important part in a Swedish CCS system. Pipelines are only used in the Swedish system when they are the only transportation option available.

5.1 Further research

There are some parameters included in the model that are uncertain or not included due to limited data. One example is the cost and capacity of CO_2 transportation by train. Another example is the cost of changing conditions at hubs, a cost that is assumed to be zero in the model.

Implementing a model where a vehicle can collect CO_2 from multiple locations in a round trip. In the current model, only transportation between two locations is possible per round trip. With multiple locations per round trip, the utilization rate of the vehicle could be increased, which lowers the cost of the specific cost of transportation. The case with the largest potential to reduce the transportation cost in the system is transportation between hubs and storage sites by large ships.

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A

Location-based data

A.1 Possible transport modes

Table A.1: Summary of conditions for implementation of different transportation modes between a transportation hub and another hub or storage, X marks possible implementations.

	Ship 10kt	Ship 50kt	Truck	Train	Pipeline onshore	Pipeline offshore
Östrand	X	X	X	X	X	X
Oxelösund	X	X	X	X	X	X
Lysekil	X	X	X		X	X
Göteborg	X	X	X	X	X	X
Helsingborg	X	X	X	X	X	X
Stockholm	X	X	X	X	X	X
Luleå	X	X	X	X	X	X
Slite	X	X				X
Varberg	X	X	X	X	X	X
Kalmar	X	X	X	X	X	X
Gävle	X	X	X	X	X	X
Norrkoping	X	X	X	X	X	X
Örnskoldsvik	X	X	X		X	X
Umeå	X	X	X	X	X	X
Skellefteå	X	X	X	X	X	X

Table A.2: Summary of conditions for implementation of different land-based transportation modes from a site to a transportation hub, X marks possible implementations.

	Truck	Train	Pipeline onshore		Truck	Train	Pipeline onshore
PP1	X	X	X	HP5	X		X
PP2	X	X	X	HP6	X	X	X
PP3	X	X	X	HP7	X		X
PP4	X	X	X	HP8	X	X	X
PP5	X	X	X	HP9	X		X
PP6	X	X	X	HP10	X		X
PP7	X	X	X	HP11	X	X	X
PP8	X	X	X	HP12	X		X
PP9	X	X	X	HP13	X	X	X
PP10	X	X	X	HP14	X		X
PP11	X	X	X	HP15	X		X
PP12	X	X	X	HP16	X		X
PP13	X	X	X	HP17	X		X
PP14	X		X	HP18	X		X
PP15	X	X	X	HP19	X		X
PP16	X	X	X	HP20	X	X	X
PP17	X	X	X	HP21	X	X	X
PP18	X	X	X	HP22	X		X
PP19	X		X	HP23	X		X
PP20	X	X	X	HP24	X		X
PP21	X		X	HP25	X	X	X
PP22	X		X	HP26	X		X
PP24	X	X	X	HP27	X	X	X
PP25	X	X	X	HP28	X	X	X
PP27	X		X	HP29	X	X	X
PP29	X	X	X	HP30	X	X	X
Ce1	X		X	HP31	X	X	X
Ce2	X	X	X	HP32	X		X
Ce3	X	X	X	HP33	X	X	X
Ce4	X		X	HP34	X		X
R1	X		X	HP35	X	X	X
R2	X	X	X	HP36	X		X
R3	X		X	HP37	X		X
IS1	X	X	X	HP38	X		X
IS2	X	X	X	HP39	X		X
IS3	X	X	X	HP40	X	X	X
C1	X	X	X	HP41	X		X
HP1	X		X	HP42	X		X
HP2	X		X	HP43	X		X
HP3	X	X	X	HP44	X		X
HP4	X	X	X	HP45	X	X	X

Table A.3: Summary of conditions for implementation of different transportation modes to a storage storage, X marks possible implementations.

	Ship 10kt	Ship 50kt	Truck	Train	Pipeline onshore	Pipeline offshore
Kollsnes	X	X	X		X	X
Denmark	X	X				X
Stavanger	X	X				X
Barents	X	X				X
Iceland	X	X				X

A.2 Coordinates and emissions

Table A.4: All hubs in the case study and their coordinates.

	Lat	Lon
Östrand	62.47530374	17.32897413
Oxelösund	58.663222	17.109210
Lysekil	58.34675159	11.42309229
Göteborg	57.692050	11.871591
Helsingborg	56.027217	12.694967
Stockholm	59.350533	18.110281
Luleå	65.549281	22.238790
Slite	57.71172344	18.80540781
Varberg	57.111730	12.247176
Kalmar	56.660961	16.362863
Gävle	60.690234	17.211775
Norrköping	58.622701	16.238282
Örnsköldsvik	63.263544	18.725143
Umeå	63.689098	20.338254
Skellefteå	64.678986	21.240414
Narvik	68.438380	17.427200
Trondheim	63.430490	10.395060
Hallsberg	59.059561	15.050611

Table A.5: All storage sites in the model and their coordinates.

	Lat	Lon
Kollsnes	60.551615	4.830563
Denmark	56.427062	5.006772
Stavanger	58.4531	4.801563
Barents	70.641339	23.83608
Iceland	63.844239	-22.43175

Table A.6: All sites in the case study, their fossil and biogenic CO_2 emissions in 2022 [34], their coordinates and the industry of the sites. This table is split over multiple pages.

	Emissions [kt]		**Coordinates**		
	Biogenic	Fossil	Lat	Lon	Plant industry
PP1	1842.83	0	57.09152546	16.55049128	Pulp and paper
PP2	1280.97	0	60.64364568	17.38985017	Pulp and paper
PP3	1419.35	71.58	63.32792368	19.16005724	Pulp and paper
PP4	1445.21	0	59.33826572	13.12154172	Pulp and paper
PP5	1197.19	0	60.68240441	17.27333698	Pulp and paper
PP6	1912.22	78.99	62.47530374	17.32897413	Pulp and paper
PP7	1191.42	0	65.31475314	21.44038572	Pulp and paper
PP8	821.08	0	58.57980097	15.89974012	Pulp and paper
PP9	1141.39	0	56.16098092	14.76467857	Pulp and paper
PP10	1823.97	0	57.22166666	12.17192747	Pulp and paper
PP11	993.93	53.70	59.31835168	13.43760246	Pulp and paper
PP12	987.73	0	61.63863899	17.09808643	Pulp and paper
PP13	797.93	0	65.79194132	23.28768535	Pulp and paper
PP14	745.75	0	56.04379387	14.47984532	Pulp and paper
PP15	654.26	0	65.27232862	21.50387968	Pulp and paper
PP16	699.64	25.19	59.47975587	15.32873919	Pulp and paper
PP17	634.62	0	62.97420348	17.72348696	Pulp and paper
PP18	561.49	0	61.18824933	17.18280888	Pulp and paper
PP19	536.79	0	59.16005641	14.18117766	Pulp and paper
PP20	433.02	0	63.26929244	18.69583889	Pulp and paper
PP21	500.95	25.70	63.70115975	20.32111476	Pulp and paper
PP22	405.97	0	58.75428566	14.80505683	Pulp and paper
PP24	260.31	0	60.20744799	16.31527613	Pulp and paper
PP25	285.51	0	56.99926015	13.23513094	Pulp and paper
PP27	181.30	16.01	58.98779753	12.25602562	Pulp and paper
PP29	135.07	11.27	58.63976302	16.26148773	Pulp and paper
Ce1	151.41	1362.72	57.71172344	18.80540781	Cement & limestone
Ce2	17.36	389.50	58.3843717	13.82477622	Cement & limestone
Ce3	10.01	189.87	59.499615	16.020977	Cement & limestone
Ce4	0	141.45	57.842529	18.802301	Cement & limestone
R1	0	1383.88	58.34675159	11.42309229	Refinery
R2	0	568.99	57.7015739	11.8795847	Refinery
R3	11.94	585.03	57.71064011	11.8237557	Refinery

	Emissions [kt]		**Coordinates**		
	Biogenic	Fossil	Lat	Lon	Plant industry
IS1	0	1573.54	65.567134	22.212282	Iron & steel
IS2	0	1562.00	65.56349277	22.20601065	Iron & steel
IS3	0	1630.45	58.67690172	17.12562022	Iron & steel
C1	0	488.33	58.08324923	11.82553951	Chemical
HP1	1005.96	38.42	59.3526	18.1057	Heat & power
HP2	470.50	324.73	59.2565	18.0614	Heat & power
HP3	783.20	157.90	59.588	16.514	Heat & power
HP4	355.29	255.67	58.621	16.232	Heat & power
HP5	321.14	278.30	58.437	15.655	Heat & power
HP6	320.55	223.27	57.732	12.053	Heat & power
HP7	302.96	282.79	55.6167	13.0333	Heat & power
HP8	324.90	92.68	59.615	17.873	Heat & power
HP9	163.65	70.52	59.1751	17.6665	Heat & power
HP10	212.32	66.12	63.869	20.413	Heat & power
HP11	386.37	46.22	59.283	15.217	Heat & power
HP12	312.12	0	59.367	16.5	Heat & power
HP13	357.37	0	56.867	14.817	Heat & power
HP14	71.47	41.72	57.729	12.929	Heat & power
HP15	168.63	0	57.652	12.9173	Heat & power
HP16	505.37	15.81	59.178	17.665	Heat & power
HP17	290.15	20.82	59.386	13.57	Heat & power
HP18	284.06	71.74	57.6978	14.1739	Heat & power
HP19	339.99	0	63.183	14.65	Heat & power
HP20	231.19	41.14	63.2833	18.7333	Heat & power
HP21	221.02	0	59.15	18.1333	Heat & power
HP22	128.00	0	60.667	17.167	Heat & power
HP23	75.92	53.50	58.5	13.167	Heat & power
HP24	121.63	92.07	56.0675	12.7367	Heat & power
HP25	81.83	83.05	56.65	12.85	Heat & power
HP26	189.66	0	57.65	12.017	Heat & power
HP27	141.14	0	56.033	14.133	Heat & power
HP28	162.80	15.33	64.744	21.044	Heat & power
HP29	112.37	89.20	62.383	17.3	Heat & power
HP30	23.69	111.22	59.1167	15.1333	Heat & power
HP31	133.30	5.94	57.729	12.0275	Heat & power

	Emissions [kt]		**Coordinates**		
	Biogenic	Fossil	Lat	Lon	Plant industry
HP32	183.12	0	60.6	15.633	Heat & power
HP33	179.96	0	58.75	0.000017	Heat & power
HP34	92.71	63.28	65.8333	21.7167	Heat & power
HP35	170.30	9.49	58.419	15.625	Heat & power
HP36	71.46	57.93	58.35	11.9167	Heat & power
HP37	111.83	0	55.866201	12.848408	Heat & power
HP38	150.12	0	59.6333	17.0833	Heat & power
HP39	199.53	0	56.034	12.694	Heat & power
HP40	226.51	0	55.783	13.233	Heat & power
HP41	120.70	0	56.25	15.6167	Heat & power
HP42	185.67	0	56.69	16.16	Heat & power
HP43	259.15	0	59.5453	17.6197	Heat & power
HP44	120.11	25.62	59.3403	14.5346	Heat & power
HP45	205.00	156.00	59.852697	17.680517	Heat & power

A.3 Storage site projects

Table A.7: All storage sites in the model and the project capacity assigned to the storage site [23].

Storage site in model	Included project
Kollsnes	Northern Lights Smeaheia Luna
Denmark	Greensand Bifrost
Stavanger	Trudvang Havstjerne
Barents	Barents Blue
Not included	CO2RYLUS

B

Nomenclature lists

Table B.1: Indices and sets in the model

Set	**Index**	**Description**
Y	y	Time steps in years, Y [2025,...,2050]
L	l	Sites included in the model
J	j	Type of stack
H	h, h'	Transportation hubs
S	s	Storage sites included in the model
K	k	Available transportation modes
I	i	Pressure and temperature condition of CO_2, I [LP,MP,pipeline]
ET	et	Type of CO_2 emission, ET [biogenic,fossil]

Table B.2: Variables in the model. This table is split over multiple pages.

Variable	**Description**	**Unit**
$c^{tot,NPV}$	NPV of total system cost	M€
c_y^{annual}	The annual system cost in year y	M€
$c_{l,j,y}^{CAPEX,capture}$	Annualized CAPEX of capture equipment for stack i at site l in year y	M€
$c_{l,j,y}^{OPEX,capture}$	OPEX of capture equipment for stack i at site l in year y	M€
$c_{l,i,y}^{CAPEX,liq}$	Annualized CAPEX of liquefaction to condition i at site l in year y	M€
$c_{l,i,y}^{OPEX,liq}$	OPEX of capture equipment for stack i at site l in year y	M€
$c_{l,i,y}^{CAPEX,storage-liq}$	Annualized CAPEX for intermediate storage of CO_2 of condition i at site l in year y	M€
$c_{l,i,y}^{OPEX,storage-liq}$	OPEX for intermediate storage of CO_2 of condition i at site l in year y	M€
$c_{h,y}^{CAPEX,storage-hub}$	Annualized CAPEX for intermediate storage of CO_2 at hub h in year y	M€

$c_{h,y}^{OPEX,storage-hub}$	OPEX for intermediate storage of CO_2 at hub h in year y	M€
$c_{et,y}^{emission}$	Cost of emission of type et during year y	M€
$c_{k,y}^{fleet,unused}$	Cost of annualized CAPEX and OPEX for unused vehicle k in year y	M€
$c_{l,h,k,i,y}^{CAPEX,transport-liq}$	Annualized CAPEX of transportation of CO_2 from site l to hub h with transportation mode k under condition i in year y	M€
$c_{l,h,k,i,y}^{OPEX,transport-liq}$	OPEX of transportation of CO_2 from site l to hub h with transportation mode k under condition i in year y	M€
$c_{h,h',k,i,y}^{CAPEX,transport-hub}$	Annualized CAPEX of transportation of CO_2 from hub h to another hub h' with transportation mode k under condition i in year y	M€
$c_{h,h',k,i,y}^{OPEX,transport-hub}$	OPEX of transportation of CO_2 from hub h to another hub h' with transportation mode k under condition i in year y	M€
$c_{h,s,k,i,y}^{CAPEX,transport-storage}$	Annualized CAPEX of transportation of CO_2 from hub h to storage site s with transportation mode k under condition i in year y	M€
$c_{h,s,k,i,y}^{OPEX,transport-storage}$	OPEX of transportation of CO_2 from hub h to storage site s with transportation mode k under condition i in year y	M€
$c_{s,y}^{storage}$	The cost of storing CO_2 at storage site s in year y	M€
c_{y}^{fixed}	Fixed OPEX for equipment	M€
$c^{CCSchain}$	The specific CCS chain cost	€/t_{CO_2}
$e_{et,y}^{captured,annual}$	Captured CO_2 of emission type et during year y	t_{CO_2}
$e_{et}^{captured,total}$	Total amount of CO_2 captured of emission type et d	t_{CO_2}
$e_{et,y}^{emission,annual}$	Amount of CO_2 emitted in year y of emission type et	t_{CO_2}
$e_{et}^{emission,total}$	Total amount of CO_2 emitted of emission type et	t_{CO_2}
$x_{l,j,y}^{stack}$	Flow of captured CO_2 from stack j at site l in year y	t_{CO_2}
$x_{l,h,k,i,y}^{liq}$	Flow of CO_2 transported from site l to hub h with transportation mode k under condition i in year y	t_{CO_2}
$x_{h,h',k,i,y}^{hub}$	Flow of CO_2 transported between hub h and hub h' with transportation mode k under condition i in year y	t_{CO_2}
$x_{h,s,k,i,y}^{storage}$	Flow of CO_2 transported from hub h to storage site s with transportation mode k under condition i in year y	t_{CO_2}
$z_{s,y}$	Stored CO_2 at storage site s in year y	t_{CO_2}
b_y	Installed capacity of equipment in year y	
a_y	Investment in equipment in year y	
$\gamma_{h,y}$	Binary variable for tracking of utilization of hub h in year y	-

Table B.3: Parameters in the model.

Parameter	**Description**	**Unit**
r	Discount rate	%
α	Annuity factor	1/year
LT	Lifetime of equipment	years
$OPEX$	Operational cost of equipment	M€/year
β	Capital expenditure	M€/unit
θ	Cost of operation and maintenance of equipment as a share of CAPEX	%
t^{op}	Yearly operating time	h
t^{rt}	Duration of one round trip	h
t_{liq}^{buffer}	Buffer for intermediate storage after liquefaction	h
t_{ship}^{sea}	Travel time of ship on open sea	h
t_{ship}^{port}	Time loading/unloading in port of ship	h
p	CO_2 capacity of trucks, ships and train wagons	t_{CO_2}
$p^{locomotive}$	Number of wagons one locomotive can pull	$\frac{\text{wagons}}{\text{locomotive}}$
d	Round trip travel distance or length of pipeline	km
$z_{s,y}^{MAX}$	Maximum capacity of storage site s in year y	t_{CO_2}
W^{truck}	Wage cost per truck	M€/truck
HC	Harbor cost per round trip	M€/trip
SC_s	Specific cost of CO_2 storage at storage site s	M€/t_{CO_2}
f_{truck}^{cost}	Cost of diesel	M€/l
f_{ship}^{cost}	Cost of ship fuel	M€/MWh
f_{truck}^{use}	Diesel consumption of truck	l/km
f_{ship}^{use}	Fuel consumption of ship on open sea	MWh/h
F_{ship}^{port}	Fuel consumption in port as share of open sea consumption	%
$q^{reboiler}$	Steam demand for the reboiler in the capture process	MWh/t_{CO_2}
f^{steam}	Cost of steam	M€/MWh
$c_{et,y}^{CO_2}$	Price of CO_2 of emission type et in year y	€/t_{CO_2}
$e_{l,et}^{CO_2}$	Annual emissions from site l of emission type et	t_{CO_2}
$CO2_{l,j}^{capture,max}$	Maximum amount of capturable CO_2 from stack j at site l	t_{CO_2}
$e_{et,y}^{target}$	Capture target of CO_2 of emission type et in year y	t_{CO_2}
$m_{l,j,et}$	Share of emission type et from stack j at site l	%

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