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Modeling a supply chain for carbon capture and offshore storage—A German–Norwegian case study

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ABSTRACT

Carbon capture and storage (CCS) for industrial emission point sources is one of the potential instruments to achieve net-zero carbon dioxide (CO_2) goals. However, emission point sources and storage formations are often far from each other, which requires capable CO_2 transportation infrastructure. While pipeline transportation promises low cost for high and stable flows of CO_2, ship transportation may be more expensive but also more flexible with regards to transport quantities and storage locations. Here, we present a mixed integer programming (MIP) model to provide decision support for a CCS Supply Chain Design Problem (CCS-SCDP) with the goal of minimizing total supply chain costs. We apply the model to four future CO_2 supply scenarios, capturing CO_2 from German industrial sources and bringing them to the Northern Lights unloading port in Kollsnes, Norway, for storage in a submarine geological formation. Our analysis reveals that the fraction of transportation costs of total supply chain costs drop considerably from 22 to 10 percent by economies of scale if annual capture volume increases. For low capture volumes, a ship-based solution is cheaper, while an offshore pipeline solution is favored for larger capture volumes. Accordingly, the potential gains from economies of scale in a pipeline-based solution must be balanced against potential lock-in effects in the investment decision for a CCS supply chain.

1. Introduction

According to the Intergovernmental Panel on Climate Change (2023), mankind needs to reduce CO_2 emissions drastically and quickly in order to fight global warming. Due to political initiatives, emitting CO_2 becomes more and more expensive for industrial companies. For example, the price for an EU ETS certificate of one tonne of CO_2-equivalent increased from 34 Euro at the beginning of 2021 to about 85.5 Euro in September 2023 (Ember Climate, 2023). With this rise in cost, alternative options for preventing CO_2 entering the atmosphere become more and more widely discussed, especially options that promise to effectively contribute to the ambitious 1.5 °C goal of the Paris Agreement (United Nations, 2015). One such option is Carbon Capture and Storage (CCS), a process that aims at capturing CO_2 at emission sources before it enters the atmosphere and transporting it to suitable geological storage locations for depositing it there permanently (Bui et al., 2018). To reach net zero emissions in 2050, the globally captured CO_2 should be at a level of 7.6 Gt per year according to the scenario of International Energy Agency (2021b). CCS has therefore been much discussed for the energy and industrial sectors, which account for the majority of CO_2 emissions worldwide (International Energy Agency, 2023). Emission-intensive industrial producers of steel, cement, fertilizer, and other chemicals might call for such an option if their enormous energy demand cannot be fully met by green and renewable energy sources in the future. For the cement and organic chemical industries in particular, CCS is one of the few alternative options for mitigating process-related emissions (International Energy Agency, 2021b).

Several CCS projects have been initialized in Europe in recent years (Al Baroudi et al., 2021). Especially the Norwegian project Northern Lights has received attention as it is the most advanced in offering ship transportation and storage infrastructure as a CCS service. With the first commercial customer, the Dutch fertilizer producer Yara, Northern Lights agreed to transport and store 0.8 mega tonnes per annum (Mtpa) CO_2 from early 2025 to its storage location (Northern Lights, 2022).

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Germany, who emits most CO_2 among all European countries, has also announced interest in using the shared infrastructure of Northern Lights and plans to establish a CCS hub at the port of Wilhelmshaven that is to be served by an onshore pipeline network as is planned by the oil and gas producers Winterhall Dea and Equinor (Wintershall Dea, 2022).

Connecting countries for large-scale CCS requires high-capacity yet cost-efficient infrastructure. Even though the capturing process of CO_2 at the emission sources is usually seen as the most costly part of the CCS supply chain (up to 75% of total system cost depending on the project, cf. National Petroleum Concil, 2019), low-cost, efficient, and reliable transport logistics between the emitters and the final storage locations is of central importance to achieving economic viability for CCS solutions.

Based on experience with similar types of goods such as liquefied natural gas (LNG) and liquefied petroleum gas (LPG), ships and pipelines are considered the main options for large-scale CCS solutions. Thereby, ship-based transportation and pipeline transportation have different technological and economic challenges associated with them (Intergovernmental Panel on Climate Change, 2005). Pipelines have been considered in the past as the most economical way of transporting large volumes of CO_2 onshore but are faced with higher costs when applied offshore. Ship-based transportation is viable for long distances with comparably low transportation volumes that do not yet justify investments in pipelines (Bennæs et al., 2022). Additionally, many countries, including Norway, Sweden, Denmark, and the Netherlands, only grant permission for offshore CCS storage. Acknowledging that there exists a public opposition to onshore underground storage of CO_2, the need for techno-economic assessments of offshore transportation technologies has increased (Holz et al., 2021). Developing a viable full-scale CCS supply chain network therefore requires to jointly consider capture processes, onshore and offshore transportation as well as offshore storage concepts.

The main objective of this paper is to develop an optimization model that provides valuable insights into the design of a viable CCS supply chain for offshore storage of CO_2. We refer to the problem as the CCS Supply Chain Design Problem (CCS-SCDP) and include the relevant supply chain components for capturing CO_2 from a set of emission sources, transporting it across land and sea by pipeline or ship, and storing it in suitable submarine geological storage locations. This is achieved by formulating a mixed integer programming (MIP) model for the CCS-SCDP that captures relevant supply chain design questions regarding onshore and offshore pipeline connections, ship fleet size and mix, fleet deployment, and fleet scheduling. The model also considers decisions regarding the capacity of port infrastructure and intermediate storage capacities within the supply chain. We analyze in a case study different CO_2 volume scenarios for a CCS supply chain connecting Germany and Norway. The model provides cost-optimal supply chain configurations for the respective CO_2 volumes. The obtained information can guide policy-makers and company managers in deploying CCS solutions in Germany and Norway.

In the following section, we provide an overview of the relevant literature. Section 3 presents a verbal problem description which is followed by the mathematical formulation of the CCS-SCDP in Section 4. Section 5 details the case study input data and the results obtained from computational experiments. Lastly, Section 6 concludes the paper.

2. Literature review

CCS is considered in the majority of governmental reports that address climate targets (e.g., Intergovernmental Panel on Climate Change (2022), International Energy Agency (2021b), Zero Emissions Platform (2019) and Intergovernmental Panel on Climate Change (2005)). They usually focus on technical requirements, infrastructure concepts, and cost estimations of CCS without analyzing the CCS logistics in depth and detail. Comprehensive reviews of CCS can be found in Bui et al. (2018) and Boot-Handford et al. (2014), which analyze the capture, transport, and storage components of CCS and identify additional research challenges. A number of techno-economic assessments focus on single components of the CCS process, e.g., Leeson et al. (2017) for industrial capture volumes and cost estimations, Aspelund et al. (2006) for ship transportation, Knoope et al. (2013) for pipeline transportation, or van den Broek et al. (2010) for transportation and storage infrastructure of CO_2. Thereby, the transportation modes and their influence on the cost and infrastructure of a CCS supply chain are widely investigated.

2.1. Single-mode transportation

The two common transportation modes are ship and pipeline transportation, which are analyzed individually and comparatively. Pipeline transportation is characterized by high investments and inflexible reaction to changing mass flows of CO_2. For example, Knoope et al. (2014) consider pipeline transportation in a cost estimation model, where they also include costs due to over-sizing pipelines. Similarly, Nie et al. (2021) introduce a multi-period optimization model to improve pipeline transportation and storage investments for uncertain capture volumes and storage capacities for the Netherlands. The choice of transportation mode also influences the structure of a supply chain as various components may or may not be part of the supply chain, e.g., compressor stations in case of pipeline transport.

Middleton and Bielicki (2009) develop a model to design a scalable transportation network for CCS, with onshore pipelines as the only transportation mode. By formulating a MIP model, they decide on the optimal geospatial arrangement with respect to the minimum total cost of the CCS system. The supply chain costs for a pipeline network in the West of the United States are calculated as 43 Euro per tonne to 47 Euro per tonne for assumed CO_2 volumes from 20 to 40 Mtpa. Santibanez-Gonzalez (2017) extend the idea of a pipeline-driven network with uncertain storage capacities and the opportunity to invest in CO_2 certificates instead of participating in the CCS supply chain.

Compared to pipeline transportation, ship transportation of CO_2 needs other types of facilities. For a detailed literature review on ship transportation for CCS, we refer to Al Baroudi et al. (2021). Roussanaly et al. (2021) focus on the choice of the optimal shipping condition for liquid CO_2 and its impact on the transportation costs for different volumes and distance scenarios. Bjerketvedt et al. (2022) develop a multi-period strategic investment model to analyze the deployment of a CO_2 ship transportation infrastructure from nine Norwegian and Swedish industrial emission sources. As a result, they observe transportation costs of 32.4 Euro per tonne for an infrastructure that can handle 3.3 Mtpa CO_2. Bennæs et al. (2022) present a MIP model for a cost-effective ship-based logistics system from mainland European ports to Norway. Their study analyzes three possible capture scenarios from the hinterland of North European ports that reflect CO_2 volumes for the years 2025, 2030, and 2050. In the context of a ship-based supply chain with offshore storage location, Nam et al. (2013) determine the optimal fleet size and mix, ship-to-route assignments, and the number of round trips to be used for a Korean CCS transportation system. Their MIP model minimizes costs by determining the location and number of liquefaction facilities to which emission sources connect by pipelines whereas offshore transportation and storage optimization makes the decisions that were mentioned before.

2.2. Multi-mode transportation

The trade-off between ship and pipeline transportation depends on transport distances and CO_2 volumes and is investigated in the following studies. Kjärstad et al. (2016) consider offshore CO_2 transportation modes and their associated costs for CO_2 sources in the Nordic region through a modular cost estimation methodology. Thus, costs of the relevant supply chain components of both offshore pipeline and ship transportation and injection are calculated as a function of either

Table 1
Selected relevant literature for this study.

Reference	Onshore mode	Offshore mode	Routing	Number of docks	Buffer management	Region
Nie et al. (2021)	Pipeline	Pipeline	–	–	–	NL
Bjerketvedt et al. (2022)	–	Ship	✓	–	✓	SWE-NOR
Middleton and Bielicki (2009)	Pipeline	–	–	–	–	US
d'Amore et al. (2021)	Pipeline	Pipeline Ship	✓	–	–	EU
Becattini et al. (2022)	Truck Train Barge Ship	Pipeline Ship	–	–	✓	CHE-NOR
This project	Pipeline	Pipeline Ship	✓	✓	✓	GER-NOR

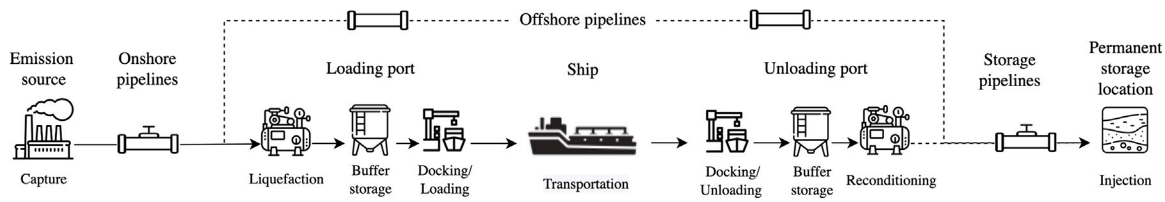


Fig. 1. Schematic CCS supply chain.

volume, distance, or both. Roussanaly et al. (2013, 2014) compare the costs of pipelines and ship transportation taking into account technical requirements for various geographical conditions, distances, and volumes. Their analyses show that pipeline transportation is especially viable for short distances with high transportation volumes. Multimodal transportation has been considered in MIP-based optimization of CCS supply chains too. Thereby onshore transportation is mostly modeled as a pipeline network, whereas ships and pipelines are the options for offshore transportation. d'Amore et al. (2021) take such a system-wide CCS supply chain design approach and present a MIP model at the example of a European CCS supply chain case. The model comprises capturing CO_2 at European emission sources, ship transportation, offshore and onshore pipeline transportation, and storage decisions. The solution of the model provides the optimal selection, sizing, and location of capture alternatives across different sectors and the optimal transportation modes, with particular attention being paid to choosing pipelines or ships to connect CO_2 sources to onshore and offshore geological storage sites. Their results show total supply chain costs of 76.5 to 81.4 Euro per tonne for different capture targets but only considering potential offshore storage. The transportation costs range from 11.7 to 14.1 Euro per tonne for scenarios with offshore storage only, using ship and pipeline. Becattini et al. (2022) consider a similar approach but complement their MIP with time-dependent truck and train transportation decisions as two more onshore transportation modes. For a Swiss case study with the storage site of the Northern Lights project and a four Mtpa CO_2 capture volume, they found that pipeline transportation is cost-optimal with supply chain costs of 150 Euro per tonne CO_2, which includes 85 Euro per tonne for transportation.

The analyzed publications represent a wide area of CCS research (see Table 1). We take up this research to design a CCS supply chain involving emitters in Germany, onshore transportation by pipelines, offshore transportation by pipelines and ships, and final storage in Norway. We furthermore determine the required capacities of buffer storages and port facilities for handling ships. By considering both modes of transport, we obtain a clearer picture of what mode to use under what conditions, which provides an advantage compared to studies like Nie et al. (2021) or Bjerketvedt et al. (2022) that focus on just one mode. In more detail, we consider a pipeline network for onshore transportation like Middleton and Bielicki (2009) but consider the extension towards offshore storage and transportation. We exclude the use of other onshore transportation modes such as trucks or trains, since the large capture volumes that are of interest for our study would require an excessive number of such vehicles. While our model is meant to provide support for strategic decisions, we also aspire to give indications towards the operational feasibility of the resulting supply chains, which differs from the models of d'Amore et al. (2021) and Becattini et al. (2022). Operational feasibility is achieved through a detailed modeling of ship operation management, encompassing aspects such as routing, unloading and loading times, waiting times, as well as the required number of docks in ports and the dimensioning of buffer storage capacities. By including all vital parts of a CCS supply chain into our model, the resulting total cost of the supply chain are determined and the corresponding cost per tonne of CO_2 allows for a comparison with the EU ETS prices and other schemes of CO_2 taxation policies, which supports the evaluation of CCS options for policy-makers.

3. The carbon capture and storage supply chain problem

Fig. 1 sketches a CCS supply chain, where offshore pipeline transportation is an alternative to ship transportation. The supply chain starts by capturing the CO_2 at inland *emission sources*, which can be different types of production facilities. Each emission source has a given rate of CO_2 emissions per time period and a cost of capturing CO_2 based on the type of the facility. The rate at which CO_2 is captured per time period can be assumed to be given and constant. After capturing the CO_2, it is transported through *onshore pipelines* to a shoreside CO_2 collecting hub (referred to as a *loading port*) either directly or indirectly via pipelines that connect emission sources with each other. Thereby, pipelines can have different diameters and flow capacities. Furthermore, it is assumed that more than one pipeline can be built between any two facilities. Having reached a loading port, the CO_2 can be further transported either by *ships* and/or by *offshore pipelines* to the *unloading ports* that are nearby the final storage locations. If transported by ship, the CO_2 needs to be liquefied and temporarily stored in a buffer storage before being loaded onto a ship. The ship then sails to the unloading port to be discharged. While a loading port must have a liquefaction unit, the unloading port must have a reconditioning unit that brings the CO_2 into a gaseous state that is suitable for geological deposition. Both types of ports also need intermediate buffer storage capabilities and a sufficient number of docks to handle the calling ships. If the amount of CO_2 in a loading port exceeds the capacity of the buffer storage, the gas has to be emitted into the atmosphere due to overspill. Ships can be of different ship types, where each type has a given transport capacity. From a perspective of ship operations management, a ship is involved in one out of three activities at any given point in time: it either is served at a port, it sails between a loading port or an unloading port, or it waits outside a port for being served next. As CO_2-ships are expected to operate in full-shipload mode, they typically serve one combination of a loading and an unloading port. Furthermore, the ships evaporate a certain share of the shipload during sailing, which is referred to as boil-off of CO_2. The alternative to ship transportation between loading ports and unloading ports are offshore pipelines where again various diameters and numbers of pipelines might be established between these locations. From the unloading port, the CO_2 is then further transported through *storage pipelines* and injected into the geological, permanent *storage location*.

The CCS Supply Chain Design Problem (CCS-SCDP) is the problem of designing this sketched supply chain by making informed decisions about the involved design options. The decisions include the choice CO_2 quantities to capture at each emission source, the design of onshore and offshore pipeline networks, the sizing and mix of a ship fleet, the ship operations management as well as the dimensioning of storage and port infrastructure. Therefore, the CCS-SCDP can be seen as a strategic planning problem where the goal is to minimize the total investment and operational costs. To guarantee operational feasibility of a solution, we also include operational management decisions in the model, for example, regarding ship routing and scheduling. We then solve the problem for a finite planning horizon, e.g., a month, to capture the operations that are going on within this system, and consider this solution to be representative for a particular CO_2 supply scenario later in our case study.

4. Mathematical model

This section presents the CCS-SCDP modeling approach. We use for this the sets and parameters listed in Table 2 and the decision variables listed in Table 3. A more detailed explanation of this notation can be found in the Appendix A.

The objective of the CCS-SCDP optimization model is to minimize the total cost of the CCS supply chain as is expressed by objective function (1). It consists of cost $C^{[Capture]}$ for capturing the CO_2 at the emission sources and cost $C^{[Store]}$ for finally storing the CO_2 in the permanent storage. Transportation of the CO_2 can be done via pipelines, where $C^{[Pipe-L]}$ refers to the costs for providing and using onshore pipelines that connect the emission sources with each other and with loading ports. $C^{[Pipe-O]}$ and $C^{[Pipe-S]}$ denote those cost for offshore pipelines that connect loading and unloading ports and for final storage pipelines to the permanent storage locations, respectively. The cost for establishing buffer storage capacities at ports and emissions due to overspill are captured in term $C^{[Buffer]}$. If CO_2 is transported by ship, we take into account cost $C^{[Hire]}$ for hiring ships, cost $C^{[Sail]}$ for sailing between ports, cost $C^{[Wait]}$ for ships waiting at ports, and cost $C^{[L+U]}$ for loading and unloading operations in the ports. For transportation by ship, CO_2 has to be liquefied at the loading ports and reconditioned at the unloading ports, which is captured by cost $C^{[Liq]}$ and $C^{[Rec]}$, respectively. The cost of providing docks at the ports is represented by $C^{[Docks]}$. The formulas for the computation of each of these cost components are provided in Appendix B.

$$\begin{aligned} \min\ CCS\text{-}cost = \ & C^{[Capture]} + C^{[Store]} + C^{[Pipe-L]} + C^{[Pipe-O]} \\ & + C^{[Pipe-S]} + C^{[Buffer]} \\ & + C^{[Hire]} + C^{[Sail]} + C^{[Wait]} + C^{[L+U]} + C^{[Liq]} \\ & + C^{[Rec]} + C^{[Docks]} \end{aligned} \tag{1}$$

Model constraints (2) ensure that no more CO_2 is captured than what is available in each emission source per period. As an emission source may also receive CO_2 from other emission sources via pipeline, Constraints (3) ensure that the incoming CO_2 together with the captured CO_2 equals the outgoing CO_2 for each emission source.

Table 2
Sets and parameters.

Set	Description
$\mathcal{N}^E$	Set of emission sources
$\mathcal{N}^S$	Set of permanent storage locations
$\mathcal{N}^L$	Set of loading ports
$\mathcal{N}^U$	Set of unloading ports
$\mathcal{N}^P$	Set of all ports, $\mathcal{N}^P = \mathcal{N}^U \cup \mathcal{N}^L$
$\mathcal{V}$	Set of ships
$\mathcal{C}$	Set of ship types
$\mathcal{V}_c$	Set of ships of type c, $\mathcal{V}_c \subset \mathcal{V}$
$\mathcal{D}$	Set of candidate pipeline diameters
$\mathcal{T}$	Set of time periods
$\mathcal{T}_i^{init}$	Set of initial time periods for port i
$\mathcal{T}_i^O$	Set of operating time periods for port i
Parameter	**Description**
P_i	Produced CO_2 in emission source i during one time period
O	Minimum share of produced CO_2 that is captured and transported to permanent storage
F_d	Maximal flow capacity through a pipeline of diameter d, in tonnes per time period
K_v	Load capacity of ship v, in tonnes of CO_2
T_v^L	Number of time periods ship v uses to fully load or unload itself
T_{ijv}	Number of time periods used by ship v to start operating in port i and, immediately after operating, sailing from port i to port j
B	Boil-off per time period, as a percentage of a complete shipload
C_i^C	Cost per tonne of CO_2 captured in emission source i
C_i^S	Cost per tonne of CO_2 stored permanently at location i
C_{ijd}^{PL}	Cost per onshore pipeline with diameter d between nodes i and j, scaled to the length of the planning horizon
C_{ijd}^{PO}	Cost per offshore pipeline with diameter d between nodes i and j, scaled to the length of the planning horizon
C_{ijd}^{PS}	Cost per storage pipeline with diameter d between nodes i and j, scaled to the length of the planning horizon
C_{ij}^V	Cost per tonne of CO_2 flowing through pipelines between nodes i and j
C^B	Cost per tonne of intermediate buffer storage capacity
C_v^H	Cost of hiring ship v during the planning horizon
C_{ijv}^T	Cost of sailing ship v from port i to port j
C_v^W	Cost of waiting of ship v outside of a port for one time period
C_i^I	Cost per tonne loaded onto or unloaded from a ship in port i
C^E	Cost per tonne of emitted CO_2 due to overspill
C^L	Cost per tonne liquefied CO_2
C^R	Cost per tonne reconditioned CO_2
C_i^D	Cost per dock in port i, scaled to the length of the central planning horizon

Constraints (4) apply for loading ports and ensure that the net change in inventory should equal the difference between all incoming CO_2 from onshore pipelines and all non-emitted CO_2 going out to either offshore pipelines or ships. The requirement for unloading ports is similar and expressed by Constraints (5). Here, the CO_2 comes in from offshore pipelines or ships and flows out via storage pipelines towards the geological storage locations. Releasing excess CO_2 into the atmosphere is not allowed at these ports. Constraint (6) ensures that at least O percent of the entire CO_2 that is produced by the emission sources throughout their operating periods is sent out from loading to unloading ports, be it by pipeline or by ship.

$$c_i \leq P_i \qquad i \in \mathcal{N}^E \tag{2}$$

$$\sum_{j \in \mathcal{N}^E \setminus \{i\}} f_{ji}^L + c_i = \sum_{j \in \mathcal{N}^E \cup \mathcal{N}^L \setminus \{i\}} f_{ij}^L \qquad i \in \mathcal{N}^E \tag{3}$$

$$\begin{aligned} s_{i,t-1} + \sum_{j \in \mathcal{N}^E} f_{ji}^L - \sum_{j \in \mathcal{N}^U} f_{ij}^O - \sum_{j \in \mathcal{N}^U} \sum_{v \in \mathcal{V}} K_v x_{ijvt} \\ = e_{it} + s_{it} \qquad i \in \mathcal{N}^L, t \in \mathcal{T}_i^O \end{aligned} \tag{4}$$

Table 3
Decision variables.

Variable	Description	Domain
h_{ijv}	Binary, 1 if ship v is hired and used on the link (i, j) where i represents a loading port, while j represents an unloading port, 0 otherwise	$h_{ijv} \in \{0,1\}\ \forall i \in \mathcal{N}^L, j \in \mathcal{N}^U, v \in \mathcal{V}$
x_{ijvt}	Binary, 1 if ship v starts operating in port i at time period t, and thereafter directly sails from port i to its dedicated port j, 0 otherwise	$x_{ijvt}, x_{jivt} \in \{0,1\}\ \forall i \in \mathcal{N}^L, j \in \mathcal{N}^U, v \in \mathcal{V}, t \in \mathcal{T}$
w_{ivt}	Binary, 1 if ship v waits outside port i in time period t, 0 otherwise	$w_{ivt} \in \{0,1\}\ \forall i \in \mathcal{N}^P, v \in \mathcal{V}, t \in \mathcal{T}$
δ_{ivt}	Binary, 1 if ship v is operating in port i in time period t	$\delta_{ivt} \in \{0,1\}\ \forall i \in \mathcal{N}^P, v \in \mathcal{V}, t \in \mathcal{T}$
d_i	Integer, number of docks in port i	$d_i \in \mathbb{Z}^+\ \forall i \in \mathcal{N}^P$
c_i	Continuous, quantity of CO_2 that is captured in emission source i during one time period	$c_i \geq 0\ \forall i \in \mathcal{N}^E$
b_i	Continuous, CO_2 buffer storage capacity in port i	$b_i \geq 0\ \forall i \in \mathcal{N}^P$
s_{it}	Continuous, inventory level in port i at the end of time period t	$s_{it} \geq 0\ \forall i \in \mathcal{N}^P, t \in \mathcal{T}$
e_{it}	Continuous, emitted CO_2 from loading port i in time period t due to overspill	$e_{it} \geq 0\ \forall i \in \mathcal{N}^L, t \in \mathcal{T}$
p^L_{ijd}	Integer, number of onshore pipelines with diameter d between emission source i and emission source or loading port j	$p^L_{ijd} \in \mathbb{Z}^+\ \forall i \in \mathcal{N}^E, j \in \mathcal{N}^E \cup \mathcal{N}^L \setminus \{i\}, d \in \mathcal{D}$
p^O_{ijd}	Integer, number of offshore pipelines with diameter d between loading port i and unloading port j	$p^O_{ijd} \in \mathbb{Z}^+\ \forall i \in \mathcal{N}^L, j \in \mathcal{N}^U, d \in \mathcal{D}$
p^S_{ijd}	Integer, number of storage pipelines with diameter d between unloading port i and storage location j	$p^S_{ijd} \in \mathbb{Z}^+\ \forall i \in \mathcal{N}^U, j \in \mathcal{N}^S, d \in \mathcal{D}$
f^L_{ij}	Continuous, per-period flow of CO_2 through onshore pipelines between emission source i and emission source or loading port j	$f^L_{ij} \geq 0\ \forall i \in \mathcal{N}^E, j \in \mathcal{N}^E \cup \mathcal{N}^L \setminus \{i\}$
f^O_{ij}	Continuous, per-period flow of CO_2 through offshore pipelines between loading port i and unloading port j	$f^O_{ij} \geq 0\ \forall i \in \mathcal{N}^L, j \in \mathcal{N}^U$
f^S_{ij}	Continuous, per-period flow of CO_2 through storage pipelines between unloading port i and permanent storage location j	$f^S_{ij} \geq 0\ \forall i \in \mathcal{N}^U, j \in \mathcal{N}^S$

$$s_{i,t-1} + \sum_{j \in \mathcal{N}^L} f^O_{ji} + \sum_{j \in \mathcal{N}^L} \sum_{v \in \mathcal{V}} \left(1 - B \cdot T_{ijv}\right) K_v x_{ijvt} = \sum_{j \in \mathcal{N}^S} f^S_{ij} + s_{it} \qquad i \in \mathcal{N}^U, t \in \mathcal{T}^O_i \tag{5}$$

$$\sum_{i \in \mathcal{N}^L} \sum_{j \in \mathcal{N}^U} |\mathcal{T}^O_i| f^O_{ij} + \sum_{i \in \mathcal{N}^L} \sum_{j \in \mathcal{N}^U} \sum_{v \in \mathcal{V}} \sum_{t \in \mathcal{T}} K_v x_{ijvt} \geq O \sum_{i \in \mathcal{N}^E} P_i |\mathcal{T}^O_i| \tag{6}$$

Constraints (7) ensure that the inventory at a port can never exceed the established buffer storage capacity. Constraints (8) ensure that the buffer storages are not filled in the initial periods except for the last of these periods at which storage operations are allowed to ramp up. Furthermore, Constraints (9) ensure for the unloading ports that the inventory is the same at the start and the end of the operating time periods, which leads to a balanced ship transportation solution.

$$s_{it} \leq b_i \qquad i \in \mathcal{N}^P, t \in \mathcal{T} \tag{7}$$

$$s_{it} = 0 \qquad i \in \mathcal{N}^P, t \in \mathcal{T}^{init}_i \setminus \{|\mathcal{T}^{init}_i|\} \tag{8}$$

$$s_{i,|\mathcal{T}^{init}_i|} = s_{i,|\mathcal{T}|} \qquad i \in \mathcal{N}^U \tag{9}$$

Each pipeline has a maximum capacity, given by its diameter d. Constraints (10), (11), and (12) ensure for onshore pipelines, offshore pipelines, and permanent storage pipelines, respectively, that the flow on an arc does not exceed this capacity.

$$f^L_{ij} \leq \sum_{d \in D} F_d p^L_{ijd} \qquad i \in \mathcal{N}^E, j \in \mathcal{N}^E \cup \mathcal{N}^L \setminus \{i\} \tag{10}$$

$$f^O_{ij} \leq \sum_{d \in D} F_d p^O_{ijd} \qquad i \in \mathcal{N}^L, j \in \mathcal{N}^U \tag{11}$$

$$f^S_{ij} \leq \sum_{d \in D} F_d p^S_{ijd} \qquad i \in \mathcal{N}^U, j \in \mathcal{N}^S \tag{12}$$

Constraints (13) to (18) ensure consistent ship operation decisions. Constraints (13) ensure that a ship can only be hired to serve one pair of an unloading port and a loading port. Constraints (14) and (15) are the general ship sailing constraints, controlling the movements and sequences of sailing, port operations, and waiting. For example, according to Constraints (14), if a ship v either arrived at an unloading port j or waited there at period $t-1$, it can further wait there in period t or return to its loading port j. Constraints (16) have two effects. First, they ensure that only a hired ship can sail or wait in any period. Moreover, since h_{ijv} is binary, they also ensure that a ship can only perform one activity during each time period. Constraints (17) enforce that a ship needs to start its operations in a loading port. Finally, Constraints (18) ensure that a ship does not conduct any activity in its initial time periods, except for the last of these periods $|\mathcal{T}^{init}_i|$. This exemption allows for ship waiting in the last period of the initial time periods, which is needed in Constraints (14) and (15) to handle the first operating time period, as the terms $w_{jv,t-1}$ and $w_{iv,t-1}$ can get assigned value 1 then.

$$\sum_{i \in \mathcal{N}^L} \sum_{j \in \mathcal{N}^U} h_{ijv} \leq 1 \qquad v \in \mathcal{V} \tag{13}$$

$$x_{ijv,t-T_{ijv}} + w_{jv,t-1} = w_{jvt} + x_{jivt} \qquad i \in \mathcal{N}^L, j \in \mathcal{N}^U, v \in \mathcal{V}, t \in \mathcal{T}^O_j \tag{14}$$

$$x_{jiv,t-T_{jivt}} + w_{iv,t-1} = w_{ivt} + x_{ijvt} \qquad i \in \mathcal{N}^L, j \in \mathcal{N}^U, v \in \mathcal{V}, t \in \mathcal{T}^O_i \tag{15}$$

$$x_{ijvt} + x_{jivt} + w_{ivt} + w_{jvt} \leq h_{ijv} \qquad i \in \mathcal{N}^L, j \in \mathcal{N}^U, v \in \mathcal{V}, t \in \mathcal{T} \tag{16}$$

$$\sum_{\tau=1}^{t} x_{ijv\tau} \geq x_{jivt} \qquad i \in \mathcal{N}^L, j \in \mathcal{N}^U, v \in \mathcal{V}, t \in \mathcal{T} \tag{17}$$

$$\sum_{t \in \mathcal{T}^{init}_i \setminus \{|\mathcal{T}^{init}_i|\}} (x_{ijvt} + x_{jivt} + w_{ivt} + w_{jvt}) = 0 \qquad i \in \mathcal{N}^L, j \in \mathcal{N}^U, v \in \mathcal{V} \tag{18}$$

Constraints (19) through (22) ensure that each port builds the number of docks needed to handle the ship traffic. Constraints (19) ensure that the binary variable δ_{ivt} gets assigned value 1 if ship v is docked in loading port i in time period t. Then, Constraints (20) ensure that the number of docks d_i to provide at port i is at least the maximum number of ships being served simultaneously at that port in any time period. Constraints (21) and (22) handle the same issues for unloading ports.

$$\sum_{j \in \mathcal{N}^U} \sum_{\tau=t-T^L_v}^{t} x_{ijv\tau} \leq \delta_{ivt} \qquad i \in \mathcal{N}^L, v \in \mathcal{V}, t \in \{\mathcal{T} | t \geq T^L_v\} \tag{19}$$

$$\sum_{v \in \mathcal{V}} \delta_{ivt} \leq d_i \qquad i \in \mathcal{N}^L, t \in \mathcal{T} \tag{20}$$

$$\sum_{j \in \mathcal{N}^L} \sum_{\tau=t-T^L_v}^{t} x_{ijv\tau} \leq \delta_{ivt} \qquad i \in \mathcal{N}^U, v \in \mathcal{V}, t \in \{\mathcal{T} | t \geq T^L_v\} \tag{21}$$

Table 4
Supply scenarios.

Scenario	Total CO_2	# Emission sources	Avg. emissions per source	Avg. capture cost per tonne
S5	5 Mtpa	1	5.0 Mtpa	€ 75.00
S20	20 Mtpa	2	9.8 Mtpa	€ 72.50
S50	50 Mtpa	9	5.6 Mtpa	€ 65.43
S100	100 Mtpa	34	2.9 Mtpa	€ 64.28

$$\sum_{v \in \mathcal{V}} \delta_{ivt} \leq d_i \qquad i \in \mathcal{N}^U, t \in \mathcal{T} \tag{22}$$

Having tested several symmetry-breaking constraints, we decided to add Constraints (23) to the model. They ensure that if several ships of the same ship type c are used in a solution, ship v needs to be used before ship $v+1$ is allowed to be used.

$$\sum_{i \in \mathcal{N}^L} \sum_{j \in \mathcal{N}^U} (h_{ijv} - h_{ij,v+1}) \geq 0 \qquad c \in \mathcal{C}, v \in \mathcal{V}_c \tag{23}$$

The domains of all decision variables are provided in Table 3. It should be noted that all variables are only defined for the relevant relations of the CCS supply chain. For example, x-variables are only defined for pairs of a loading port and an unloading port but not between two loading ports or between two unloading ports.

5. Case study

We apply the developed model to a case with emission sources in Germany and a permanent CO_2 storage under the seabed of the North Sea outside of Norway. We investigate under which conditions ships and/or pipelines are the preferred CCS infrastructure. For this, we analyze the sensitivity of the results, e.g., with respect to capture volumes and offshore transportation distances. Section 5.1 presents the input data for this German-Norwegian CCS supply chain case. The results are analyzed in Section 5.2.

5.1. Input data

We consider Wilhelmshaven as a planned CCS loading port in mainland Europe and the Northern Lights unloading port with its nearby geological storage in Kollsnes, Norway. We analyze four supply scenarios, as summarized in Table 4, with one to 34 emission sources in Germany and a total CO_2 capture volume of 5 to 100 million tonnes per annum (Mtpa). The region as well as the considered nodes for the case study are shown in Fig. 2.

For each scenario, the model is solved over a representative planning horizon $\mathcal{T}$ of 30 days. This horizon is subdivided into indexed time periods $t \in \mathcal{T}$ with equal length of 12 h each. The initial time period set $\mathcal{T}_i^{init}$ is of cardinality equal to the minimum number of time periods it takes for a ship to sail from its initial position to a loading port. After the initial time periods, the operating time periods $\mathcal{T}_i^O$ complement the horizon $\mathcal{T}$.

The amounts P_i of CO_2 generated per time period at inland emission sources $i \in \mathcal{N}^E$ are taken from German Environment Agency (2018). Capture costs C_i^C of emission sources $i \in \mathcal{N}^E$ are primarily dependent on the type of combustion process that releases the CO_2 and may vary significantly among different industries. To estimate the capture costs, the emission sources have been mapped to a set of industry-specific CO_2 capture processes provided by Bains et al. (2017) and the International Energy Agency (2021a) through their NACE sector. The capture cost estimate for all emission sources is set to the average value reported in Table 4 for each of the scenarios. A detailed overview of the considered emission sources can be found in Appendix C. We furthermore request that minimum $O = 97\%$ of the emissions are captured. We chose this high value because the eventual goal for all industries should be net zero emissions, which, however, is not perfectly achievable due to leakage or boil-off effects. We could also test for lower values of O but decided against this as our different capture scenarios already reflect settings with less ambitious capture targets. The cost of the final storage C_i^S is set to 6 Euro per tonne, which reflects a saline aquifer geological storage with a capacity of 200 Mtpa (Zero Emissions Platform, 2011).

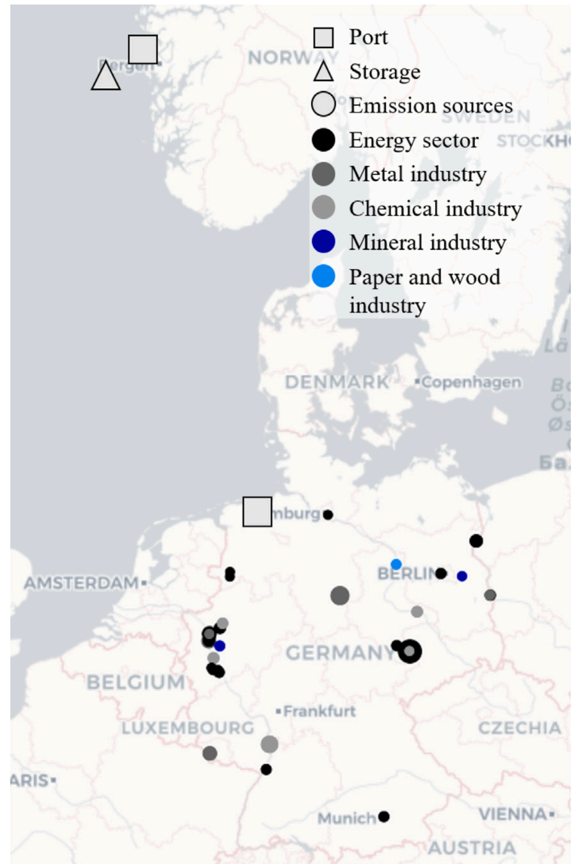


Fig. 2. Region of the case study (size of the bubbles in relation to their CO_2 emission volumes).

Table 5
Parameters of the considered pipeline options.

Index d	Diameter (m)	Max. flow rate F_d (tonnes/time step)	Annual capacity (Mtpa)	Construction cost rate (in thousand Euro/km)
1	0.2	2307	1.7	565
2	0.3	5191	3.8	605
3	0.4	9229	6.7	661
4	0.5	14420	10.5	733
5	0.6	20765	15.2	821
6	0.7	28263	20.6	925
7	0.8	36915	26.9	1045
8	0.9	46721	34.1	1181
9	1.0	57680	42.1	1333

For pipeline transportation, we consider a set of nine inner pipeline diameter options $\mathcal{D}$ ranging from 0.2 to 1.0 m, with parameters as shown in Table 5. The range of pipeline diameters is based on the diameter options considered by Serpa et al. (2011). In a CO_2 pipeline, the diameter is a compromise between material cost and the flow capacity. Increasing the flow capacity through a larger diameter necessitates an increase in both the material thickness of the pipeline and the pressure level. Currently planned CCS projects like Wintershall Dea (2022) would require a pipeline with a diameter of about 0.8 about according to Serpa et al. (2011). For more detailed information on the dimensioning of CO_2 pipelines, we refer to Knoope et al. (2013). The CO_2 flow capacity F_d depends on the pipeline diameter and is derived from a widely used velocity-based equation of Knoope et al. (2013), assuming the super-critical state of CO_2. The investment costs C^{PL}_{ijd}, C^{PO}_{ijd} and C^{PS}_{ijd} of onshore-, offshore- and storage-pipelines, are derived from a construction cost per km that depends on the flow capacity F_d (see Serpa et al. (2011) and Table 5). These costs are applied over the length of a pipeline, which is computed by the haversine distance between the connected nodes i and j using an adjusting length factor of 1.2 and a terrain factor that is set to 1.2 for onshore and 2.0 for offshore pipelines, see Serpa et al. (2011). The cost rates are then estimated by assuming a yearly depreciation of 5% of the investments over a lifetime of 20 years and adding an assumed operational costs of 2.5% of the investments (Knoope et al., 2013). The variable pipeline transportation cost C^{V}_{ij} mostly consists of the cost of electricity needed to boost the pressure along a pipeline and keep the CO_2-flow above the critical point. The corresponding booster pumping power requirements are computed based on McCollum and Ogden (2006).

For ship transportation, we consider six ship types C and 12 indexed ships of each type, i.e., $|\mathcal{V}_c| = 12$. The load capacities K_v of the ships depend on their type and range from 50 000 to 100 000 tonnes (Roussanaly et al., 2021). For the ship hiring costs C^{H}_{v}, we follow Roussanaly et al. (2021) and set these to 10% of the initial investment costs, where ship-type dependent investment costs are derived from Element Energy (2018). The operating costs C^{T}_{ijv} are composed of sailing costs and port fees. The cost of sailing a route is derived from the distance between the involved ports, the ship's fuel consumption rate, and a fuel price of 500 Euro per tonne (Ship & Bunker, 2022). The fuel consumption of the six ship types ranges from 0.260 to 0.328 tonne of fuel per kilometer for an assumed service speed of 14 knots (Roussanaly et al., 2021). The intermediate buffer storage costs C^{B} are calculated based on the storage capacity and have two components. Like Bjerketvedt et al. (2022), we consider 478 Euro per tonne storage capacity as investment costs and a further fixed share which is of those investments to reflect yearly fixed operating costs. The port fees are dependent on the ship size and follow Element Energy (2018), where we assume equal fees for all involved ports. The combined travel and service time T_{ijv} depends on the distance between ports i and j under the service speed of 14 knots and an operating time of one time period (12 h) to load or unload in a port, i.e., $T^{L}_{v} = 1$ (European Commission, 2021). The boil-off rate B is set to 0.1% of the full shipload for all ship types (International Energy Agency, 2004). The waiting cost C^{W}_{v} of a ship refers to the fuel consumption of the auxiliary engine, which is estimated to be 15% of the consumption when sailing (Global Maritime Energy Efficiency Partnerships, 2022; Li and Jia, 2020). Further cost rates are summarized in Table 6.

Table 6
Additional cost rates for ship transportation.

Description	Parameter	Value	Reference
Liquefaction cost rate	C^L	€ 3.50 per tonne	Bjerketvedt et al. (2020)
Recondition cost rate	C^R	€ 1.27 per tonne	Bjerketvedt et al. (2020)
Loading/unloading cost rate	C^I_i	€ 0.163 per tonne	Roussanaly et al. (2021)
Cost per dock	C^D_i	€ 90 million	Andhra Pradesh Gas Distribution Cooperation Ltd. (2012)
Overspill cost rate	C^E	€ 80 per tonne	Ember Climate (2023)

5.2. Results

We first report the optimal supply chain configurations for each of the four scenarios S5, S20, S50, and S100. For this purpose, the CCS-SCDP model has been implemented and solved using Python v.3.8 and Gurobi v.9.1.2 on a Dell PowerEdge R640.

Table 7 reports key performance indicators for the solutions to the four scenarios measures include the total supply chain costs over the 30 days planning horizon, the total volume of CO_2 handled within that time span, the total supply chain costs per tonne, the transportation costs per tonne and the share of transportation cost against total supply chain cost. We observe that the resulting CCS costs per tonne are 103.1, 87.3, 79.0, and 76.5 Euro for the scenarios S5, S20, S50, and S100, respectively. Considering that the current EU ETS price is at about 80 Euro per tonne and likely to increase in the future, CCS constitutes a viable offsetting option for companies, even from an economic point of view. Especially, the reduction of the current and future supply of allowances and the planning horizon of the future market for allowances will increase the EU ETS price (Quemin and Trotignon, 2021). Nevertheless, industries so far struggle to integrate CCS in their emission reduction actions. This can be explained, for example, by a lack of regulatory framework for the transportation of CO_2 across national borders (Global CCS Institute, 2023), by a lack of public acceptance (Merk et al., 2022) or simply by a lack of available CCS infrastructure (as is addressed in our study). Furthermore, the transportation cost of the CCS solutions ranges from 22.1 Euro per tonne in scenario S5 to 7.0 in scenario S100, which indicates that the CCS logistics is relatively inexpensive compared to the cost of capturing the CO_2 at the point sources (see Table 4). The remaining gap to the supply chain cost per tonne stems from these capture cost and the 6 Euro per tonne for the final deposition. The significant drop in transportation cost from S5 to S20 is due to a switch from ship to pipeline transportation in the corresponding supply chain configurations as is discussed subsequently. Correspondingly, the relative share of transportation costs per tonne ranges from 21.5% for S5 to about 10% for S20 to S100. A detailed split of the transportation cost per tonne for scenario S5 is shown in Fig. 3. From this, next to the onshore pipeline costs, the hiring of ships, liquefaction of CO_2, and variable sailing costs are the main cost drivers.

Regarding the choice of transportation modes, ships are used only in scenario S5, see Table 8. In this solution, two ships, one with a capacity of 50 kt and one with a capacity of 90 kt, are hired. No offshore pipelines are used in this solution, making it a 'pure ship' solution for the offshore part. The ships conduct five roundtrips within the 30 days planning horizon, where one dock per port is sufficient for loading and unloading the CO_2. Buffer storages of about 100 kt are required in both the loading and the unloading port to handle the steady inflow from the emitters and outflow to the final storage, respectively. The bunker consumption of the ships scaled up to one year of operations causes emissions of 69.6 kt CO_2, based on calculations of International Maritime Organization (2020). This corresponds to about 1.3% of the transported CO_2 volume, which indicates that logistics-related emissions do not counteract the effectiveness of CCS.

In contrast to the solution for scenario S5, the solutions for scenarios S20, S50 and S100 all involve pure pipeline networks. An overview of the total length and numbers onshore, offshore and storage pipelines for each scenario is presented in Table 9. This illustrates that the investments in pipelines pay off for large volumes of CO_2 due to the lower operational transportation cost. The resulting pipeline networks for scenarios S50 and S100 are sketched in Fig. 4. These networks involve several thousand kilometers of pipelines, where larger diameters are chosen with increasing total CO_2 volume. Table 10 provides an overview of the pipeline infrastructure for scenario S100. It can be seen that a large number of onshore pipelines are established to connect the larger number of emission sources in Germany with each other and to

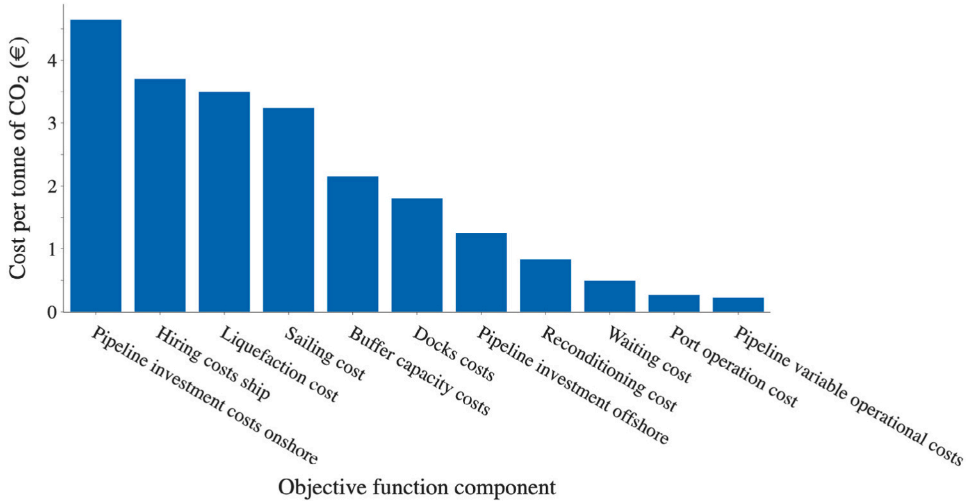


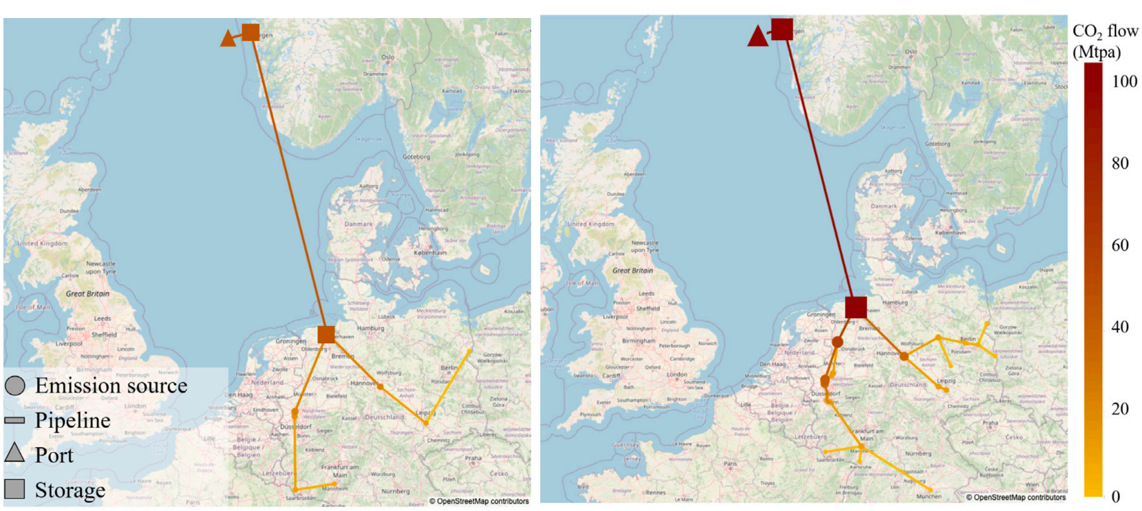
Fig. 3. Cost breakdown of transportation cost per tonne CO_2 in scenario S5.

Table 7
Summary of performance measures for 30 days planning horizon.

Scen.	Total supply chain cost	Volume of CO_2	Total supply chain cost per tonne	Transportation cost per tonne	Transportation cost/Total cost
S5	M€ 41.4	0.4 Mt	€ 103.1	€ 22.1	21.5%
S20	M€ 137.9	1.6 Mt	€ 87.3	€ 8.3	9.6%
S50	M€ 323.9	4.1 Mt	€ 79.0	€ 7.9	10.0%
S100	M€ 619.7	8.1 Mt	€ 76.5	€ 7.0	9.2%

Table 8
Summary of key supply chain components of the optimal solutions.

Scen.	# Included emission sources	Total length of pipelines	# Pipelines	# Ships	# Round trips	# Docks in each port	Buffer storage capacity in Kollsnes	Buffer storage capacity in Wilhelmshaven
S5	1	458.3 km	2	2	5	1	91.2 kt	113.1 kt
S20	2	1265.2 km	4	–	–	–	–	–
S50	9	2993.2 km	13	–	–	–	–	–
S100	33	4270.6 km	39	–	–	–	–	–



(a) Scenario S50 (b) Scenario S100

Fig. 4. Sketch of pipeline infrastructure for scenarios S50 and S100 (Note: pipelines are depicted here as straight lines even though their actual pathway might deviate, which is accounted for by length adjustments in the computational experiments.).

the loading port in Wilhelmshaven. Thereby, all considered pipeline diameters occur in the solution because the emitters strongly differ in their individual CO_2 volumes. For the offshore link and the final storage link, two pipelines of the largest diameters are combined with one pipeline of medium diameter, which altogether provides an annual capacity of 100 Mtpa, see Table 5.

Due to the high efficiency of pipeline transportation for larger volumes of CO_2, the transportation cost is 8.3, 7.9, and 7.0 Euro per tonne

Table 9
Pipelines in the optimal solution for scenario S5-100.

Pipeline diameter	Onshore pipelines		Offshore pipelines (W.haven - Kollsnes)		Storage pipelines (Kollsnes - Storage)	
	# Pipelines	Total pipeline length	# Pipelines	Total pipeline length	# Pipelines	Total pipeline length
S5	1	389.4 km	–	–	1	68.9 km
S20	2	390.3 km	1	806.0 km	1	68.9 km
S50	9	1243.4 km	2	1612.0 km	2	137.8 km
S100	33	2095.5 km	3	2418.0	3	206.7 km

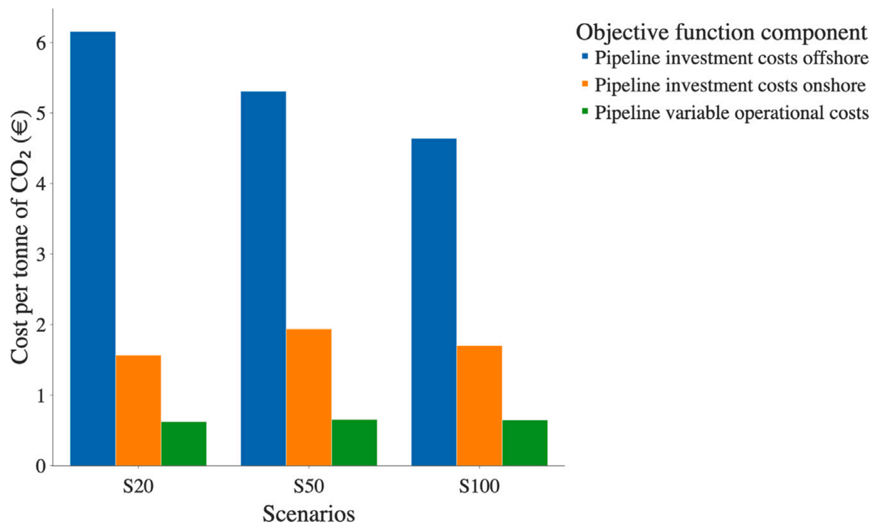


Fig. 5. Cost breakdown of transportation cost in the scenarios S20, S50, and S100.

Table 10
Pipelines in the optimal solution for scenario S100.

Pipeline diameter	Onshore pipelines		Offshore pipelines (W.haven - Kollsnes)		Storage pipelines (Kollsnes - Storage)	
	# Pipelines	Total pipeline length	# Pipelines	Total pipeline length	# Pipelines	Total pipeline length
0.2 m	1	3.4 km	–	–	–	–
0.3 m	4	429.8 km	–	–	–	–
0.4 m	4	259.3 km	–	–	–	–
0.5 m	3	151.1 km	–	–	–	–
0.6 m	6	398.3 km	1	806.0 km	1	68.9 km
0.7 m	3	189.8 km	–	–	–	–
0.8 m	4	152.9 km	–	–	–	–
0.9 m	2	155.1 km	–	–	–	–
1.0 m	6	356.2 km	2	1612.0 km	2	137.8 km
Total	**33**	**2095.9 km**	**3**	**2418.0 km**	**3**	**206.7 km**

in scenarios S20, S50, and S100, respectively. Fig. 5 breaks down these costs, illustrating that the largest share is caused by the investment into offshore pipelines. The figure also illustrates the decrease in the cost per tonne, which results from economies of scale due to the high utilization of larger offshore pipelines in scenarios S50 and S100. The increase of the share of transportation cost against total supply chain cost from S20 to S50 can be explained by the increasing investment costs for onshore pipelines due to an expanded onshore pipeline network with lower utilization.

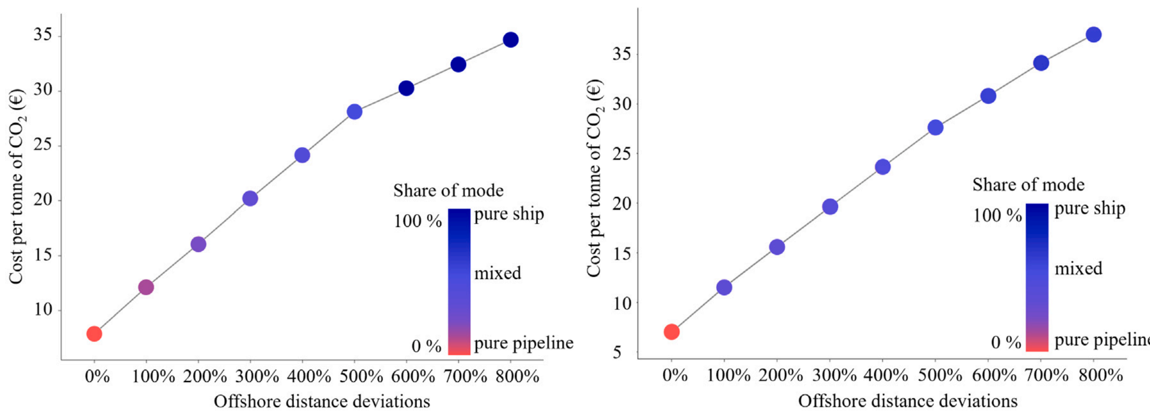
To get a deeper understanding of the role of ship and pipeline transportation for the different scenarios, we enforce in this experiment that the optimization model uses the sub-optimal transportation mode for each scenario. More precisely, we enforce for S5 to establish a pipeline solution and for S20 to S100 to solely use ships for offshore transportation. Table 11 summarizes the corresponding results.

For scenario S5, when forcing pipeline transportation from Wilhelmshaven to Kollsnes, the total supply chain cost per tonne changes slightly from 103.1 to 103.7 Euro per tonne, which corresponds to a relative increase of merely 0.6%. Considering the uncertainty of the input parameters that go into the model, the costs can be considered equal for all practical purposes. Thus, it seems that even the 5 Mtpa scenario could well be served through a network of pipelines. In contrast, when enforcing ship transportation for scenarios S20, S50, and S100, we observe an increase in the supply chain cost per tonne. This cost amounts to 92.4, 83.8, and 81.8 Euro for the three scenarios, respectively, which are increases of up to 6.9% compared to the optimal choice of a transportation mode. The increase is due to the offshore transportation cost per tonne, which is now even higher than the total supply chain transportation cost per tonne in the optimal solutions, compare Tables 7 and 11. Furthermore, we observe that these solutions require substantial ship fleets of up to 11 large-sized ships in scenario S100. These ships have to conduct a total of 82 round trips within the 30 days horizon. Managing such a number of port visits represents a further obstacle for using ships in the transportation of large volumes of CO_2. Nevertheless, as the construction of a pipeline network takes time and cannot be done step-wise with gradually increasing CO_2 volumes, ships might be used as the more flexible transport option in the ramp-up phase of using CCS technologies.

Norway and other countries may open up further geological storages for CCS in the future. For CCS supply chains, this may come along with

Table 11
Performance measures for solutions with enforced usage of sub-optimal transportation mode.

Scen.	Enforced transp. mode	Total supply chain cost per tonne	Relative change	Transportation cost per tonne	Relative change	# Pipelines/ Ships	# Round trips	Buffer storage capacity in ports (GER/NOR)
S5	Pipelines	€ 103.7	0.6%	€ 22.7	2.7%	3	–	
S20	Ships	€ 92.4	5.8%	€ 13.3	60.2%	1 × 50 kt	4	111.3 kt/119.5 kt
						1 × 90 kt	7	
						1 × 100 kt	8	
S50	Ships	€ 83.8	6.1%	€ 12.7	60.8%	1 × 60 kt	6	115.7 kt/100.3 kt
						5 × 100 kt	37	
S100	Ships	€ 81.8	6.9%	€ 12.2	74.3%	1 × 90 kt	8	158.7 kt/164.7 kt
						10 × 100 kt	74	



(a) S50 (b) S100

Fig. 6. Offshore distance sensitivity analysis.

substantially longer offshore transport distances compared to the 806 km that we considered so far in the case study. We conduct a sensitivity analysis with respect to increased offshore transportation distances. In general, when increasing distance, our cost model favors ship transportation over pipelines as the latter requires huge investments that exceed the higher operational transportation cost of ships. We therefore analyze scenarios S50 and S100, where pipelines are optimal under the offshore distance of 806 km and stepwise extend this distance multiple times. The resulting transportation cost per tonne for these stepwise changes in offshore transportation distance and the resulting transportation modes are visualized in Fig. 6.

For S50, we observe that a twice as large offshore distance (+100% increase), which would allow to reach storage locations in Iceland, favors a mix of pipeline and ship transportation, where ships handle the marginal share of CO_2 volume that does not justify the construction of a further pipeline. Note that Iceland's Carbfix project envisions ship-only transportation for its open storage concept and offers its infrastructure to emissions sources in Northern Europe (Carbfix, 2023). For much larger distances (>600%), we then observe a switch to pure ship transportation. For S100 we also observe a switch to a mixed usage of transportation modes but not to the pure usage of ships. This confirms that very large volumes of CO_2 justify the construction of pipelines even over very large distances, where ships are used to handle those volumes that exceed the capacity of the constructed pipelines. To conclude, we observe for several solutions a mix of transportation modes in this sensitivity analysis. This mix might well be influenced by the pipeline diameter options considered in our study. Nevertheless, as we already have a fine granularity of diameters (0.1, 0.2, … 1.0 m), we doubt that further diameter options change solutions a lot. Furthermore, in practice, one would likely oversize pipelines to some extent in order to hedge against variations in emission volumes, which fits to our model where a next-larger diameter is chosen whenever economically viable. Finally, if a CCS network operator prefers to only use a single transportation mode, a further analysis with enforced modes can be conducted (see Table 11) to identify the additional costs of such preferred options.

6. Conclusion

To cope with CO_2 emissions from energy producers and industry, Carbon Capture and Storage (CCS) can be a viable option. In this context, we have investigated the strategic CCS-Supply Chain Design Problem (CCS-SCDP). The CCS-SCDP is about designing a multi-modal supply chain, utilizing ships and/or pipelines to transport CO_2 that is captured at inland emission sources to permanent storage locations at the lowest possible cost. The proposed MIP model encapsulates the most important CCS supply chain design decisions like the volumes of CO_2 to capture at each emitter; the number, capacity, and placement of pipelines; ship fleet size and deployment, as well as intermediate storage and service capacities at the loading and unloading ports. The model is tested on four scenarios with CO_2 volumes of 5, 20, 50, and 100 Mtpa for a German-Norwegian CCS supply chain case. In this case study, emissions are captured at German sources, transported to a projected CO_2-hub port in Wilhelmshaven, Germany, and then shipped to the Northern Lights port Kollsnes, Norway. The results show that the supply chain costs per tonne decrease with increasing CO_2 volumes from 103.1 to 76.5 Euro per tonne. These costs are in the range of the current EU ETS price of about 80 Euro per tonne and show that CCS could soon become a beneficial alternative for emission-intensive industries to reach zero emissions. The economies of scale observed for larger CO_2 volumes are mostly due to the switching to high-capacity pipelines that are well utilized. Indeed, ship transportation is only preferred for the scenario with a volume of 5 Mtpa, as Roussanaly et al. (2013) could also show for cases of similar distance. However, the studied supply chain between Germany and Norway is 50 Euro per tonne cheaper than the pipeline-based Swiss-Norwegian supply chain of Becattini et al. (2022) due to the lower transportation cost per tonne CO_2. Especially the consideration of the operational feasibility of the transportation component makes it possible to generate more detailed cost information. All larger volumes investigated foster pipeline transportation. The conducted computational analyzes actually show that a pipeline network is a viable option in all considered CO_2 volume scenarios. A mixture of ships and pipelines is only observed in rare cases of particular constellations of offshore distance and transportation volumes. In practical situations, opting for a single transportation mode with slightly higher transportation cost may be a more preferred option than going for a mixed transportation system. This is supported by the results of the European-wide supply chain of d'Amore et al. (2021) for offshore storage only which obtain similar total supply chain costs per tonne. However, their transportation costs per ton are higher compared to our solution for the larger volume scenarios S50 and S100 due to longer transportation distances, the use of a mix of ship and pipeline transportation, and a possible cost overestimation due to a lack of operational flexibility. As building pipeline networks takes time, we suggest that future research investigates a multi-period version of the CCS-SCDP that helps to find a cost-efficient ramp-up of the CCS supply chain infrastructure over time. Furthermore, we assumed for this study direct pipeline links for connecting nodes, whereas junctions in pipeline networks (Steiner points/Steiner trees) or actual geographical circumstances (see, e.g., Middleton et al., 2012) could lead to more detailed insights. One could also investigate alternative onshore transportation modes such as trucks or trains but these are surely relevant only for small capture volumes or while the pipeline networks are under construction.

CRediT authorship contribution statement

Anders Bennæs: Conceptualization, Methodology, Software, Writing – original draft, Visualization. **Martin Skogset:** Conceptualization, Methodology, Software, Writing – original draft, Visualization. **Tormod Svorkdal:** Conceptualization, Methodology, Software, Writing – original draft, Visualization. **Kjetil Fagerholt:** Conceptualization, Writing – review & editing, Supervision. **Lisa Herlicka:** Conceptualization, Writing – review & editing, Resources. **Frank Meisel:** Conceptualization, Writing – review & editing, Supervision. **Wilfried Rickels:** Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Notation explanation

The model uses the following sets for representing locations. The set of emission sources is denoted $\mathcal{N}^E$. The permanent storage locations are contained in set $\mathcal{N}^S$. Sets $\mathcal{N}^L$ and $\mathcal{N}^U$ denote the loading ports and unloading ports, respectively. The set of all ports is denoted $\mathcal{N}^P = \mathcal{N}^L \cup \mathcal{N}^U$. Furthermore, we have a set $\mathcal{V}$ of available ships and a set $\mathcal{C}$ of ship types, where $\mathcal{V}_c \subset \mathcal{V}$ denotes the subset of ships belonging to ship type $c \in \mathcal{C}$. Pipelines are distinguished based on their inner diameter, which in turn determines their capacity to handle a flow of CO_2. The set of pipeline diameters is denoted $\mathcal{D}$. As the model is based on discrete time, we denote by $\mathcal{T}$ the set of all time periods in the planning horizon. For each node $i \in \mathcal{N}^P$, we split the planning horizon into two disjoint subsets of *initial time periods* $\mathcal{T}_i^{init}$ (i.e., the minimum number of time periods it takes for a ship to sail from its initial position to a loading port or back to an unloading port, respectively) and *operating time periods* $\mathcal{T}_i^O$, with $\mathcal{T} = \mathcal{T}_i^{init} \cup \mathcal{T}_i^O$.

The following parameters and decision variables are used for modeling the role of the emission sources in the CCS-supply chain. Emission source $i \in \mathcal{N}^E$ is assumed to generate a given and constant amount of P_i tonnes of CO_2 each time period. As the CCS-network might not handle all of this, the continuous decision variable c_i represents the actual amount of CO_2 captured from emission source i per time period, i.e., the capture rate of that source. Furthermore, a given parameter O denotes the percentage share of the total CO_2 generated by all emission sources that must be captured and transported through the supply chain to the permanent storage locations. As the industrial processes for capturing CO_2 at the emission sources may vary significantly, we consider a source-dependent cost rate C_i^C for capturing one tonne of CO_2 at node $i \in \mathcal{N}^E$. For similar reasons, storing one tonne of CO_2 at the final storage location $i \in \mathcal{N}^S$ is accounted for by a location-dependent cost C_i^S per tonne stored.

CO_2 can be transported through pipelines and by ships. The following parameters and decision variables are associated with the pipeline transportation. The integer decisions variables p_{ijd}^L (superscript L for land, onshore), p_{ijd}^O (superscript O for offshore), and p_{ijd}^S (superscript S for storage) denote the number of onshore, offshore and storage pipelines with diameter option $d \in \mathcal{D}$ that are to be built for a relevant link i and j. A cost rate C_{ijd}^{PL} for onshore pipelines, C_{ijd}^{PO} for offshore pipelines and C_{ijd}^{PS} for storage pipelines expresses the construction cost of such a pipeline, scaled down to the length of the planning horizon. Each pipeline has a maximum flow capacity F_d related to its diameter d. The amount of CO_2 transported through pipelines between two nodes i and j is assumed to be equal in all time periods and represented by the continuous decision variables f_{ij}^L, f_{ij}^O, and f_{ij}^S for the different pipeline types, respectively. Furthermore, each tonne of CO_2 transported through pipelines between nodes i and j is assigned a variable cost C_{ij}^V.

For the transportation by ship, we introduce a binary variable h_{ijv} that takes value 1 if ship $v \in \mathcal{V}$ is hired for transporting CO_2 between loading port i and unloading port j. The cost of hiring a ship for the considered planning horizon is denoted C_v^H. The operations of ships are captured by binary variables x_{ijvt}, which take value 1 if ship v starts operating (loading or unloading) in port i at time period t and afterwards sails to (unloading or loading) port j. The cost related to each such port operation and subsequent sailing is denoted C_{ijv}^T. We assume that ship v uses T_v^L time periods to fully load or unload in a port and that it takes T_{ijv} time periods for being fully served in port i and then sail to port j, if the port operation starts in period t. The transport capacity of ship v is denoted by K_v, measured in tonnes of CO_2. During sailing, a percentage B of the loaded CO_2 is released every time period due to boil-off. When a ship is neither operating nor sailing, it has to wait. This is represented by binary variable w_{ivt}, which takes value 1 if ship v waits outside port i in time period t. The cost associated with ship v waiting for one time period is denoted C_v^W.

Serving ships requires liquefying the gas in loading ports and reconditioning it in unloading ports. The liquefaction cost per tonne is denoted C^L, and the reconditioning cost per tonne is denoted C^R. When loaded onto ships and unloaded from ships in a given port i, each tonne of CO_2 is assigned the cost of loading or unloading, denoted C_i^I. All ship activities are time-dependent to allow informed decisions regarding the dimensioning of the ports' docking and buffer storage capacities. If ship v operates in port i during time period t, the binary variable δ_{ivt} gets assigned value 1. This variable is further used to identify the number of docks d_i needed in port i, which also refers to the number of ships port i can serve simultaneously. We assume a cost C_i^D for building a dock in a port i. For temporary storage of CO_2, loading and unloading ports have to have buffers of sufficient capacity. The continuous variable b_i

represents the maximum buffer storage capacity needed in port i. Each tonne of capacity comes at a cost C^B. The inventory level in port i in time t is denoted by the continuous decision variable s_{it}. CO_2 that exceeds the buffer capacity has to be released. The amount of such overspill in port i in time period t is captured by the variable e_{it}. Each tonne of CO_2 emitted due to overspill is penalized by a cost C^E. In our model, overspill is only allowed in loading ports.

Appendix B. Cost functions

$$C^{[Capture]} = \sum_{i \in \mathcal{N}^E} |\mathcal{T}_i^O| C_i^C c_i \tag{B.1}$$

$$C^{[Store]} = \sum_{i \in \mathcal{N}^U} \sum_{j \in \mathcal{N}^S} |\mathcal{T}_i^O| C_i^S f_{ij}^S \tag{B.2}$$

$$C^{[Pipe-L]} = \sum_{i \in \mathcal{N}^E} \sum_{j \in \mathcal{N}^E \cup \mathcal{N}^L} \sum_{d \in D} C_{ijd}^{PL} p_{jd}^L + \sum_{i \in \mathcal{N}^E} \sum_{j \in \mathcal{N}^E \cup \mathcal{N}^L} |\mathcal{T}_i^O| C_{ij}^V f_{ij}^L \tag{B.3}$$

$$C^{[Pipe-O]} = \sum_{i \in \mathcal{N}^L} \sum_{j \in \mathcal{N}^U} \sum_{d \in D} C_{ijd}^{PO} p_{ijd}^O + \sum_{i \in \mathcal{N}^L} \sum_{j \in \mathcal{N}^U} |\mathcal{T}_i^O| C_{ij}^V f_{ij}^O \tag{B.4}$$

$$C^{[Pipe-S]} = \sum_{i \in \mathcal{N}^U} \sum_{j \in \mathcal{N}^S} \sum_{d \in D} C_{ijd}^{PS} p_{ijd}^S + \sum_{i \in \mathcal{N}^U} \sum_{j \in \mathcal{N}^S} |\mathcal{T}_i^O| C_{ij}^V f_{ij}^S \tag{B.5}$$

$$C^{[Buffer]} = \sum_{i \in \mathcal{N}^P} C^B b_i + \sum_{i \in \mathcal{N}^L} \sum_{t \in \mathcal{T}_i^O} C^E e_{it} \tag{B.6}$$

$$C^{[Hire]} = \sum_{i \in \mathcal{N}^L} \sum_{j \in \mathcal{N}^U} \sum_{v \in \mathcal{V}} C_v^H h_{ijv} \tag{B.7}$$

$$C^{[Sail]} = \sum_{i \in \mathcal{N}^L} \sum_{j \in \mathcal{N}^U} \sum_{v \in \mathcal{V}} \sum_{t \in \mathcal{T}_i^O} C_{ijv}^T x_{ijvt} + \sum_{i \in \mathcal{N}^U} \sum_{j \in \mathcal{N}^L} \sum_{v \in \mathcal{V}} \sum_{t \in \mathcal{T}_i^O} C_{ijv}^T x_{ijvt} \tag{B.8}$$

$$C^{[Wait]} = \sum_{i \in \mathcal{N}^P} \sum_{v \in \mathcal{V}} \sum_{t \in \mathcal{T}_i^O} C_v^W w_{ivt} \tag{B.9}$$

$$C^{[L+U]} = \sum_{i \in \mathcal{N}^L} \sum_{j \in \mathcal{N}^U} \sum_{v \in \mathcal{V}} \sum_{t \in \mathcal{T}_i^O} C_i^I K_v x_{ijvt} + \sum_{i \in \mathcal{N}^U} \sum_{j \in \mathcal{N}^L} \sum_{v \in \mathcal{V}} \sum_{t \in \mathcal{T}_i^O} \left(1 - B \cdot T_{jiv}\right) C_i^I K_v x_{ijvt} \tag{B.10}$$

$$C^{[Liq]} = \sum_{i \in \mathcal{N}^L} \sum_{j \in \mathcal{N}^U} \sum_{v \in \mathcal{V}} \sum_{t \in \mathcal{T}_i^O} C^L K_v x_{ijvt} \tag{B.11}$$

$$C^{[Rec]} = \sum_{i \in \mathcal{N}^U} \sum_{j \in \mathcal{N}^L} \sum_{v \in \mathcal{V}} \sum_{t \in \mathcal{T}_i^O} \left(1 - B \cdot T_{ijv}\right) C^R K_v x_{ijvt} \tag{B.12}$$

$$C^{[Docks]} = \sum_{i \in \mathcal{N}^P} C_i^D d_i \tag{B.13}$$

Appendix C. List of emission sources

See Table C.12.

Table C.12
List of considered emission sources.

Scenario	Source	Quantity Mtpa	Sector	Capture cost € per tonne	latitude, longitude
S5–100	LEAG Lausitz Energie Kraftwerke AG Kraftwerk Lippendorf	11.7	Energy sector	75	51.18413954, 12.37164339
S20–100	Salzgitter Flachstahl GmbH	7.94	Metal industry	70	52.15476492, 10.40307531
S50–100	BASF SE	6.94	Chemical industry	30	49.51739119 8.423445647
S50–100	Hüttenwerke Krupp Mannesmann GmbH	4.98	Metal industry	70	51.36823117, 6.712267332
S50–100	thyssenkrupp Steel Europe AG	4.82	Metal industry	70	51.5036903, 6.735907484
S50–100	ROGESA Roheisengesellschaft Saar mbH	4.68	Metal industry	70	49.35213699, 6.743652603
S50–100	thyssenkrupp Steel Europe AG	4.51	Energy sector	70	51.49125002, 6.726482842
S50–100	PCK Raffinerie GmbH Schwedt	3.81	Energy sector	67.5	53.08758529, 14.23812153
S50–100	thyssenkrupp Steel Europe AG	3.56	Energy sector	70	51.46030211, 6.731030496
S100	Ruhr Oel GmbH	2.86	Energy sector	67.5	51.59603275, 7.028908506
S100	Hüttenwerke Krupp Mannesmann GmbH	2.77	Energy sector	75	51.37090094, 6.719117326
S100	INEOS Manufacturing Deutschland GmbH	2.77	Chemical industry	30	51.06763602, 6.846742503
S100	SKW Stickstoffwerke Piesteritz GmbH	2.67	Chemical industry	30	51.87859337, 12.57512855
S100	Evonik Degussa GmbH	2.39	Chemical industry	30	51.67838615, 7.103039879
S100	Basell Polyolefine GmbH	2.18	Chemical industry	67.5	50.83268204, 6.94406668
S100	Vattenfall Wärme Berlin AG HKW Reuter-West	2.15	Energy sector	75	52.53525666, 13.24372661
S100	TOTAL Raffinerie Mitteldeutschland GmbH	2.14	Energy sector	67.5	51.28764321, 12.00011797
S100	VEO Vulkan-Energiewirtschaft - Oderbrücke GmbH	2.14	Energy sector	75	52.16280988, 14.63339772
S100	Shell Deutschland Oil GmbH	2.14	Energy sector	67.5	50.81411042, 7.005756279
S100	Pruna Betreiber GmbH	2.06	Energy sector	46	51.50099128, 6.728879811
	SWM Heizkraftwerk Nord	2.04	Energy sector	75	48.18120037, 11.63977268
S100	MIRO-Mineralölraffinerie Oberrhein GmbH & Co.KG	2.02	Energy sector	67.5	49.05780929, 8.329049992
S100	RWE Power AG Veredlungsstandort Knapsacker Hügel	1.98	Energy sector	75	50.8635988, 6.833008002
S100	Rheinkalk GmbH	1.94	Mineral industry	90	51.28003622, 7.022492879
S100	ArcelorMittal Eisenhüttenstadt GmbH	1.8	Metal industry	70	52.16614052, 14.61768224
S100	Zellstoff Stendal GmbH	1.8	Paper Wood Industry	30	52.69061825, 11.98589833
S100	RWE Power AG-Fabrik Frechen	1.41	Energy sector	75	50.89424619, 6.791055593
S100	CEMEX Zement GmbH	1.4	Mineral industry	90	52.48906926, 13.83692917
S100	Shell Deutschland Oil GmbH	1.31	Energy sector	67.5	50.85499337, 6.976845536
S100	thyssenkrupp Steel Europe AG	1.3	Metal industry	70	51.49125002, 6.726482842
S100	Dow Olefinverbund GmbH Werk Böhlen	1.28	Chemical industry	30	51.1914252, 12.3560994
S100	BP Europa SE	1.18	Energy sector	67.5	52.56185428, 7.311814641
S100	Gaskraftwerk Emsland	1.18	Energy sector	75	52.48072556, 7.306057251
S100	Vattenfall Wärme Hamburg	1.17	Energy sector	75	53.5260858, 10.06551948

References

Al Baroudi, H., Awoyomi, A., Patchigolla, K., Jonnalagadda, K., Anthony, E., 2021. A review of large-scale CO_2 shipping and marine emissions management for carbon capture, utilisation and storage. Appl. Energy 287, 116510.

Andhra Pradesh Gas Distribution Cooperation Ltd., 2012. Development of offshore LNG FSRU facility at kakinada deep water port. http://environmentclearance.nic.in/writereaddata/form-1A/PFR/9_PRE%20FEASIBILITY%20REPROT.pdf. Accessed 20 July 2023.

Aspelund, A., Mølnvik, M., De Koeijer, G., 2006. Ship transport of CO_2: Technical solutions and analysis of costs, energy utilization, exergy efficiency and CO_2 emissions. Chem. Eng. Res. Des. 84 (9), 847–855.

Bains, P., Psarras, P., Wilcox, J., 2017. CO_2 capture from the industry sector. Prog. Energy Combust. Sci. 63, 146–172.

Becattini, V., Gabrielli, P., Antonini, C., Campos, J., Acquilino, A., Sansavini, G., Mazzotti, M., 2022. Carbon dioxide capture, transport and storage supply chains: Optimal economic and environmental performance of infrastructure rollout. Int. J. Greenh. Gas Control 117, 103635.

Bennæs, A., Skogset, M., Svorkdal, T., Fagerholt, K., Herlicka, L., Meisel, F., Rickels, W., 2022. Optimization of a ship-based logistics system for carbon capture and storage. In: de Armas, J., Ramalhinho, H., Voß, S. (Eds.), Computational Logistics. Springer International Publishing, Cham, pp. 44–59.

Bjerketvedt, V.S., Tomasgard, A., Roussanaly, S., 2020. Optimal design and cost of ship-based CO_2 transport under uncertainties and fluctuations. Int. J. Greenh. Gas Control 103, 103190.

Bjerketvedt, V.S., Tomasgard, A., Roussanaly, S., 2022. Deploying a shipping infrastructure to enable carbon capture and storage from Norwegian industries. J. Clean. Prod. 333, 586–601.

Boot-Handford, M.E., Abanades, J.C., Anthony, E.J., Blunt, M.J., Brandani, S., Mac Dowell, N., Fernández, J.R., Ferrari, M.-C., Gross, R., Hallett, J.P., et al., 2014. Carbon capture and storage update. Energy Environ. Sci. 7 (1), 130–189.

van den Broek, M., Brederode, E., Ramírez, A., Kramers, L., van der Kuip, M., Wildenborg, T., Turkenburg, W., Faaij, A., 2010. Designing a cost-effective CO_2 storage infrastructure using a GIS based linear optimization energy model. Environ. Model. Softw. 25 (12), 1754–1768.

Bui, M., Adjiman, C.S., Bardow, A., Anthony, E.J., Boston, A., Brown, S., Fennell, P.S., Fuss, S., Galindo, A., Hackett, L.A., et al., 2018. Carbon capture and storage (CCS): the way forward. Energy Environ. Sci. 11 (5), 1062–1176.

Carbfix, 2023. Coda terminal. https://www.carbfix.com/codaterminal. Accessed 16 October 2023.

d'Amore, F., Romano, M.C., Bezzo, F., 2021. Optimal design of European supply chains for carbon capture and storage from industrial emission sources including pipe and ship transport. Int. J. Greenh. Gas Control 109, 103372.

Element Energy, 2018. Shipping CO_2 - UK cost estimation study. www.gov.uk/government/publications/shipping-carbon-dioxide-co2-uk-cost-estimation-study. Accessed 20 July 2023.

Ember Climate, 2023. Daily carbon prices. https://ember-climate.org/data/carbon-price-viewer/. Accessed 20 July 2023.

European Commission, 2021. Candidate PCI projects in cross-border carbon dioxide (CO_2) transport networks. https://energy.ec.europa.eu/system/files/2021-04/detailed_information_regarding_the_candidate_projects_in_co2_network_0.pdf. Accessed 20 July 2023.

German Environment Agency, 2018. German pollutant release and transfer register. https://www.thru.de/thrude/downloads/?L=3#c1318. Accessed 20 July 2023.

Global CCS Institute, 2023. Global status of CCS 2022. https://status22.globalccsinstitute.com/wp-content/uploads/2022/11/Global-Status-of-CCS-2022_Download.pdf. Accessed 22 October 2023.

Global Maritime Energy Efficiency Partnerships, 2022. Improved auxiliary engine load. https://glomeep.imo.org/technology/improved-auxiliary-engine-load/. Accessed 20 July 2023.

Holz, F., Scherwath, T., Crespo del Granado, P., Skar, C., Olmos, L., Ploussard, Q., Ramos, A., Herbst, A., 2021. A 2050 perspective on the role for carbon capture and storage in the European power system and industry sector. Energy Econ. 104, 105631.

Intergovernmental Panel on Climate Change, 2005. IPCC Special Report on Carbon Dioxide Capture and Storage. https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf. Accessed 20 July 2023.

Intergovernmental Panel on Climate Change, 2022. Climate Change 2022, Mitigation of Climate Change: Summary for Policy Makers. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SummaryForPolicymakers.pdf. Accessed 20 December 2023.

Intergovernmental Panel on Climate Change, 2023. Climate Change 2023: Synthesis Report. IPPC, Geneva, Switzerland, https://www.ipcc.ch/report/ar6/syr/. Accessed 20 December 2023.

International Energy Agency, 2004. Ship transport of CO_2. https://ieaghg.org/docs/General_Docs/Reports/PH4-30%20Ship%20Transport.pdf. Accessed 20 July 2023.

International Energy Agency, 2021a. Is carbon capture too expensive? https://www.iea.org/commentaries/is-carbon-capture-too-expensive. Accessed 20 July 2023.

International Energy Agency, 2021b. Net zero by 2050. https://www.iea.org/reports/net-zero-by-2050. Accessed 20 July 2023.

International Energy Agency, 2023. CO2 emissions in 2022. https://www.iea.org/reports/co2-emissions-in-2022. Accessed 14 October 2023.

International Maritime Organization, 2020. Fourth IMO greenhouse gas study 2020. https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx. Accessed 20 July 2023.

Kjärstad, J., Skagestad, R., Eldrup, N.H., Johnsson, F., 2016. Ship transport—A low cost and low risk CO_2 transport option in the Nordic countries. Int. J. Greenh. Gas Control 54, 168–184.

Knoope, M., Guijt, W., Ramírez, A., Faaij, A., 2014. Improved cost models for optimizing CO_2 pipeline configuration for point-to-point pipelines and simple networks. Int. J. Greenh. Gas Control 22, 25–46.

Knoope, M., Ramírez, A., Faaij, A., 2013. A state-of-the-art review of techno-economic models predicting the costs of CO_2 pipeline transport. Int. J. Greenh. Gas Control 16, 241–270.

Leeson, D., Mac Dowell, N., Shah, N., Petit, C., Fennell, P., 2017. A techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources. Int. J. Greenh. Gas Control 61, 71–84.

Li, J., Jia, Y., 2020. Calculation method of marine ship fuel consumption. IOP Conf. Ser.: Earth Environ. Sci. 571, 012078.

McCollum, D., Ogden, J., 2006. Techno-Economic Models for Carbon Dioxide Compression, Transport, and Storage & Correlations for Estimating Carbon Dioxide Density and Viscosity. University of California.

Merk, C., Nordø, Å.D., Andersen, G., Lægreid, O.M., Tvinnereim, E., 2022. Don't send us your waste gases: Public attitudes toward international carbon dioxide transportation and storage in Europe. Energy Res. Soc. Sci. 87, 102450.

Middleton, R.S., Bielicki, J.M., 2009. A scalable infrastructure model for carbon capture and storage: SimCCS. Energy Policy 37 (3), 1052–1060.

Middleton, R.S., Kuby, M.J., Bielicki, J.M., 2012. Generating candidate networks for optimization: The CO_2capture and storage optimization problem. Comput. Environ. Urban Syst. 36 (1), 18–29.

Nam, H., Lee, T., Lee, J., Lee, J., Chung, H., 2013. Design of carrier-based offshore CCS system: Plant location and fleet assignment. Int. J. Greenh. Gas Control 12, 220–230.

National Petroleum Concil, 2019. Meeting the dual challenge - Chapter five - CO_2 capture. https://dualchallenge.npc.org/files/CCUS-Chap_5-030521.pdf. Accessed 22 October 2023.

Nie, Z., Korre, A., Durucan, S., Fraga, D., Neele, F., Mikunda, T., 2021. CO_2 pipeline transport and storage network cost modelling and multi-period multi-scenario stochastic optimisation. In: Proceedings of the 15th Greenhouse Gas Control Technologies Conference 15-18 March 2020. pp. 15–18.

Northern Lights, 2022. Major milestone for decarbonising Europe. https://norlights.com/news/major-milestone-for-decarbonising-europe%ef%bf%bc/. Accessed 20 July 2023.

Quemin, S., Trotignon, R., 2021. Emissions trading with rolling horizons. J. Econom. Dynam. Control 125, 104099.

Roussanaly, S., Brunsvold, A.L., Hogne, E.S., 2014. Benchmarking of CO_2 transport technologies: Part II – Offshore pipeline and shipping to an offshore site. Int. J. Greenh. Gas Control 28, 283–299.

Roussanaly, S., Deng, H., Skaugen, G., Gundersen, T., 2021. At what pressure shall CO_2 be transported by ship? An in-depth cost comparison of 7 and 15 barg shipping. Energies 14 (18), 5635.

Roussanaly, S., Jakobsen, O.J.P., Hognes, E.H., Brunsvold, A.L., 2013. Benchmarking of CO_2 transport technologies: Part I—Onshore pipeline and shipping between two onshore areas. Int. J. Greenh. Gas Control 19, 584–594.

Santibanez-Gonzalez, E.D., 2017. A modelling approach that combines pricing policies with a carbon capture and storage supply chain network. J. Clean. Prod. 167, 1354–1369.

Serpa, J., Morbee, J., Tzimas, E., 2011. Technical and Economic Characteristics of a CO_2 Transmission Pipeline Infrastructure. Publications Office of the European Union.

Ship & Bunker, 2022. Rotterdam bunker prices. https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam. Accessed 20 July 2023.

United Nations, 2015. Report of the Conference of the Parties on its Twenty-First Session, Held in Paris from 30 November to 13 December 2015. https://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf. Accessed 20 July 2023.

Wintershall Dea, 2022. Wintershall Dea and Equinor partner up for large-scale CCS value chain in the North Sea. https://wintershalldea.no/en/newsroom/wintershall-dea-and-equinor-partner-large-scale-ccs-value-chain-north-sea-0. Accessed 19 July 2023.

Zero Emissions Platform, 2011. The costs of CO_2 storage post-demonstration CCS in the EU. https://www.globalccsinstitute.com/archive/hub/publications/119816/costs-co2-storage-post-demonstration-ccs-eu.pdf. Accessed 20 July 2023.

Zero Emissions Platform, 2019. The costs of CO_2 capture, transport and storage - Post-demonstration CCS in Europe. https://zeroemissionsplatform.eu/document/the-costs-of-co2-capture-transport-and-storage/. Accessed 20 July 2023.