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# Optimal design and cost of ship-based CO<sub>2</sub> transport under uncertainties and fluctuations

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## ABSTRACT

This study investigates the impact of operational fluctuations and uncertainties on the design and expected cost of ship-based CO<sub>2</sub> transport. The model analysis is based on a two-stage stochastic investment model for a single-source single-sink CCS value chain with a ship-based transport system. The sailing time of the ship is uncertain due to changing weather conditions. The optimal investment decisions are driven by the expected cost of operating the value chain in the stochastic operational scenarios. This approach is demonstrated on a case study in which 0.4 MtCO<sub>2</sub>/y is transported over 715 km, from a cement plant located in Brevik to a harbor in Kollsnes in Norway.

The results show that a transport rate of 99 % of the available CO<sub>2</sub> leads to the lowest average cost of transport at 33.8 €/ton. Once the delays caused by the weather are considered, the buffer storage capacity that is 18 % above the ships transport capacity, seems to be the most efficient solution for recovering normal operation after weather delays. The expected transport cost increases with 1.9 €/ton (i.e. 5%) when the uncertainty in weather conditions is neglected in the value chain design decisions. Furthermore, seasonal variations in emissions lead to the need of a larger ship rather than maintaining the same ship size and increasing the power when required. The seasonal storage of CO<sub>2</sub> never appears to be a cost-efficient strategy, compared to increasing ship capacity. Finally, the risks of higher future fuel prices and ship breakdowns will cause the value of buffer storage capacity to increase, and thus resulting to select a buffer capacity up to 73 % larger than the ship size.

## 1. Introduction

Many international organizations, such as the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC), emphasize the important role of carbon capture and storage (CCS) in decarbonizing the world economy (IPCC, 2018; IEA, 2019). This is especially the case for non-power industrial emissions from steel, cement, refining, fertilizer and petrochemicals, which represent 21 % of global emissions and where CCS may be the way to ensure the deep decarbonization level required (Gardarsdottir et al., 2019; Benhelal et al., 2013; Kajaste and Hurme, 2016).

Today, 19 CCS facilities are operating, and more projects are planned to be built soon (GCCSI, 2019).

As most of the industrial CO<sub>2</sub> emitters are located away from suitable storage sites, the CO<sub>2</sub> must be transported to its permanent storage or

conversion site after being captured. This can in practice be achieved through several means: pipeline, ships, train, truck or combinations of those. While all currently operating CCS chains are based on pipeline-based transport, ship-based transport is now seen as key to enable early deployment of CCS from European industrial emissions due to the low-cost, low investment and flexibility of this option to reach offshore CO<sub>2</sub> storages (Roussanaly et al., 2014). This is, for example, the case for the Norwegian full-scale CCS project that our study focuses on. In the Norwegian full-scale project, the CO<sub>2</sub> captured from a cement plant and a waste-to-energy plant will be transported to a receiving terminal prior to subsequent transport and storage.

The main contribution of our paper is the development of a techno-economic optimization model and a capacity study in the transport section of the value chain. While the case study is based on the Norwegian full-scale value chain, the model itself is of general interest with

*Abbreviations:* CCS, carbon capture and storage; GHG, greenhouse gas; IEA, international energy agency; IPCC, intergovernmental panel on climate change; O&M, operational and maintenance; VVS, value of stochastic solution.

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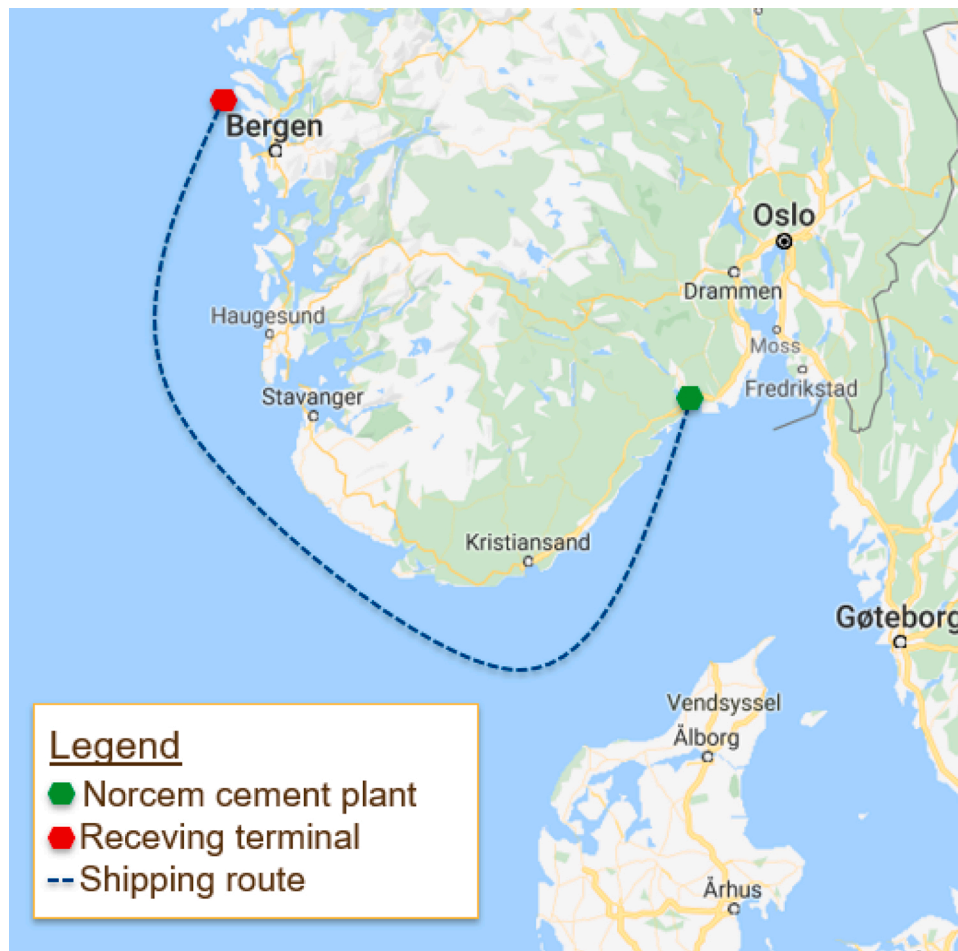


Fig. 1. Source and sink locations.

a methodological focus on incorporation of uncertain sailing times and seasonal fluctuation in captured CO<sub>2</sub> and the effects these factors have on capacities and investments in the value chain.

Although there is significant less literature available on ship-based transport of CO<sub>2</sub> compared to studies for pipelines (Knoope et al., 2013; McCoy, 2009; Skaugen et al., 2016), several studies have looked at the important aspects of CO<sub>2</sub> shipping. Roussanly et al. assessed the cost of conditioning and transport of CO<sub>2</sub> via pipeline and ship as a function of the transport distance and capacity. They examined under which conditions ship and pipelines were the most cost-efficient option and which parameters that have the strongest impact on this choice Roussanly et al. (2014). Their results were consistent with case-specific comparisons published in the literature (Roussanly et al., 2013a; Coussy et al., 2013; Metz et al., 2005; Jakobsen et al., 2017a) and were also reproduced by Geske et al. (2015).

Several studies have focused on more detailed aspects of the value chain logistics and design of ship-based CO<sub>2</sub> transport. Alabdulkarem et al., (2012) investigated different CO<sub>2</sub> liquefaction processes and concluded that CO<sub>2</sub> liquefaction based on an ammonia liquefaction cycle was the most efficient option. Similarly, Lee et al. (2017) investigate the different design alternatives and process conditions to minimize the energy requirement associated with re-liquefaction of boil-off CO<sub>2</sub> during ship transport.

Several papers consider buffer sizes in the value chain design. Aspelund, 2006 considered intermediate storage sizes 50 % larger than the considered ship size when designing a ship-based transport system with direct offshore unloading. Similar numbers were considered by Roussanly et al. (2013a). Based on experience from LNG shipping, Yoo et al. (2013) suggested a buffer capacity of 120 % ship size. Finally,

Vermeulen (2010) suggested a buffer storage capacity equal to the ship capacity at each port, also found to be cost-optimal in the case of Seo, 2017. Overall, no consensus on required or optimal buffer storage capacity has emerged. Beyond this issue, Vermeulen (2010) also investigated different options for offshore offloading.

In most of the literature, the design, assessment and optimization of the shipping supply chain is performed deterministically, using sensitivity analysis to understand the impact of changes in the parameters. This type of deterministic analysis does not capture the fact that investment decisions often are based on uncertain information where the outcomes will be available only after the decisions are made. It is our hypothesis that it is important for the design of the shipping chain to consider the associated uncertainties in operations, when investments are made. In order to analyze this, we use stochastic programming where different operational scenarios represent uncertainty that is resolved after investments are done (King and Wallace, 2012), minimizing the joint expected cost of investment and operations. Alternatively, optimizing an investment decision based on the worst-case scenario may lead to too high expected costs due to excess capacities in the transport system. On the other hand, a deterministic design will typically lead to a shortage in capacity and high costs due to the expectation on expensive operational compensation for the shortages in capacity. As a result, a contribution from our work is reduced expected cost and a more robust CCS value chain.

Building on the study from Jakobsen et al. (2017b) and the recent updates of the Norwegian full-scale CCS project, we explore the case of transporting 400 ktCO<sub>2</sub>/y from a cement plant in Brevik (Norway) to a receiving terminal located in Kollsnes (Norway). First, the impact of uncertainties associated with travel time caused by weather conditions

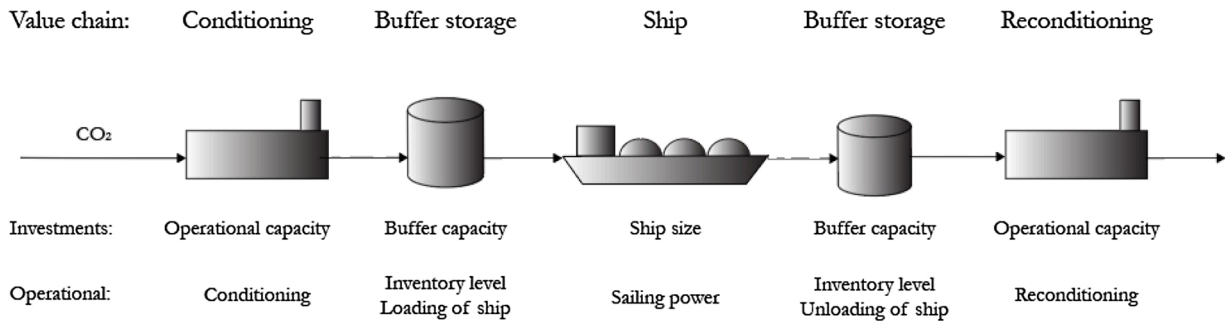


Fig. 2. Value chain description and decisions.

in the Skagerrak and the North Sea region is investigated and compared to the cost of a design based on average weather conditions. Furthermore, the effect of seasonal variations in CO<sub>2</sub> emissions on design and cost of transport is also analyzed. At last, the impact of uncertainties in the shipping fuel cost and unplanned maintenance need is presented.

The paper is structured as follows: the coming Section 2 presents a description of the case study and the CCS transport chain, followed by a Section 3 that introduces the value chain model. Section 4 continues with a presentation of the data and the analysis of the uncertainty for travelling times. Section 5 shows the results and discussion of the optimization model. The key findings of the study are summarized in Section 6. At last, in Appendix A the techno-economic modeling of the CO<sub>2</sub> conditioning and shipping supply chain is presented.

## 2. Description of the case study and the transport chain

The industries and the Norwegian state collaborate on developing the first European industrial CCS project. This project, called the Norwegian full-scale project, is centered around two industrial sites. The first is a cement plant located in Brevik (Norway) and owned by Heidelberg Cement, while the second one is a waste-to-energy plant located in Oslo owned by Fortum Varme. In the Norwegian full-scale project, the CO<sub>2</sub> capture from each industrial site is to be transported to Kollsnes (West coast of Norway) by ship and subsequently, via pipeline, to an offshore saline aquifer for permanent storage. The transport and storage section of the project is called the Northern Lights initiative with aims to demonstrate ship-based CCS. The project could be the key to safely and cost-efficiently transport and store CO<sub>2</sub> from European sources on the Norwegian Continental Shelf. Our study focuses only on a single source, the transportation of the emissions of Norcem cement from Brevik to Kollsnes.

The cement production sector is responsible for 5 % of the global anthropogenic CO<sub>2</sub> emissions (Chen et al., 2010; Feiz et al., 2015). In practice, ensuring a deep decarbonization of these emissions without

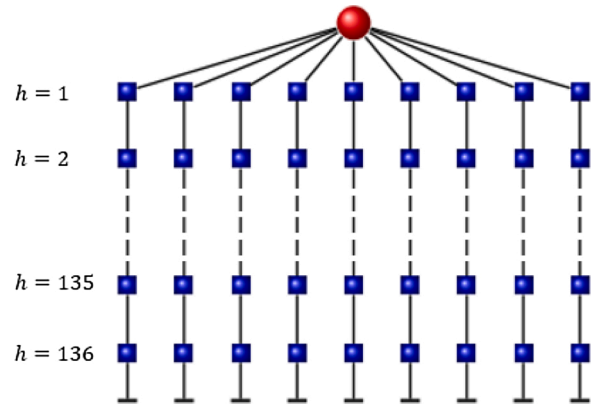


Fig. 3. Two-stage scenario tree with 136 time steps.

CCS is very challenging, as about 60 % of the plant emissions is related to the calcination of limestone during the cement production, which cannot be avoided through the typical GHG emissions means, such as fuel switching, energy efficiency, etc. (Zuberi and Patel, 2017; Sharma and Goyal, 2018; Jokar and Mokhtar, 2018). Norcem Brevik will be the world's first cement plant retrofitted with a CO<sub>2</sub> capture plant. The factory produces 1.2 million tons of cement annually. A byproduct of the cement production is heat, which can be utilized to regenerate the amine solvent used to capture of CO<sub>2</sub> from the flue gas at a low-cost. As a result of both of this aspect and the high technology maturity, an amine concept was selected for the project although other capture technologies like membrane, oxy-combustion, adsorption, low-temperature, and calcium looping could be considered (Voldsund et al., 2019) This residual heat, combined with heat integration within the capture and conditioning process, will be used to produce enough steam to capture approximately 400 000 ton of CO<sub>2</sub> yearly, which accounts for half of the

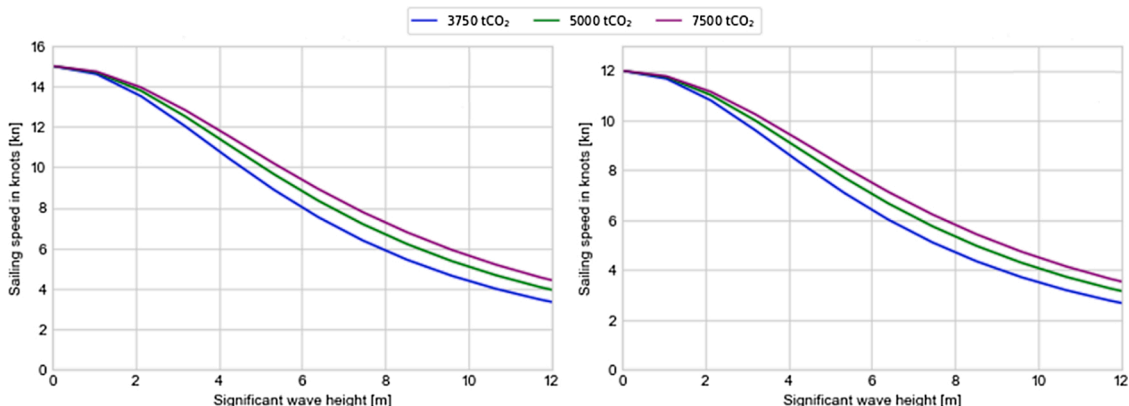


Fig. 4. Sailing speed as a function of significant wave height and transport capacity.

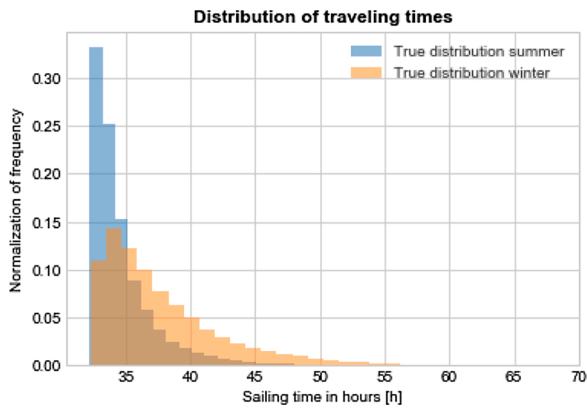


Fig. 5. Distribution of travelling times from Brevik to Kollsnes.

emissions of the cement factory.

In addition to the CO<sub>2</sub> capture plant, a conditioning facility is needed for a ship-based transport. In this step, the gaseous CO<sub>2</sub> is pressurized to around 30 bar before being cooled and expanded to obtain liquid CO<sub>2</sub> that can be stored in buffer storages and subsequently ships. More details on this process can be found in Appendix A and Deng et al. (2019). It is worth noting that conditioning prior to CO<sub>2</sub> shipping is typically more expensive than conditioning prior to pipeline transport (Jakobsen, et al., 2017a; ZEP, 2011).

The CO<sub>2</sub> transport chain includes conditioning, buffer storage prior to shipping, shipping, buffer storage after shipping and reconditioning, see Fig. 2. The CO<sub>2</sub> capture plant and its operation at the facility in Brevik is considered as fixed in our model. The conditioned CO<sub>2</sub> is transported by ship along the route, as illustrated in Fig. 1. The CO<sub>2</sub> is unloaded at the receiving terminals at Kollsnes. As an amine-based capture is considered, the CO<sub>2</sub> after capture is very pure and thus no CO<sub>2</sub> is expected to be lost during the liquefaction based on Deng et al., 2019. The only way that captured CO<sub>2</sub> can be released to the atmosphere is when the shipping logistics cannot handle the amount of CO<sub>2</sub> transported or if it is too costly to do so (marginal transport cost must remain below 100 €/t). Fig. 2 shows the investment and operational decision along the value chain. The design decisions are: Conditioning and reconditioning capacity, buffer capacities and ship size. The operational decisions are: Conditioning, inventory levels of buffer storages and ship, sailing power, and reconditioning.

Our analysis minimizes the expected cost of investments and operations in the transport chain. In our model investment and operation of the elements from conditioning to reconditioning are included, see Fig. 2. The operator of the chain minimizes the transport cost of CO<sub>2</sub>, which are taken as an input parameter for the scenarios with uncertain delays on shipping over a 25-year time-horizon.

The problem is formulated as a two-stage mixed integer stochastic

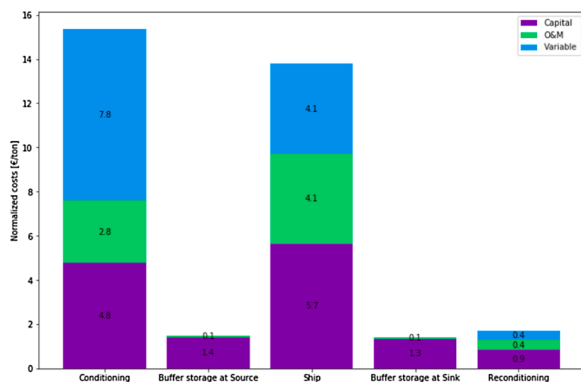


Fig. 6. Break down of cost in the transport chain.

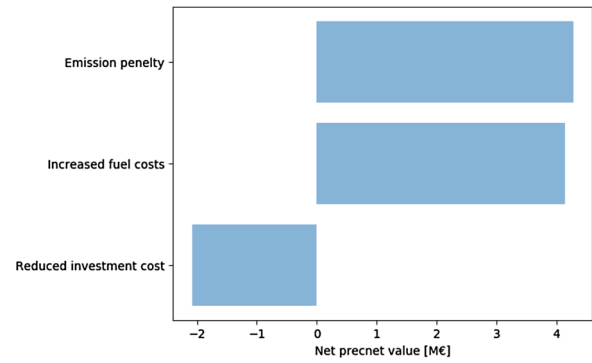


Fig. 7. Net present value of planning of delays.

program with recourse (Louveaux and Birge, 2008). The two-stage formulation is preferred since the utility of today’s decisions are determined by the realization of the future uncertainty. The design of the chain is determined prior to operation and the decision maker needs to consider the future expected operational cost based on scenario probabilities and corresponding decisions. The first-stage decisions are the investments in capacity along the transport chain, and the second stage decisions are the scenario dependent operations after uncertainty is resolved. This is illustrated in Fig. 3, with the strategic decisions in the red node and the sequences of scenario dependent operational decisions in blue. The lifetime of the project is set to 25 years, and the discount rate is 8 %.

In a scenario, an operational season is 136 operational time steps, with a duration of three hours each. Hence, each season consists of 408 h from 17 representative days. There is a trade-off between the computational burden and the precision of the approximation of our problem when determining the length of operational seasons. The expected duration of the heaviest storms each year is only a couple of days. Hence, the operator of the chain can retrieve delays over multiple transport cycles. A scenario consists of a summer season and a winter season. In the analysis, we use thirteen scenarios, which mimics the operation of the transport chain in 442 representative days.

Note that in a two-stage model, all uncertainties are resolved at the same time, which means that the operational conditions for the full 17 days are known in a scenario. The operational recourse-actions used to respond to the weather uncertainty in the scenarios, are the increase and decrease of the ship’s engines power. The important trade-off at the investment stage is the robustness that comes from investments in buffer storage capacity versus the flexibility of increasing the sailing power when weather related delays occur.

A two-stage model can be considered as an optimistic approach as in each scenario the whole 17-day periods are assumed to be forecasted perfectly. Consequently, the model slightly underestimates the need for capacity in the transport chain, and it gives a lower bound for actual operational costs.

### 3. The CCS value chain model

The following section translates the previous description of the CCS value chain into a mathematical model.

#### 3.1. Nomenclature

##### Sets

$\Omega$  : Set of stochastic scenarios

$S$  : Set of seasons

$H$  : Set of operational time steps

$V$  : Set of power strategies for the ship

##### Parameters

$\Pi_\omega$  : Probability of stochastic scenario  $\omega$

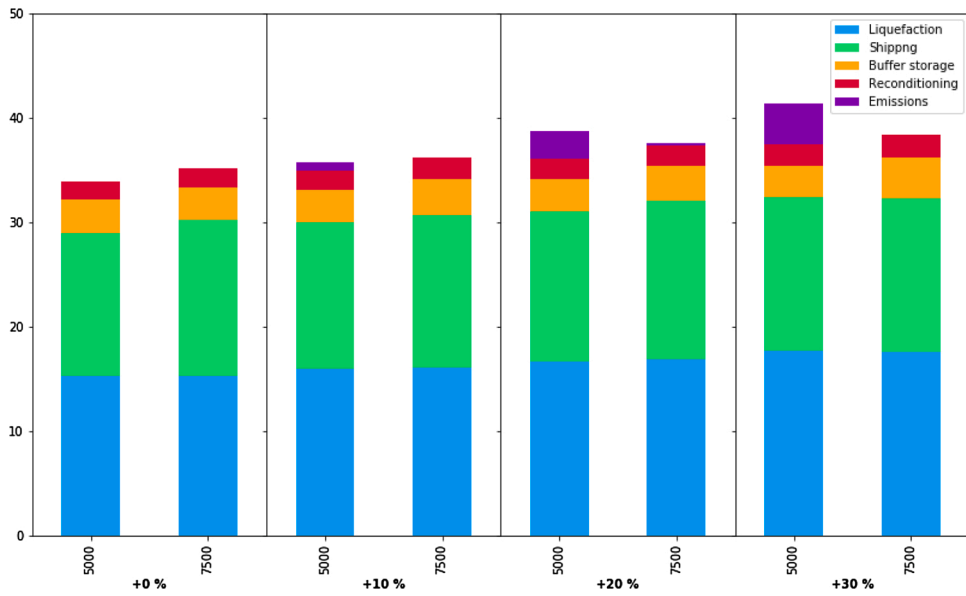


Fig. 8. Break down of cost for cases with seasonal variations in emission.

$\theta_s$  : Seasonal weight of season  $s$  Type equation here.  
 $a$  : Annuity factor  
 $\alpha$  : Minimum transport requirement  
 $IC^{Con}$  : Fixed cost of investing in one ton of conditioning capacity  
 $IC^{Re-con}$  : Fixed cost of investing in one ton of re – conditioning capacity  
 $IC^{Buffer}$  : Fixed cost of investing in one ton of buffer storage capacity  
 $p^{Carbon}$  : Penalty for one unit of CO<sub>2</sub> emission  
 $MC^{Con}$  : Marginal cost of conditioning one ton of CO<sub>2</sub>  
 $MC^{Re-con}$  : Marginal cost of re – conditioning one ton of CO<sub>2</sub>  
 $VC^{Ship}$  : Fuel cost of power strategy  $v$   
 $OM^{Con}$  : O&M cost of operating one ton of conditioning capacity  
 $OM^{Re-con}$  : O&M cost of operating one ton of re – conditioning capacity  
 $OM^{Buffer}$  : O&M cost of operating one ton of buffer storage capacity  
 $E_{osh}$  : CO<sub>2</sub> captured at source at stoc

hastic scenario  $\omega$  in season  $s$  at time step  $h$

$\beta$  : Operational flexibility at conditioning plant  
 $\gamma$  : Operational flexibility at re – conditioning plant  
 $W_{vosh}^{Loading}$  : Time slot for loading of ship at power  $s$  strategy  $v$  in stochastic scenario  $\omega$  season  $s$  in operational time step  $h$   
 $W_{vosh}^{Unloading}$  : Time slot for unloading of ship at power strategy  $v$  in stochastic scenario  $\omega$  season  $s$  in operational time step  $h$   
 $T^{Port}$  : Time used for loading or unloading at a port

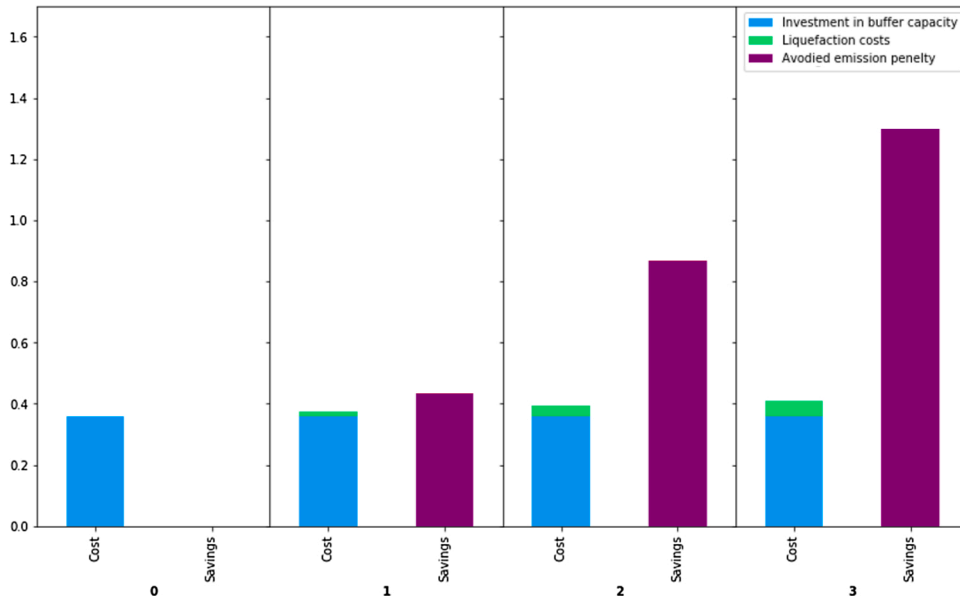


Fig. 9. Cost of extra buffer storage compared to avoided emission costs in case of zero to three ship breakdown per year.



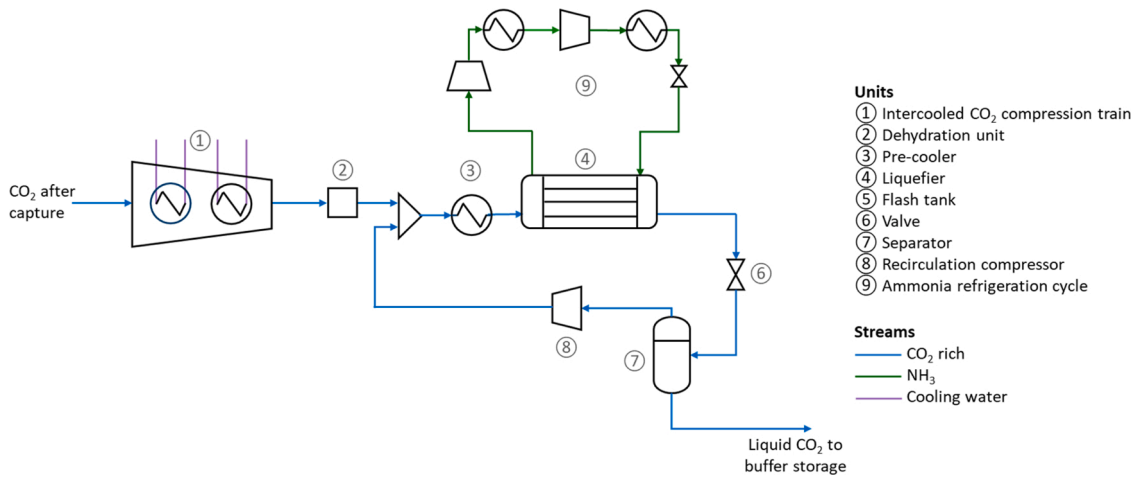


Fig. 10. Process flow diagram of the CO<sub>2</sub> conditioning process before ship transport (Deng et al., 2019).

$CAP^{Ship}$  : Transport capacity of ship

**Variables**

**Investment**

$X^{Con}$  :

Investment in units of operational capacity at the conditioning plant

$X^{BufferAtCon}$  :

Investment in units of buffer storage at conditioning plant

$X^{Re-Con}$  : Investment in units of operational capacity at the re-conditioning plant

$X^{BufferAtRe-con}$  : Investment in units of buffer storage at re-conditioning plant

**Operational**

$x_{osh}^{Con}$  :

Tons of CO<sub>2</sub> conditioned at the conditioning plant in stochastic scenario  $\omega$  in season  $s$  at operational time step  $h$

$x_{osh}^{Emission}$  : Tons of CO<sub>2</sub> emitted at the conditioning plant in stochastic scenario  $\omega$  in season  $s$  at operational time step  $h$

$y_{osh}^{Con}$  : Inventory level of the buffer storage located at the conditioning plant in stochastic scenario  $\omega$  in season  $s$  at operational time step  $h$

$y_{osh}^{Re-con}$  : Inventory level of the buffer storage located at the re-conditioning plant in stochastic scenario  $\omega$  in season  $s$  at operational time step  $h$

$x_{osh}^{Loaded}$  : Units of CO<sub>2</sub> loaded on the ship in stochastic scenario  $\omega$  in season  $s$  at operational time step  $h$

$x_{osh}^{Unloaded}$  : Units of CO<sub>2</sub> unloaded from the ship in stochastic scenario  $\omega$  in season  $s$  at operational time step  $h$

$\Delta_{vos}$  : Binary variable of power strategy  $v$  in stochastic scenario  $\omega$  in season  $s$

$y_{osh}^{Ship}$  : Inventory level of the ship in stochastic scenario  $\omega$  in season  $s$  at operational time step  $h$

$x_{osh}^{Re-con}$  : Tons of CO<sub>2</sub> reconditioned at the re-conditioning plant in stochastic scenario  $\omega$  in season  $s$  at operational time step  $h$

$x_{osh}^{Re-con}$  : Tons of CO<sub>2</sub> reconditioned at the re-conditioning plant in stochastic scenario  $\omega$  in season  $s$  at operational time step  $h$

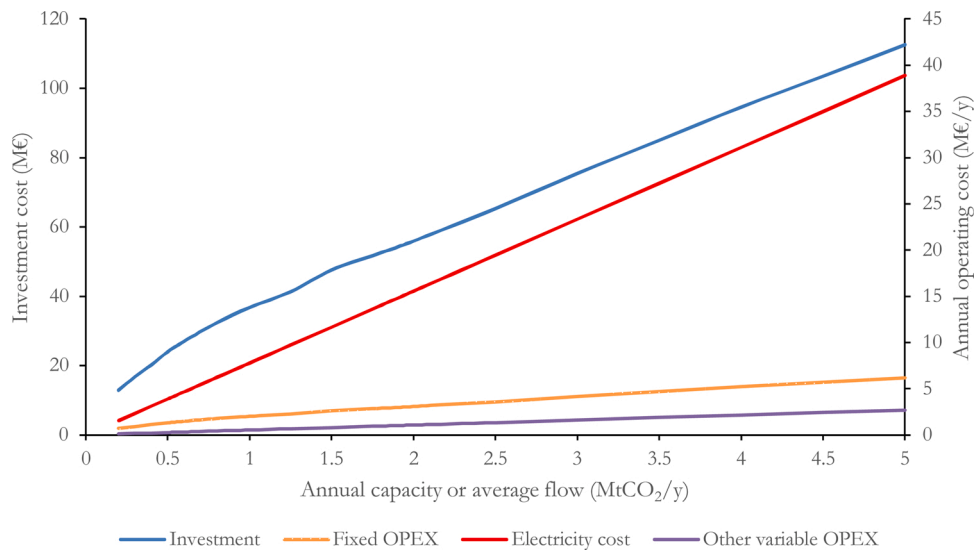


Fig. 11. Investment and operating costs of the CO<sub>2</sub> conditioning process as a function of the annual capacity or average flow<sup>a</sup>.

<sup>a</sup>Investment and fixed operating cost are a function of the annual capacity while the electricity and other operating cost are a function of the annual average flow.

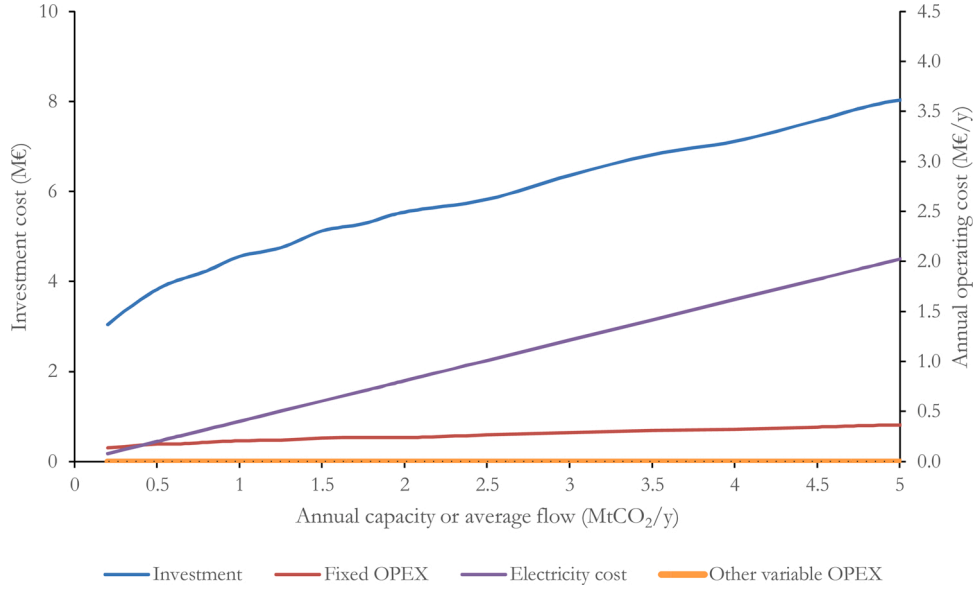


Fig. 12. Investment and operating costs of the CO<sub>2</sub> reconditioning process as a function of the annual capacity or average flow<sup>a</sup>.

<sup>a</sup>Investment and fixed operating cost are a function of the annual capacity while the electricity and other operating cost are a function of the annual average flow.

d at the reconditioning plant in stochastic scenario  $\omega$  in season  $s$  at

operational time step  $h$

### 3.2. Objective function

The objective, Eq (1), is to minimize total expected cost, consisting of the investment cost,  $IC$ , and the expected cost of the recourse decisions in the second stage,  $OC$ , where  $a$  is the annuity factor.

$$\min z = IC + a \cdot OC \quad (1)$$

The investment costs are the sum of investment costs in conditioning  $IC^{Con}X^{Con}$ , re-conditioning  $IC^{Re-con}X^{Re-con}$ , buffer storages  $IC^{Buffer}(X^{BufferAtCon} + X^{BufferAtRe-con})$  and the predefined ship cost,  $IC^{Ship}$ :

$$IC = IC^{Con}X^{Con} + IC^{Re-con}X^{Re-con} + IC^{Buffer}(X^{BufferAtCon} + X^{BufferAtRe-con}) + IC^{Ship} \quad (2)$$

The expected operational cost is the probability weighted sum of all the scenarios costs, with probabilities represented by  $\Pi_{\omega}$ . Each operational scenario is divided into two operational seasons indexed by  $s$ . The winter season is December to March, and the summer season is March to December. The parameter  $\theta_s$  is used as a seasonal weight factor. The expected operational costs are given by Eq. (3):

$$OC = OM + \sum_{\omega \in \Omega} \sum_{s \in S} \Pi_{\omega} \theta_s \cdot (Var_{\omega s} + P^{Carbon} \sum_{h \in H} x_{\omega sh}^{Emission}) \quad (3)$$

The operational costs include scenario with independent operational and maintenance cost  $OM$ , as well as scenario with dependent variable costs  $Var_{\omega s}$  and the penalty of CO<sub>2</sub> emissions. The emissions are summed over all time-steps  $h$  in the operational scenario  $\omega$ .

$$OM = OM^{Con}X^{Con} + OM^{Re-con}X^{Re-con} + OM^{Buffer}(X^{BufferAtCon} + X^{BufferAtRe-con}) + OM^{Ship}, \quad (4)$$

where  $OM^{Con}X^{Con}$  is the operational and maintenance cost of the conditioning plant,  $OM^{Re-con}X^{Re-con}$  is the cost of the re-conditioning plant,

$OM^{Buffer}(X^{BufferAtCon} + X^{BufferAtRe-con})$  is the cost of buffer storages and  $OM^{Ship}$  the cost of the ship.

The variable cost is the unit cost of energy for conditioning and reconditioning of the CO<sub>2</sub> and the fuel cost of the transport ships power strategy, eq (5):

$$Var_{\omega s} = \sum_{h \in H} MC^{Con}x_{\omega sh}^{Con} + MC^{Re-con}x_{\omega sh}^{Re-con} + \sum_{v \in V} VC_v^{Ship} \Delta_{vos} \quad (5)$$

The cost parameters and cost modelling of each section of the transport chain are summarized in Appendix A.

### 3.3. Constraints

Norcem Cement plant has  $E_{\omega sh}$  tons of pure CO<sub>2</sub> captured in stochastic scenario  $\omega$  in season  $s$  at operational time step  $h$ . The CO<sub>2</sub> can either be conditioned for transport,  $x_{\omega sh}^{Con}$ , or emitted,  $x_{\omega sh}^{Emission}$ . Eq. (6), ensures the mass balance at the source in all scenarios, seasons and operational time steps:

$$E_{\omega sh} - x_{\omega sh}^{Con} - x_{\omega sh}^{Emission} = 0, \quad \omega \in \Omega, s \in S, h \in H \quad (6)$$

The conditioning plant's operational upper bound is determined by the investment decision,  $X^{Con}$ . The conditioning process cannot be stopped; hence the process has an operational lower bound:

$$(1 - \beta) X^{Con} \leq x_{\omega sh}^{Con} \leq X^{Con}, \quad \omega \in \Omega, s \in S, h \in H \quad (7)$$

The flexibility parameter,  $\beta$ , represents the maximal downward adjustment of the process from the plant's operational capacity. Constraint (7) ensures that the amount of CO<sub>2</sub> is within the operational bounds of the conditioning plant for all scenarios, seasons and time-steps.

The CO<sub>2</sub> is temporarily stored after the conditioning, then shipped to the onshore facility at Kollsnes. The inventory level of the buffer storage is represented by the variable,  $y_{\omega sh}^{Con}$ . The CO<sub>2</sub> levels need to be non-negative and not exceed the investment in buffer storage capacity,  $X^{BufferAtCon}$ :

$$0 \leq y_{\omega sh}^{Con} \leq X^{BufferAtCon}, \quad \omega \in \Omega, s \in S, h \in H \quad (8)$$

The inventory level at the end of time-step  $h$ ,  $y_{\omega sh}^{Con}$ , are the inventory level at previous time step,  $y_{\omega s(h-1)}^{Con}$ , where the CO<sub>2</sub> loaded onto the ship,

**Table 1**  
Input parameters base case.

Parameter	Value
$\alpha$ [-]	10.56
$\gamma$ [-]	0.5
$\beta$ [-]	0.5
$IC^{Con}[\text{€}/\text{ton}]$	50.5
$IC^{Re-con}[\text{€}/\text{ton}]$	9.00
$IC^{Buffer}[\text{€}/\text{ton}]$	982
$IC^{Ship}[\text{M€}/\text{ship}]$	22.31
$MC^{Con}[\text{€}/\text{ton}]$	7.78
$MC^{Re-con}[\text{€}/\text{ton}]$	0.41
$OM^{Con}[\text{€}/(\text{ton}\cdot\text{y})]$	2.78
$OM^{Re-con}[\text{€}/(\text{ton}\cdot\text{y})]$	0.41
$OM^{Buffer}[\text{€}/(\text{ton}\cdot\text{y})]$	54.0
$OM^{Ship}[\text{M€}/\text{y}]$	1.49
$T^{Port}[\text{h}]$	12
$Fuel\ cost[\text{€}/\text{ton}]$	325
$CAP^{Ship}[\text{ton}]$	5 000

$x_{osh}^{Loaded}$ , is subtracted and the CO<sub>2</sub> conditioned,  $x_{osh}^{Con}$ , is added:

$$y_{os(h-1)}^{Con} + x_{osh}^{Con} - x_{osh}^{Loaded} - y_{osh}^{Con} = 0, \omega \in \Omega, s \in S, h \in H \quad (9)$$

$$y_{os|H}^{Con} + x_{osh}^{Con} - x_{osh}^{Loaded} - y_{osh}^{Con} = 0, \omega \in \Omega, s \in S, h = 1 \quad (10)$$

The buffer storage flexibility can only be utilized within one operational season, from  $h = 1$  to  $h = |H|$ . Therefore, the inventory level of the last operational time step,  $y_{os|H}^{Con}$ , and the inventory level of the first operational time step,  $y_{os1}^{Con}$ , are connected in one season as presented in Eq. (10).

The available loading and unloading slots for the ship are dependent on the chosen power strategy, where  $\Delta_{vos}$  expresses the binary choice of sailing power strategy  $v$  in scenario  $\omega$  in season  $s$ . For power strategy  $v$ , there are time slots for loading and unloading the ship. These slots are represented by parameters  $W_{vos}^{Loading}$  and  $W_{vos}^{Unloading}$  taking values zero when not available, and the value one if the operations is available in period  $h$  in scenario  $\omega$  in season  $s$ . The ship can load up to the total capacity of the ship divided by the time in the port,  $\frac{CAP^{Ship}}{T^{Port}}$ . For loading, this is derived by:

$$x_{osh}^{Loaded} \leq \sum_{v \in V} \frac{CAP^{Ship}}{T^{Port}} W_{vos}^{Loading} \Delta_{vos}, \omega \in \Omega, s \in S, h \in H, \quad (11)$$

and for unloading:

$$x_{osh}^{Unloaded} \leq \sum_{v \in V} \frac{CAP^{Ship}}{T^{Port}} W_{vos}^{Unloading} \Delta_{vos}, \omega \in \Omega, s \in S, h \in H \quad (12)$$

In each scenario  $\omega$  and season  $s$ , at most one power strategy can be chosen:

$$\sum_{v \in V} \Delta_{vos} \leq 1, \omega \in \Omega, s \in S \quad (13)$$

The inventory level of the ship  $y_{osh}^{Ship}$  is bounded by the capacity,  $CAP^{Ship}$ :

$$0 \leq y_{osh}^{Ship} \leq CAP^{Ship}, \omega \in \Omega, s \in S, h \in H \quad (14)$$

The mass balance of the CO<sub>2</sub> transported by the ship is described by the mass balance equations:

$$y_{os(h-1)}^{Ship} + x_{osh}^{Loaded} - x_{osh}^{Unloaded} - y_{osh}^{Ship} = 0, \omega \in \Omega, s \in S, h \in H \quad (15)$$

$$y_{os|H}^{Ship} + x_{osh}^{Loaded} - x_{osh}^{Unloaded} - y_{osh}^{Ship} = 0, \omega \in \Omega, s \in S, h = 1 \quad (16)$$

**Table 2**  
Ship parameter.

Design parameter	Cargo Capacity		
	3 750 tons	5 000 tons	7 500 tons
Design power, $P$ [W]	1 500	2 000	2 500
Ship width, $B$ [m]	15	16	17
Ship length, $L_{BWL}$ [m]	90	95	100
Fuel constant power [ton/h]	0.5	0.6	0.7
Fuel at full speed [ton/h]	0.8	0.9	1.1
Investment costs [M€]	23.0	23.9	25.7

The unloaded CO<sub>2</sub> at the receiving terminal for temporary storage will be reconditioned before being sent to the permanent storage. This process is the reverse process of the conditioning. The mass balance at the ports buffer storage is given as:

$$y_{os(h-1)}^{Re-con} + x_{osh}^{Re-con} - x_{osh}^{Unloaded} - y_{osh}^{Re-con} = 0, \omega \in \Omega, s \in S, h \in H \quad (17)$$

$$y_{os|H}^{Re-con} + x_{osh}^{Re-con} - x_{osh}^{Unloaded} - y_{osh}^{Re-con} = 0, \omega \in \Omega, s \in S, h = 1 \quad (18)$$

The capacity of the buffer storage is determined by the investment decision,  $x_{BufferAtRe-con}$ . The inventory level of the buffer storage is restricted by the investments in buffer storage capacity:

$$0 \leq y_{osh}^{Re-con} \leq x_{BufferAtRe-con}, \omega \in \Omega, s \in S, h \in H \quad (19)$$

When the conditioned CO<sub>2</sub> is stored at the buffer storage, it could be reconditioned and transported by the pipeline to the permanent storage at the Norwegian Continental Shelf. The recondition process needs to be operated within the plant operational limits:

$$(1 - \gamma)x_{osh}^{Re-con} \leq x_{osh}^{Re-con} \leq x_{osh}^{Re-con}, \omega \in \Omega, s \in S, h \in H, \quad (20)$$

where  $\gamma$  is the flexibility parameter for the re-conditioning process and  $x_{osh}^{Re-con}$  is the investments in the operational capacity at the conditioning plant. Similarly, the reconditioning plants operation needs to be within bounds in order to avoid high start-up cost of the plant and secure a steady stream of CO<sub>2</sub> through offshore pipelines to the permanent storage.

The minimum required transport rate  $\alpha$  ensures that a given percentage of the total emission is reconditioned at the sink node:

$$\sum_{\omega \in \Omega} \sum_{s \in S} \sum_{h \in H} x_{osh}^{Re-con} \leq \alpha \sum_{\omega \in \Omega} \sum_{s \in S} \sum_{h \in H} E_{osh} \quad (21)$$

## 4. Data and analysis

The purpose of the analysis is to study the combinations of value chain design and operation under different assumptions on the input data. In subsection 4.1, we present the data and the problem instances. Then the assumptions and input data for ships and travelling times are presented. Finally, the results of the optimization will be presented and carefully discussed.

### 4.1. Data and problem instances

In the base case scenario, the emissions from the cement plant are constant, capturing a yearly total of 400 000-ton CO<sub>2</sub>. Three additional problem instances are added where we investigate the effect of seasonal fluctuations in CO<sub>2</sub> emissions. The emissions are moved from the summer season to the winter season, keeping the total yearly emissions unchanged from the base case. Three additional instances are added, based on the base case with fuel prices increased. Finally, an ex-post analysis of the cost of unplanned maintenance are performed.

Table 1 gives a brief summary of the input parameters in the base case.

Before we go into the results, we will next discuss in detail our



**Table 3**  
Statistical properties of sailing times by season.

Statistical properties	Summer	Winter
Mean	34.68	37.69
Std	2.61	4.63
75 % >	35.38	39.71

estimation of the stochastic travelling times and fuel consumption related to power strategies for the ships. For detailed information about the cost estimation for other input data see Appendix A.

#### 4.2. Stochastic travelling times and CO<sub>2</sub> shipping

The transport network in the first stage of the Norwegian full-scale project is planned to have one ship per capture plant. In this section we present characteristics of potential ships. Furthermore, the method for estimating the sailing times are briefly explained. Finally, the historical weather conditions and the impact on the sailing speed simulations are presented.

##### 4.2.1. Ship design parameters and fuel consumption

Table 2 shows the candidate ships design parameters and ship fuel consumptions. The statistics on propulsion power and ship geometry in LNG ship design are provided by Turbo (2013). Kristensen (2013) and Levander (2006) are other sources used for ship statistics, design geometry and estimates on transport capacity. Wigforss (2012) is used to obtain bunker consumption rates.

##### 4.2.2. STAwave-1

Complex hydrodynamic calculations are required for accurate estimates of sailing speed. The calculations are based on the ship design parameters and weather conditions. Despite the complexity, the relationship between the weather and the ship sailing speed can be simplified as a function of significant wave height. For further reading in hydrodynamics basics, the recommended texts are Volker (2011) and Kristensen and Lützen (2012).

Van den Boom et al. (2008) compare several existing methods for estimating the additional resistance generated from waves during speed trails on ships. Their research concludes with the same recommendation as ITTC (2005) with using the methods STAwave-1 and STAwave-2. The other existing wave correction methods seem to have major weaknesses. STAwave-1 is the simplest of the two recommended methods. The most important simplification lies in the assumption that all waves are head waves.

The total resistance of the ship is the sum of ship resistance at clear water,  $R_{cw}$ , and the increased resistance due to waves,  $R_{aw}$ . The clear water resistance is given by:  $R_{cw} = P/V^3$ , where  $P$  is the ships motor power and  $V$  is the ships design speed. The increased resistance due to the significant wave height is given by,  $R_{aw} = \frac{1}{16} \rho g H_s B \sqrt{\frac{B}{L_{BWL}}}$ , where  $\rho$  is the relative density of saltwater,  $g$  is the gravitation constant,  $B$  is the ships width,  $L_{BWL}$  is the ships length and  $H_s$  is the significant wave height.

The sailings speed, as a function of significant wave height, is given by:

$$V(H_s) = P \cdot \left( R_f + \frac{1}{16} \rho \cdot g \cdot H_s^2 \cdot B \cdot \sqrt{\frac{B}{L_{BWL}}} \right)^{-1} \quad (22)$$

The soundness of using such a method for this application has been checked with a ship operator and compared with real operational data.

##### 4.2.3. Power strategies

The speed of the ships decreases with increasing wave height. The selected design speed for all ships is 12 knots. The ship with a transport capacity of 3750 tons is more sensitive to increased wave height compared to the larger ships with capacities of 5000 and 7500 tons.

**Table 4**  
Investment in buffer capacity in different fuel price scenarios.

Fuel price scenario	Base case	+50 %	+100 %	+150 %
Buffer capacity	5120	5235	5235	5480
% of ship size	102.4	104.7	104.7	110.0
% of average cycle	118.3	121.0	121.0	126.5

Fig. 4, shows the sailing speeds for the three different ship cargo as a function of significant wave height.

The left illustration in Fig. 4 shows the sailing speeds with constant power strategy, ensuring that the highest efficiency of the motor is utilized. The ship can increase the sailing speed by 25 % with an increase in fuel-cost of approximately 40 %. The right Fig. 4 illustrates the sailing speed during power-up as a function of significant wave height. The ships can also reduce the sailing speed by 12.5 %, 25 %, 37.5 % and 50 % with corresponding savings in fuel consumption.

##### 4.2.4. Data and simulation of sailing times and costs

The data is downloaded from Meteorologisk Institutt (2020). The measurements of significant wave height are sampled every three hours from January 1st 1987 until December 31st 2016. The data set has measurements of 1106 different geographical points in the North Sea and Skagerrak. From the data set, the model has simulated more than 87, 000 sailing times.

During a simulation of a transport leg the ship operates at constant power, which implies a constant fuel consumption per hour. The ships sailing speed is affected by the significant wave height at the geographical location along the route at a given time. From the simulation of a route we get an estimate of the sailing time and the corresponding fuel costs of the given ship sailing at a fixed power setting.

There is great variation among the 87, 000 simulated travelling times. For the 715 km long route, calm water will give a travelling time of 32.5 h at sailing speed 12 knots, while the travelling times can in worst case be doubled at stormy weather conditions. Accounting for the increased resistance from waves, the fuel consumption increases with 9.9 % compared to a case where the ship sails in clear water.

The statistical properties of the travelling times are presented in Table 3, and the distributions are plotted in Fig. 5. The average sailing time in the winter season is 37.69 h, this is slightly higher than the average sailing time during summer with 34.68 h. The expected deviation is 4.63 h in the winter season and 2.61 h in the summer season. The expected sailing time between summer and winter season is relatively similar, however, there are greater differences between the seasons in terms of expected delays.

The longest delays occur during the winter months from January to February. Along the route, significant wave heights above 8 m is expected to occur on average 2.3 times per year. The average duration of the storms, where the significant wave height is above 8 ms, is 11 h. The storms rarely calm down to quiet water, and the wave heights can be expected to exceed 4 m in exposed water for a longer period of time.

The scenario tree is populated with scenarios from the set of sailing time simulations that maintain the statistical properties of the simulations. The solved instance is reduced from a problem with a potential of 87 000 operational seasons to only 26 operational seasons. Despite the large reduction in computational burden, the problem maintains its key properties.

## 5. Results and discussion

The model was implemented with Python/Pyomo and solved with GUROBI 8.1.0. The solution time of the base case was 435 s on a Lenovo NextScale nx360 M5, CPU: 2 × 2,3 GHz Intel E5–2670v3 – 12 core, RAM 64 GB.

**Table 5**  
Utility costs.

Utilities	Reference costs	Cost Units
Electricity (Eurostat, 2017)	65.2	€/MWh
Cooling water (Gardarsdottir et al., 2019)	0.04	€/m <sup>3</sup>
Shipping fuel cost (Worldwide, 2017)	325	€/t <sub>fuel</sub>
Harbor fees (Roussanaly et al., 2013a)	1.1	€/t <sub>CO<sub>2</sub>, transported</sub>

### 5.1. Base case

In the base case study, we have investigated both a situation where we capture and transport 100 % of the available CO<sub>2</sub> and a situation where we relax this requirement and find the lowest unit cost of the transport value chain.

#### 5.1.1. Capture and transport rate 99 %

The lowest unit cost of transportation is achieved when the rate of capturing and transport is 99 % of the available CO<sub>2</sub> emissions. We give the details for this capture rate first. The projects life cycle cost is 143 M€ and the unit cost of transport is 33.8 €/ton. Fig. 6 shows the breakdown of the cost in the transport chain.

The conditioning and shipping are the major parts of the total transportation cost. The conditioning has a cost of 15.4 €/ton, where 7.8 €/ton covers the cost of electricity. The cost of shipping per ton of CO<sub>2</sub> is 13.8 €/ton, where 4.1 €/ton are the fuel costs. The total energy cost of conditioning and shipping is 11.8 €/ton. The remaining cost in the transport chain is the buffer storages at 2.9 €/ton and reconditioning at 1.7 €/ton.

In both cases, the transportation ship with 5000 tons capacity is the preferred solution. The buffer capacity located at the cement plant is 5120 tons, which is equivalent to storing CO<sub>2</sub> emissions of four days and 16 h. The average transport cycle is three days and twenty-three hours. The buffer capacity is 102 % of the transportation ship's volume and 118 % of the emissions captured over the time of an average transport cycle.

Notably, the buffer capacity is 18 % higher than required if there were no delay due to the weather conditions. When delays occur, it is cheaper to sail at constant power and invest a-priori in buffer capacity.

The ship operates at constant power in most of the winter season scenarios. The only scenario where the ship chooses the power-up strategy is under the 25-year storm. The increased fuel prices and emissions are preferred instead of the upfront investment cost in excess buffer capacity for the 25-year storm. In 62 % of the summer scenarios, the ship reduces the sailing power to save fuel. The net present value of reducing the power is 1.0 M€ and the reduced fuel cost is equivalent to a reduction of 0.24 €/ton of transported CO<sub>2</sub>.

#### 5.1.2. Capture and transport rate of 100 %

With the requirement of transporting 100 % of the available CO<sub>2</sub>, the life cycle cost increases by 1.8 M€. The average cost of transporting the last 1 % is 41.9 €/ton, that is 24 % more expensive than the average price of transporting the first 99 %. The optimal size of the buffer storage is in this case is 5890 tons. The new size of the storage is 118 % of the transport ships capacity and 136 % of the average cycle capacity.

In both cases, the model invests in buffer capacity above the ship size. If there is a delay of 12 h the 5000-ton ship can retrieve the delay in the next transport cycle. In case of longer delays, the ship can speed up, or alternatively invest in buffer capacity above the ship capacity and retrieve delays over multiple transport cycles.

The buffer storages above the ship capacity may have value if there is slack in the normal transport schedule (without delays), meaning that the inventory of the buffer storage can be gradually reduced over several cycles. From our analysis we see a small increase in the total cost when 100 % of the CO<sub>2</sub> is transported. It is fair to believe that there will be larger challenges and at higher cost on capturing the last percent of CO<sub>2</sub> rather than transporting the CO<sub>2</sub>.

**Table 6**  
Ship investment and fixed operating cost (Jakobsen et al., 2017a).

Ship size [t <sub>CO<sub>2</sub></sub> ]	Total investment cost [M€/ship]	Annual ship fixed operating cost [M€/y/ship]
3 750	23.0	1.58
5 000	23.7	1.61
7 500	25.7	1.66

Several Norwegian shipping companies state that they experience longer delays, like the extreme weather scenario, for short periods of time during a normal winter season. The STAwave-method of estimating travelling times may be a source of error in extremely heavy weather. This, in combination with planned and unplanned maintenance, can drive the value of excess buffer capacity up.

### 5.2. The value of using a stochastic model

If the investment in transport capacity is made under the assumption that there will be no delays, disturbances can increase the actual transport cost and reduce the transport rate when delays occur due to rough weather conditions. This is because the deterministic solution has a minimum of flexibility since we do not consider weather uncertainty, and the optimal size of the buffer storage is 4 330 tons.

This is the same buffer capacity as the stochastic model with a required transport rate of only 83 %. Hence, using a deterministic approach will underestimate the buffer need for any transport requirement higher than that. As the world is stochastic, this comes at a cost when facing the operational situations. As an example, we study a case where the transport requirement is 100 % and the emission penalty of CO<sub>2</sub>,  $P^{Carbon} = 100$  €/ton. The value of the stochastic solution (VSS) is the expected cost of not planning for delays when making the capacity decision, but having to deal with the operational consequences. In our case the expected increased cost is 6.4 M€, which is 4.5 % of the transport cost.

The reduced buffer capacity leads to an increase in 25 % of fuel consumption. In the optimal stochastic solution, the ship sails at constant power most of the winter and reduces the sailing speed when possible during calm weather. With the underinvestment in buffer capacity the ship is forced to increase the sailing speed. In 53 % of the scenarios, the power-up strategy must be chosen and in the remaining 47 % scenarios the constant power strategy is chosen, resulting in an increased fuel cost with an expected net present value of 4.1 M€. In addition, the transport rate decreases with 1% leading to emissions of 4 000 CO<sub>2</sub> per year. By planning for constant traveling times and no safety margin, the transport price would increase in total by 1.9 € per ton, 5.6 %.

When uncertainty is neglected the optimal capacity covers only the average sailing time. Hence, there is zero excess capacity in case of disturbances. There are large seasonal variations in the North Sea weather conditions, which affect the sailing times in Fig. 5 *Distribution of travelling times from Brevik to Kollsnes*. During the winter season, on expectation, the sailing times are three hours longer and the standard deviation of the distribution is close to 80 % higher, Table 3. With no spare capacity and the seasonal variations in sailing times, the operator of the transport chain faces high fuel-cost as the ship speeds up, in addition to penalties or lost revenue when the transport chain face bottlenecks (100 €/ton).

To summarize, the deterministic model does not value any flexibility. Hence, it underestimates the buffer need and pays the penalty of higher fuel costs and emission costs when exposed to the stochastic scenarios.

### 5.3. Seasonal variations in emission and ship preferences

The seasonal variations in emissions from source can affect the optimal design of the transport chain. The increased emissions during

the winter season will increase the need for transport capacity or buffer capacity. For the three instances with seasonal variations, the CO<sub>2</sub> emissions are shifted from the summer season to the winter season. The percentage change is the increase in hourly emissions for winter seasons compared to summer seasons. In all instances, the total yearly emissions are 0.4 Mton and the emission penalty is 100 €/ton.

At 10 % seasonal variations, the 5000-ton ship is still preferred over the 7500-ton ship, with a margin of 1.3 € per ton of transported CO<sub>2</sub>. During the winter season, the expected emissions from the transport chain is 3 250 tons, which has a yearly expected cost of 0.33 M€. The emission penalty is equivalent to the cost of additional 2 500 ton of buffer capacity. During the winter season, it is possible to recover the delays with the additional buffer capacity.

The operational seasons in the model are only four transport cycles long and intermediate storage between several months is therefore not an option. Nevertheless, we could see the value of increasing the buffer capacity from 115 % to 165 % of the ships transport capacity when the price on CO<sub>2</sub> is 100 €/ton.

With a 10 % increase in the winter emissions, the capacity required for an average winter transport cycle is 4 990 tons. This is close to the transport capacity of the 5000-ton ship. The delays will therefore cause emissions if the buffer capacity is not larger than the size of the ship. With an average emission of 4 990 ton per transport cycle there are few opportunities to recover the delays (Fig. 7).

For seasonal variations of 20 % and larger the 7500-ton ship is preferred. In Fig. 8, the breakdown of the transport chains cost is presented.

When the emissions per transport cycle exceeds the ships capacity, it is inevitable with large emissions unless seasonal storage is accepted. In the case of 20 % increased emissions, there is a lack of 445 tons transport capacity in an average winter transport cycle. Keeping the small ship and increasing the size of the buffer capacity with nearly 10 000 tons and an additional 6 % of conditioning capacity, will never be competitive with the 7500-ton ship transport solution. In the case of 30 % seasonal variations, the negative effects of the low transport capacity only become clearer.

#### 5.4. Fuel cost sensitivity

Future regulatory requirements on a low Sulphur-fuel and carbon taxes may drive up the fuel costs, which may as a result change the optimal buffer capacity as part of the transport logistic optimization. Thus, a sensitivity analysis is performed on the base case with 99 % transport requirement by increasing the fuel cost from base case level at 325 €/ton by respectively 50 %, 100 % and 150 %. This analysis is performed with the same settings as in the base case analysis.

The investments in buffer capacity increase with the price of fuel, from 102.4 % to 110.0 % of the ship transport capacity. With an increase in fuel-prices, the relative cost of buffer storage has decreased. Hence planning for using the flexibility in excess buffer capacity becomes a preferred option compared to the flexibility of adjusting the sailing power of the ship. The results show once more that there is value in having the buffer capacity larger than the ship size. The increased buffer capacity ensures that the ship can recover from the disruptions during the following transport cycles.

The value of buffer storage increases with the fuel price. Nevertheless, the sensitivity analysis does not show the cost of over- or under-investing in buffer capacity. With 150 % increased fuel prices, resolving the operational scenarios show that the optimal base case investments have an expected net present cost of 2.1 M€ higher than the optimal investment decisions if selected initially. In the opposite case, resolving the operational scenarios with a fuel price at the base case level and the optimal investment decisions with an increased fuel price of +150 %, the expected net present cost is 0.73M€ higher than if the base case solution was decided initially.

The results show an asymmetric cost of investing with wrong belief

of future fuel prices, meaning that there is a larger disadvantage of having insufficient buffer capacity than excessive. The available buffer capacity can be exploited by reducing the sailing speed of the ship, thereby reducing the fuel costs. Conversely, underestimating the need of buffer capacity will limit the system's flexibility. Hence, the only solutions are to increase the sailing speed and accept the higher fuel consumption.

#### 5.5. Cost of ship breakdown

Technical faults may lead to docking of the ship for several days. If a fault causes a delay of one average transport cycle or more, the only way to keep a capture and transport rate at 100 % is to have enough buffer capacity or an extra ship. We study an ideal situation with no weather uncertainty.

To avoid emissions during a full cycle docking of the ship, the required buffer capacity at the source must be set to 200 % of the average transport cycle emissions, 8 660 tons in total. In the base case, we saw that the optimal design is to have a buffer storage with a capacity of 5 890 tons, when the ship had a transport capacity of 5 000 tons. By investing in additional 2 760 tons of capacity, the transport system may handle delays of one cycle if the faults occur in a period without other delays.

Fig. 9 shows the cost of investing in the extra buffer capacity, and the savings of cost if there occur zero to three ship breakdowns of a full cycle per year.

The result shows that if a full cycle fault (4 days) occurs each year, the cost of emitting CO<sub>2</sub> is higher than the cost of investing and operating the storage and the cost of liquefying the CO<sub>2</sub>.

In case of shortage in buffer capacity, the conditioning plant will reduce the liquefaction rate to the lower operational boundary at a level of 50 % installed capacity in order to avoid a full shut-down. This will also reduce the emissions of liquefied CO<sub>2</sub> to a minimum. If one yearly fault occurs, there is an expected positive net present value of investing in buffer capacity of 8 660 tons, which is equivalent to 173 % of the ship's capacity. If the fault occurs more than once per year, the value of the buffer storage increases correspondingly, as shown in the right panels in Fig. 9.

The frequency and duration of planned and unplanned faults in the transport chain is crucial in deciding whether a buffer capacity larger than 118 % of the ship's capacity is required. This is the optimal design of the base case with a transport rate of 100 %. The lack of operational experience of ship-based CO<sub>2</sub> transport systems makes it hard to estimate the fault rates, and hence also hard to estimate the value of large buffer capacity.

## 6. Conclusions

This paper evaluates the capacity investments in a ship-based CO<sub>2</sub> transport chain with a specific focus on the impact of stochastic travelling times. The analysis optimizes the transport capacity, the intermediate CO<sub>2</sub> storage in the Norwegian CCS value chain and the trade-offs between the different operations schemes to ensure the lowest expected value chain cost. The results are obtained using a model for joint analysis of investment and operations with operational uncertainty on weather conditions in the Skagerrak and the North Sea.

The analysis shows that a buffer capacity of 118 % of the transport ships capacity is the most favorable design in the base case. The lowest unit transport cost is found when 99 % of the emissions are captured and transported with a unit cost in the transport value chain of 33.8 €/ton. If there is a 100 % requirement, the average cost of the last 1 % is 41.9 €/ton, that is 24 % more expensive than the average price of transporting the first 99 %.

By not considering the weather uncertainty and the potential delays when investing in buffer storage, the reduced capacity would lead to an expected cost increase of 1.9 €/ton in fuel costs. In addition, it would

lead to an increase in emissions of 4000 tons compared to the design found by the stochastic model.

The sensitivity analysis gives some insights on ship size. The seasonal variations in emissions lead to a preference for a larger ship when compared to a stable emission capture over the year. The increased fuel consumption for a larger ship due to its size is offset by the smaller ships' need for increased power-up and speed. The sensitivity analysis of increasing future fuel prices shows that the value of buffer capacity increases, as this avoids the increased cost of recovering delays by increasing the sailing speed (Table 4).

Furthermore, the results conclude that a buffer capacity of up to 118 % of the ship capacity may be optimal to balance the uncertainties related to weather condition, however capacities up to 173 % of the ship may be needed to minimize the expected cost, if one expects that a potential ship breakdown for a full transport cycle (4 days) happens at least yearly.

#### CRedit authorship contribution statement

**Vegard Skonseng Bjerketvedt:** Conceptualization, Methodology, Visualization, Investigation, Software, Writing - review & editing.

#### Appendix A. Techno-economic modelling of the CO<sub>2</sub> conditioning and shipping supply chain

The techno-economic modelling of the CO<sub>2</sub> conditioning and transport supply chain is based on the iCCS tool for CO<sub>2</sub> value chain developed by SINTEF Energy Research (Jakobsen et al., 2017a) (Roussanaly et al., 2013b). The following sections summaries the underlying technical and cost modelling. It is worth noting that the scale effect of capacity and transport distance on the cost of CO<sub>2</sub> conditioning and shipping is illustrated in (Roussanaly et al., 2014).

All costs presented in this work are given in 2017 price level. Cost data taken from literature and available in different years were update to 2017 price level using cost updating index such as: the CEPCI index (Chemical Engineering, 2019), IHS upstream costs indexes (IHS, 2018), or inflation (Trading Economics, 2018).

##### A.1 CO<sub>2</sub> conditioning before shipping

After a post-combustion CO<sub>2</sub> capture process, the CO<sub>2</sub> must be conditioned from near-ambient conditions to liquid CO<sub>2</sub> at 6.5 bar and -50 °C (ZEP, 2011). This step consists of multi-stage compression train, combined with removal of unwanted components<sup>1</sup>, followed by a liquefaction process based here on ammonia cooling cycles as shown in Fig. 10. The underlying technical characteristics and performances of this process were evaluated based on process simulations performed in Aspen HYSYS.

A bottom up approach was considered to assess the investment cost of this process as a function of the considered capacity. In this approach, the direct costs of each equipment of the process was assessed using Aspen Process Economic Analyzer® based on process characteristics derived from the process simulations. The total investment costs of the process is then obtained by multiplying the total direct cost of the process by an overall factor to include indirect cost, EPC costs, contingencies, owner cost, etc. (Deng et al., 2019)

While the annual fixed operating costs<sup>2</sup> are assumed to represent 5.5 % of the investment costs (Roussanaly et al., 2013b), the variable operating cost are estimated based on utilities consumption assessed through the process simulation and the utility costs presented in Table 5.

The techno-economic modelling of the CO<sub>2</sub> conditioning before shipping results in cost functions, presented in Fig. 11, for investments, fixed operating cost, energy cost and other variable operating costs.

##### A.2 CO<sub>2</sub> shipping supply chain

As illustrated in Fig. 2, the shipping supply chain considered here consist of 1) buffer storage prior shipping 2) loading facility 3) a shipping fleet 4) unloading facility 5) buffer storage after shipping 6) reconditioning to meet up the conditions required at the inlet of an offshore CO<sub>2</sub> pipeline. The costs of these different steps are assessed as follow.

The investment costs of buffer storages, either prior or after shipping, are assessed considering a cost of 1.13 k€ per cubic meter of buffer storage capacity (Roussanaly et al., 2013). The investment costs of loading and unloading facilities at each harbor are scaled from Knoope et al. (Knoope, 2015) using the power law presented in Eq. 1. The reference cost for each loading or unloading facility is 7.9 M€ for annual reference capacity of 3 MtCO<sub>2</sub>/y and is scaled assuming a power exponent of 0.85. Meanwhile, the investments of the ships are calculated based on the number of ships in the fleet and an estimated cost per ship function of the selected ship size as shown in Table 6. Finally, the reconditioning investment costs were modelled as a function of capacity following a bottom up approach as presented in section 0. The results of the techno-economic modelling of the reconditioning process is presented in Fig. 12.

While the annual operating costs of the shipping fleet are assessed based on the annual fixed operating costs per ship are presented in Table 6, the

**Asgeir Tomasgaard:** Methodology, Supervision, Writing - review & editing. **Simon Roussanaly:** Data curation, Validation, Supervision, Writing - review & editing.

#### 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.

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<sup>1</sup> Water removal based on TEG dehydration unit.

<sup>2</sup> Covering maintenance, insurance and labour costs.



annual operating cost of the others steps of the CO<sub>2</sub> shipping supply chain are assumed to correspond to 5.5 % of the investment costs (Roussanaly et al., 2013b). Finally, variable operating cost are assessed based on the estimated utility consumption and the costs presented in Table 5.

$$\text{Investment cost} = \text{Reference investment cost} \times \left( \frac{\text{Considered capacity}}{\text{Reference capacity}} \right)^{0.8} \quad (1)$$

### A.3 Key performance indicator

The CO<sub>2</sub> conditioning and transport cost (Skaugen et al., 2016) is used as key performance indicator for the considered value chains. This key performance indicator approximates the average discounted cost of CO<sub>2</sub> conditioning and transport based on Eq. 2. The CO<sub>2</sub> conditioning and transport costs are calculated based on a real discount rate of 8% and an economic lifetime of 25 years (Anantharaman et al., 2011). Finally, investment costs are assumed to take place over three years with a 40/30/30 cost allocation.

$$\text{CO}_2 \text{ conditioning and transport cost} = \frac{\text{Annualized investment} + \text{Annual OPEX}}{\text{Annual amount of CO}_2 \text{ transported}} \quad (2)$$

## Appendix B. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.ijggc.2020.103190>.

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