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Can subsea shuttles be a cost-competitive solution for CO_2 transport?

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Abstract

Considering the role that offshore CO_2 storage is expected to play in deploying carbon capture and storage, enabling cost-efficient and flexible solutions for transporting CO_2 to relevant storage locations. While several pipeline and ship-based approaches have been proposed to do so, subsea shuttles are a new concept that has also been proposed in the past couple of years. The present study seeks to understand if this new approach could be cost-efficient compared to current and upcoming ship-based transport concepts.

The result shows that the shuttle concept could be cost-competitive to currently mature 15 barg-based shipping, especially if the subsea shuttle connects to a CO_2 pipeline infrastructure rather than to the reservoir directly, although cost-competitiveness is achieved only for a limited range of volumes and distances. However, it is unlikely that this concept would be cost-attractive compared to the upcoming 7 barg-based shipping, and sensitivity analyses highlight that the subsea shuttle investment cost would need to fall to unlikely low levels to reverse this trend. Thus, this study concludes that the subsea shuttle concept is unlikely to become a significant solution for transporting CO_2 to offshore storage.

Keywords: Carbon capture and storage, CO_2 transport, offshore storage, subsea shuttle, techno-economic analysis

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1. Introduction

Carbon Capture and Storage (CCS) has been consistently highlighted by the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) as a key element of achieving the net-zero ambition [1, 2]. In particular, CCS is foreseen to contribute to reducing emissions from power, industry, hydrogen, fossil fuel production, as well as enable negative emissions via direct air capture (DAC) and bioenergy with CCS (bioCCS) [2]. According to IEA's net-zero by 2050 roadmap [2], 1.67 and 7.61 Gt_{CO_2}/y are to be captured globally by 2030 and 2050, of which the vast majority is expected to be permanently stored in geological formations.

As the facilities where the CO_2 shall be captured are often not close to where it needs to be stored, CCS chains must usually include one, or multiple, transport step(s). The most mature and common way of transporting CO_2 is via onshore pipelines; however, several other options exist [3]. For example, CO_2 can also be transported in-land via truck, train, or barge [4]. With the relevance and/or necessity of storing CO_2 offshore in certain regions, like Europe, the interest in transporting CO_2 at sea has significantly grown over the past decade [5, 6]. In such cases, CO_2 would typically be transported via offshore pipelines or ships. For both inland and at-sea transports, the cost-optimal transport mean depends on the transport distance, the transport volume, the quality of the CO_2, opportunities for clustering, etc [7, 8, 9].

With the rising interest in transport to offshore storage, more research and development focus has been put on maturing the relevant technologies, optimising transport conditions and impurities, and understanding when each technology is most suited. A new transport concept that has recently been proposed for CO_2 transport is autonomous subsea shuttles [10, 11], as illustrated in Figure 1. The interest in this concept transferred from the oil and gas sector, where it is also considered for transporting oil, gas, or hydrogen with the perspective of reducing manning, infrastructure requirements, etc. This concept is expected to present similar advantages as ship-based transport (lower investment, flexibility, etc.), as well as several shuttle-specific advantages such as low manning and low sensibility to weather. As a result, several studies started to look at different aspects of such a concept. Ma et al. [12] discussed the potential challenges associated with such a concept [12] and proposed a baseline design of the shuttle concept. Xing

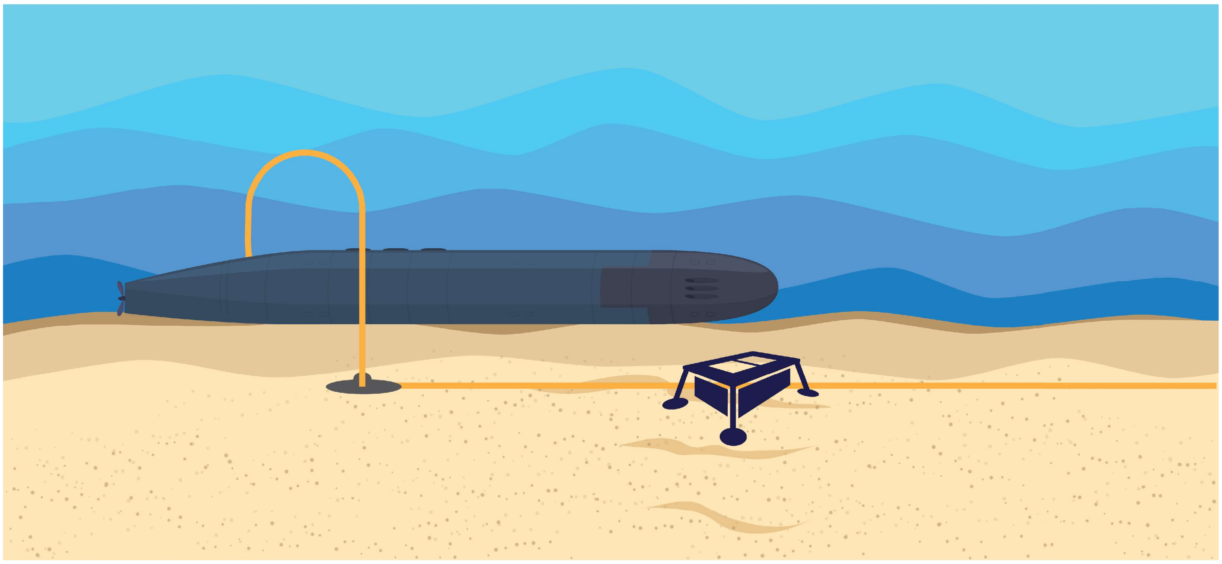

Figure 1: Illustration of the autonomous subsea shuttle concept for CO_2 transport
. Reproduced from [18]

et al. [13] and Patel et al. [14] investigated different aspects of the shuttle design. Xing et al. [15] investigated the hydrodynamic resistance during subsea shuttle transport to better understand the power requirement to ensure reliable and safe operations. Dai et al. [16] studied the design of discharging flowlines for CO_2-transporting subsea shuttles. Finally, Xing et al. [17] performed a first techno-economic analysis of the concept, indicating that the concept could be interesting for short transport distances and volumes.

With significant technical confidence in the concept resulting from the studies published in the literature, an in-depth understanding of the potential of such a concept to cost-efficiently transport CO_2 is missing. The present study thus seeks to

1. evaluate the cost of transporting CO_2 via subsea shuttle to understand both cost performances and drivers,
2. perform an in-depth comparison of this concept with conventional ship-based transport of CO_2, and
3. understand the impact of key uncertainties on this comparison.

The paper is organised as follows. First, the study concept and methodology adopted are presented, including study concept, modelling approach, and key performance indicators. Secondly, the results from the evaluation of specific cases, the in-depth comparison, and the uncertainty of selected parameters are presented and discussed. Finally, the overall conclusions of the study are drawn.

2. Study concept

This study aims to understand the techno-economic performances of the subsea shuttle concept, as well as if and when it could be more cost-efficient than conventional approaches to transport CO_2 to offshore storage fields. In order to do so, this study will look at three types of evaluations:

- First, the concept is assessed and compared for three specific cases, summarised in Table 1, to understand cost performance and the cost drivers of the shuttle concept;
- Secondly, a wide range of transport distances and transport volumes are considered in order to understand the full potential of the shuttle concept;

- Finally, the impact of uncertainties in subsea shuttle CAPEX on the potential of the concept is discussed.

The subsea shuttle concept is compared to shipping with a receiving terminal at the storage area for consistency in terms of asset flexibility of the transport option. While shipping at 15 barg is the current conventional way of shipping CO_2, a recent study has shown that shipping at 7 bar is a more cost-efficient approach [7], and industrial actors are now moving towards it [19]. Hence, both options are here used as reference in the present study.

Table 1: Characteristics of the selected cases.

	Case A	Case B	Case C
Transport volume [Mt_{CO_2}/y]	2.3	2.3	1.25
Distance [km]	83	50	166

2.1. Subsea shuttle concept

To model and evaluate the subsea shuttle concept, it is important to understand the different steps it entails:

1. After CO_2 capture, the purified CO_2 must be conditioned to the desired transport conditions. As typically considered for tanked-based transport, the CO_2 is expected to be transported in liquid form, thus requiring a liquefaction process;
2. After the liquefaction, a buffer storage facility is used to ensure the continuous operations of the system as the subsea shuttle(s) are batch processes while the CO_2 capture and liquefaction are continuous processes;
3. As the subsea shuttles are foreseen to be loaded on the seabed to avoid having the subsea shuttle moving between the ocean surface and the seabed, an onshore-offshore landfall is used to bring the CO_2 to a subsea loading station;
4. The autonomous subsea shuttle is loaded with the CO_2, navigates to the targeted unloading area, unloads the CO_2, and navigates back to the loading area.
5. A subsea receiving facility offloads the CO_2 from the shuttle and sends it to the injection infrastructure. It is worth noting that no buffer storage is considered at this step due to the associated prohibitive costs.

These steps are illustrated in Figure 2. The system boundaries adopted in this study start from the liquefaction process until the CO_2 offloading facility.

2.2. Transport conditions

While sub-zero temperatures are typically considered for CO_2 transport via ships, such conditions are foreseen to be difficult to maintain for the subsea shuttle concept. Indeed, due to the sea's higher thermal capacity and conductivity than air, CO_2 transported at sub-zero temperatures is expected to warm up faster than when transported on a ship. Insulation can be expected to slow down this increase, but only limited quantities can be considered in practice for cost reasons. Thus, this concept should be more compatible with transport conditions above the temperature of the surrounding sea environment (i.e., above 4 °C considering the relevant water depths). Furthermore, during periods when the subsea shuttle is not loading, the CO_2 in the near-surface part of the onshore-offshore landfall could potentially warm up to near ambient temperature. Thus, to ensure that CO_2 also remains liquid in this part of the infrastructure, even in such cases, it is deemed important that the CO_2 is transported at conditions that ensure that it remains liquid even at temperatures around 20 °C.

Considering these aspects, the selected transport pressure after liquefaction and for transport was set to 62.5 bar with an associated temperature of 20 °C. This pressure provides around 5 bar of margin compared to the liquefaction pressure of CO_2 at 20 °C, which is 57.6 bar.

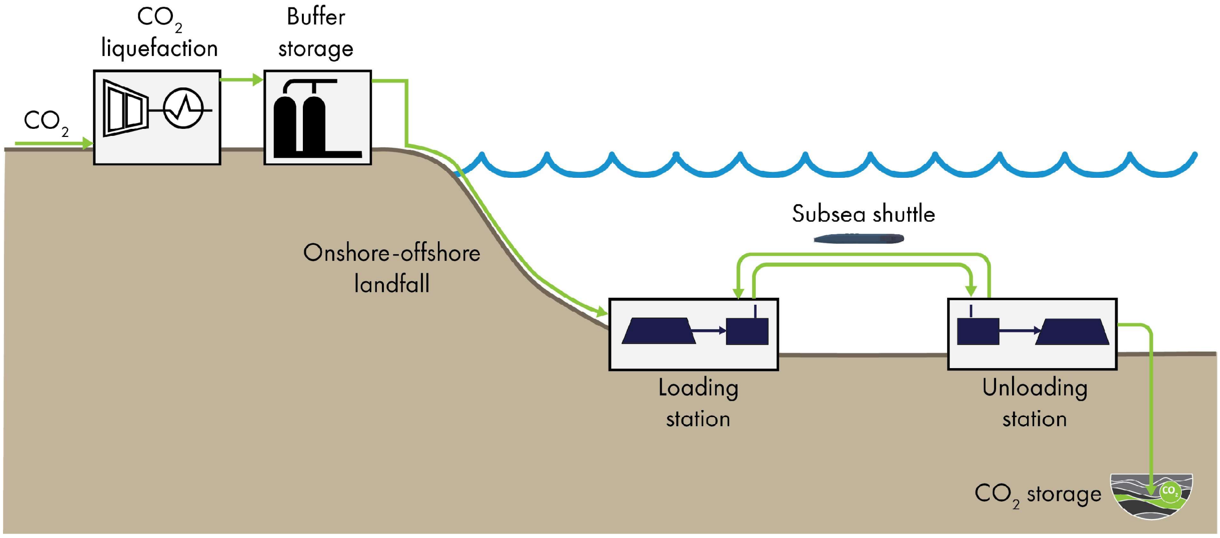

Figure 2: Schematic illustration of a subsea shuttle concept. The dimensions are not to scale.

3. Methodology

While the technical and cost evaluation approaches used to evaluate the reference ship-based transport are based on the methodology and data presented in Roussanaly et al. [7], the following sections summarise the methods and data used to evaluate the characteristics and performances of the subsea shuttle approach.

3.1. CO_2 conditioning

In order to cost-efficiently transport CO_2 over significant distances, the CO_2 typically needs to first be densified compared to the near ambient conditions at which it is usually available after CO_2 capture. Transport via tank-based approaches (ships, barges, trains, trucks) is mainly based on a liquid-based transport at what is called medium pressure (15 barg and −30 °C) or low-pressure (15 barg and −50.3 °C). As mentioned in Section 2.2, the CO_2 in the subsea shuttle concept is expected to be transported at 62.5 bar and 20 °C.

To reach these conditions, a succession of intercooled compression stages with water removal is adopted. In this process, CO_2 is compressed through three compression stages to successfully 6.4, 21.5, and 62.5 bar. After each compression stage, the CO_2 is cooled to 20 °C via a water-cooled heat exchanger to minimize the compression work, followed by a flash separator to remove condensed water. After the last compression stage, the CO_2 stream passes through a molecular sieve unit to reach a water content below 50 ppm[1]. A schematic process flow diagram of the liquefaction process is presented in Figure 3. In addition, the characteristics of the CO_2 through different steps of the liquefaction process, as well as the corresponding compression power and cooling duty of each compression stage, are provided in Appendix A (in Table A.1 and Table A.2, respectively).

Based on a process design, a techno-economic evaluation of the liquefaction process was carried out following the approach laid in Deng et al. [20] and considering an electricity cost of 80 €/MWh [20]. The evaluation resulted in a liquefaction cost of 11.9 $€/t_{CO_2}$ with a breakdown of 28, 15, and 57 % between CAPEX, fixed OPEX, and variable OPEX. The liquefaction cost was extrapolated for other annual volumes using the cost power low for CAPEX scaling based on a power exponent of 0.9. An illustration of the liquefaction costs, as a function of the annual volume, obtained for the subsea shuttle concept, as well as for transport via ship at 7 and 15 barg, is presented in Figure 4.

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[1] As the presence of water with other potential impurities could lead to for example corrosion.

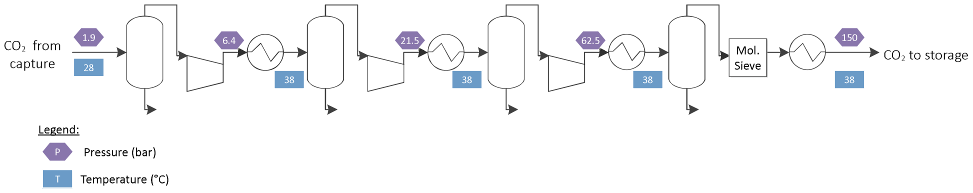

Figure 3: Schematic process flow diagram of the liquefaction process.

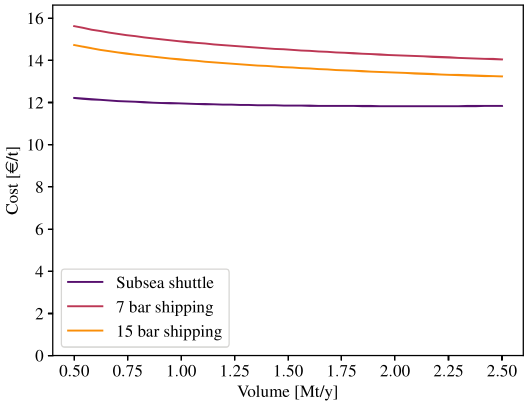

Figure 4: Liquefaction cost [€/t] as a function of the annual volume [$\mathrm{Mt}_{\mathrm{CO}_2}$/y] for the subsea shuttle concept, as well as for transport via ship at 7 and 15 barg.

3.2. Subsea shuttle logistics

The subsea shuttle logistics here refer to the steps 2 to 5 described in Section 2.1: onshore buffer storage, onshore-offshore landfall and loading station, subsea shuttle(s), and subsea offloading station.

3.2.1. Selected logistical approaches

Compared to ships, subsea shuttles are more costly for the same size, can be manufactured for smaller sizes, thus limiting economies of scale, and are slower. As a result, logistical approaches suitable for small distances and small volumes will likely offer the most potential. Three logistic approaches are considered:

S1 The first logistical approach, referred to as S1 considers two subsea shuttles in its fleet. This approach allows a subsea shuttle to serve as a loading vessel near the coast while the other unloads at the desired location. Once the loading shuttle has loaded up and the unloading shuttle is emptied, the shuttles navigate to exchange locations and functions. In order to ensure continuous operations, a buffer storage is considered at shore. It is worth noting that the logistic chain must ensure that the injection well is not continuously idle for more than 36 h to maintain normal operations.

S2 In the second logistical approach, referred to as S2, only one subsea shuttle is considered. This implies that a larger buffer storage than the first is required to ensure continuous operations. Similarly to the first approach, the logistics must ensure that the injection well is not continuously idle for more than 36 h. This constraint significantly limits the achievable transport distances.

S3 The third approach, referred to as S3, is similar to the second approach. However, in this case, it is assumed that the subsea shuttle would unload the CO_2 into a pipeline infrastructure receiving CO_2 from other sources. This assumption would allow forgo the implications resulting from the need to keep the injection well non-idle for more than 36 h.

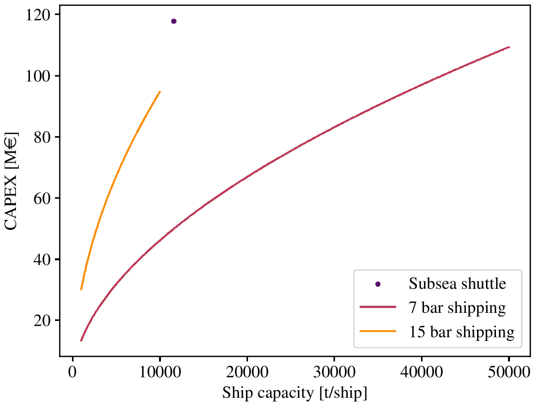

Figure 5: Investment cost of subsea shuttle and ships for transport of CO_2 depending on its capacity.

3.2.2. Logistics modelling

As mentioned earlier, a buffer storage must be used at the shore in order to ensure the feasibility of the continuous operation of the shuttle-based CCS chain. The sizing of this buffer is thus set to ensure that CO_2 arriving from the liquefaction can be stored for the period during which a shuttle stops loading and when a subsea shuttle can restart loading. Considering the high pressure, the costs of this part of the process are estimated assuming a CAPEX of 3000 €/m^3 and a fixed annual operating cost corresponding to 5 % of the CAPEX [21].

Between the buffer storage and the subsea shuttle transport, two systems are required: the CO_2 needs to be brought to the seabed via a pipeline placed on an onshore-offshore landfall, and a subsea loading station is necessary to connect and transfer the CO_2 on the shuttle. The cost of the onshore-offshore landfall, including the pipeline, together with the subsea loading station, was estimated to 17 M€, for an annual volume of 1.3 $\mathrm{Mt_{CO_2}}$/y. This cost was scaled based on the power law for other annual volumes, considering a power factor of 0.29 due to the significance of the onshore-offshore landfall [7]. A fixed annual operating cost corresponding to 6 % of the CAPEX is also considered.

Subsea shuttles with a CO_2 transport capacity of 15 000 m^3 (i.e. 11 607 $\mathrm{t_{CO_2}}$) are considered here[2]. The subsea shuttles are considered to navigate at a speed of 6 knots (i.e., 11.1 km/h). It is worth noting that this speed is considerably lower than the sailing speed of a ship-based solution, which is around 14 knot (i.e. 25.9 km/h). It is assumed that a minimum of 12 hours[3] are required for the approach, connection, loading or unloading, disconnection, and departure of the shuttle. This assumption is consistent with the duration considered for mooring, connection, loading or unloading, disconnection, and departure of CO_2 ship at a harbour, but shorter[4] than the 36 h considered when a ship unloads to a receiving floating facility as considered in the ship-based transport. The investment cost of a subsea shuttle is assumed to be 118 M€ [17][5] and an annual operating cost of 1.9 M€/y, which includes the power consumption required to operate the subsea shuttle [17]. As one could expect, the subsea shuttles are much more expensive than a ship of the same size, as illustrated in Figure 5. However, it is worth noting that due to the unmanned operation and their electrification, they have lower operating costs.

Finally, a subsea receiving facility is required after the subsea shuttle transport. The subsea receiving facility was assumed to cost 6.9 M€ for an annual volume of 1.3 $\mathrm{Mt_{CO_2}}$/y, and to scale linearly with the annual volume. A fixed annual operating cost corresponding to 6 % of the CAPEX is also considered.

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[2] Meanwhile, as explained in [7], the ship size is optimisation amongst a set of ship size. The maximum ship size for medium and low pressure ships are set to 10 and 50 $\mathrm{kt_{CO_2}}$ per ship.

[3] Of which 4 h are required for approach, connection, disconnection, and departure of the shuttle.

[4] Indeed, a longer time period is normally required to ensure suitable alignment of the ship during unloading.

[5] The subsea shuttle investment cost was scaled linearly from a 10 569 m^3 subsea shuttle costing 83 M€.

3.3. Key performance indicators

The cost of CO_2 transport, including conditioning [20], is expressed as in Equation (1). It is here used as a cost performance metric for both optimisation and comparison of the transport chains. This cost performance metric is computed considering a real discount rate of 8 %, a project duration of 25 years, and an operating rate of 85 %.

$$\text{CO}_2 \text{ transport cost } [\text{€/t}] = \frac{\text{Annualised investment + Annual OPEX}}{\text{Annual amount of CO}_2 \text{ transported}}, \tag{1}$$

4. Results and discussions

4.1. Evaluation of the specific case studies

In order to first understand the cost performance and the cost drivers of the shuttle concept, the different subsea shuttle configurations (scenarios S1-S3) are designed and evaluated for the three specific cases presented in Table 1 and compared to transport with shipping at 15 and 7 barg. Figure 6 present the result of this evaluation including the cost breakdown between the different elements of the transport system.

In case A, presented in the leftmost in Figure 6, it is first worth noting that subsea shuttle configurations based on a single-shuttle logistic (scenarios S2 and S3) cannot transport the quantities of CO_2 over the considered distance. However, scenario S1 is both able to meet the logistic requirement but also outperform transport via 15 barg pressure ship. As can be seen from the cost breakdown, this can be explained by the lower liquefaction cost and the fact that the ship-based approaches considered require the use of a ship to serve as a receiving facility near the offshore storage site, which comes at significant costs. These cost reductions manage to overcome the higher investment costs of buffer storage and carriers (subsea shuttle). However, despite these cost reductions, the subsea shuttle concept does not manage to outperform the 7 barg-based shipping approach.

In case B, presented in the middle bar plot, all the subsea shuttle configurations (scenarios S1-S3) can meet the logistic requirement to transport the CO_2 over the considered distance. As a result, the subsea shuttle scenarios S2 and S3 result in lower cost than the configuration S1, as these configurations have a subsea shuttle less. In this case, the subsea shuttle concept is able to enable significant cost reductions compared to 15 barg-based shipping (23.9 %) and a small reduction compared to 7 barg-based shipping (4.4 %). While the first comparison has underlying causes similar to case A, the latter comparison shows that the lower investment costs of 7 barg ship limit the cost advantages of the subsea shuttle concept significantly.

Finally, in case C, presented in the most-right part of the figure, the subsea shuttle configurations S2 cannot meet the transport requirement due to the “long” transport distance. As in case A, the subsea shuttle concept is able to outperform the 15 barg-based shipping concept, especially when the subsea shuttle logistic scenario S1 can be used. However, as in case A, none of the logistic scenarios enable the subsea shuttle to be cost-competitive with 7 barg-based shipping.

4.2. In-depth comparison of the subsea shuttle concept

While case-specific evaluations of the subsea shuttle concept provide a good understanding of trends and underlying cost drivers of the subsea shuttle concept, its performances and the outcome of its comparison with ship-based transport will vary with the considered transport distance and annual volume. As a result, in order to achieve a proper understanding of the potential of the concept, a wide range of transport distances and annual volumes must be considered. This is here performed by considering transport distances up to 300km and annual volumes up to 2.5 Mt/y. It is worth noting that the comparison with is here done in two steps: first, to currently mature 15 barg-based shipping and, secondly, to the upcoming 7 barg-based shipping [7].

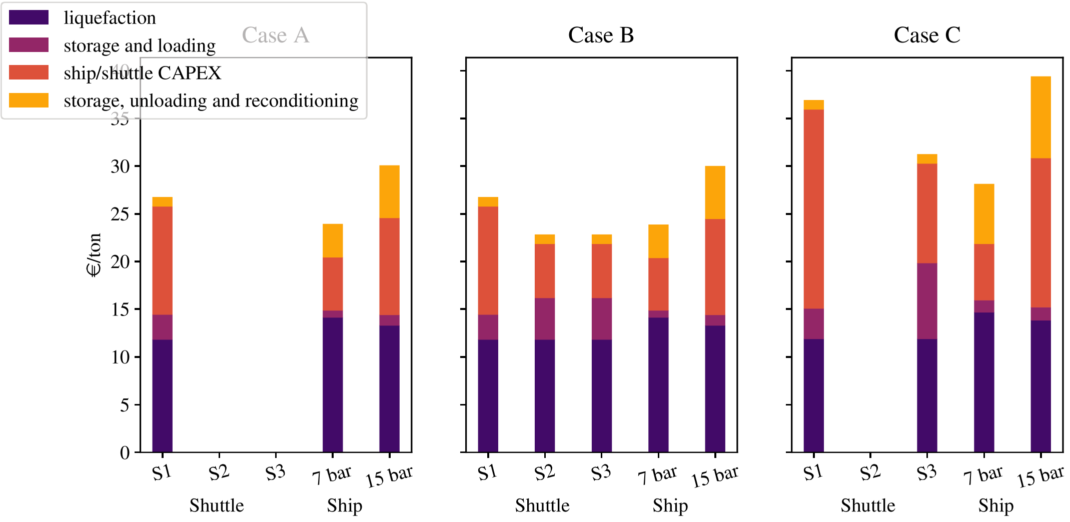

Figure 6: CO2 conditioning and transport cost of the cases A-C, including cost breakdown. From the left: annual volume of 2.3 $\mathrm{Mt_{CO_2}}$/y and transport distance of 83 km. Middle: annual volume of 2.3 $\mathrm{Mt_{CO_2}}$/y and distance of 50 km. To the right: annual volume of 1.25 $\mathrm{Mt_{CO_2}}$/y, and distance of 166 km. The combinations where one of the shuttle scenarios has no cost represents a case where the combination of annual volume and distance is infeasible due to the restriction of a single shuttle for scenarios S2 and S3.

4.2.1. Comparison of the subsea shuttle concept with 15 barg*-based shipping*

Figure 7 presents the different results of the evaluation and comparison of the subsea shuttle concept compared to the currently mature 15 barg-based shipping for a wide range of transport distances (X-Axis) and annual volume (Y-axis). In particular, Figure 7(a) and (c) display the cost-optimal option between the different subsea shuttle configurations and 15 barg-based shipping when considering (a) subsea shuttle configurations constraint by the maximum well idle time (configurations S1 and S2) (c) all subsea shuttle configurations (S1-S3). Meanwhile Figure 7(b) and (d) show the cost reduction potential of the subsea shuttle concept compared to the ship-based option when considering (b) subsea shuttle configurations constraint by the maximum well idle time (configurations S1 and S2) (d) all subsea shuttle configurations (S1-S3). Figure 7 (a) and (c) highlight that the subsea shuttle could outperform ship-based transport for a wide range of cases, especially when the subsea shuttle concept is not constrained by the maximum well idle time requirement. It also shows that subsea shuttle configurations based on a single shuttle (S2 and S3) tend to be cheaper than the concept with two shuttles (S1) but can operated for a more limited range of transport distances and annual volumes. As can be seen in these figures, the subsea shuttle concept outperforms ship-based transport for a wide range of annual volumes at low transport distance, but this range reduces and even closes down as the transport distance increases. In terms of cost reduction potential, Figure 7 (b) and (d) shows that the cost reduction potential of the subsea shuttle could be higher than 25 % but varies significantly for the set of cases considered and is especially impacted by the annual transport volume.

4.2.2. Comparison of the subsea shuttle concept with both 7 and 15 barg*-based shipping*

While low-pressure (7 barg) shipping is currently not commercially available, studies have shown that transitioning to low-pressure would significantly reduce shipping costs compared to the commercially available 15 barg shipping (mid-pressure) [7]. As a result, industrial actors have been actively working towards maturing this option and it is expected to become commercially available in the next few years [22]. This expected shift also means that the subsea shuttle concept must actually be compared to ship-based transport at both 7 and 15 barg if one wants to understand the potential of the concept. Figure 8 hence displays the same aspects[6] as Figure 7 but also including, this time, 7 barg-based shipping as a transport option. The results show that the lower cost of low-pressure shipping deeply impairs the

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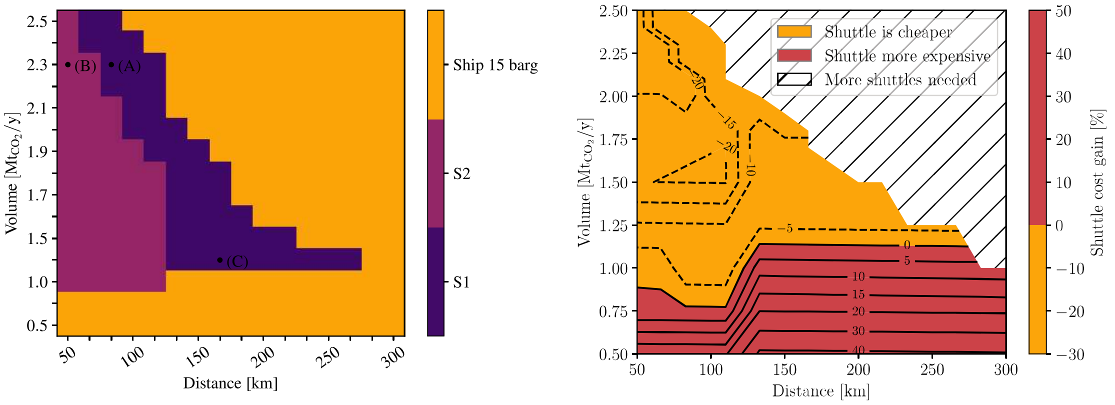
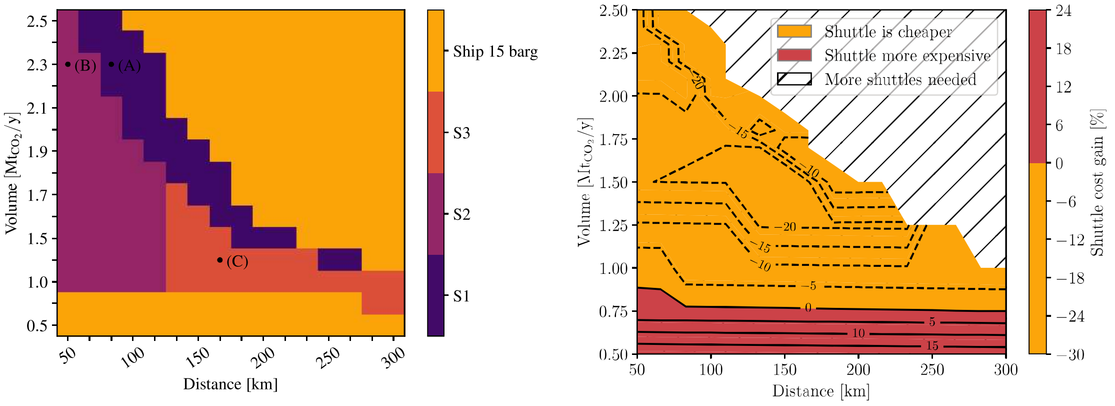
[6] Only one row of figures is here presented as excluding or not the subsea shuttle configuration S3 results in the same figures.



(a) Optimal transport strategy (S1, S2 or 15 barg shipping).

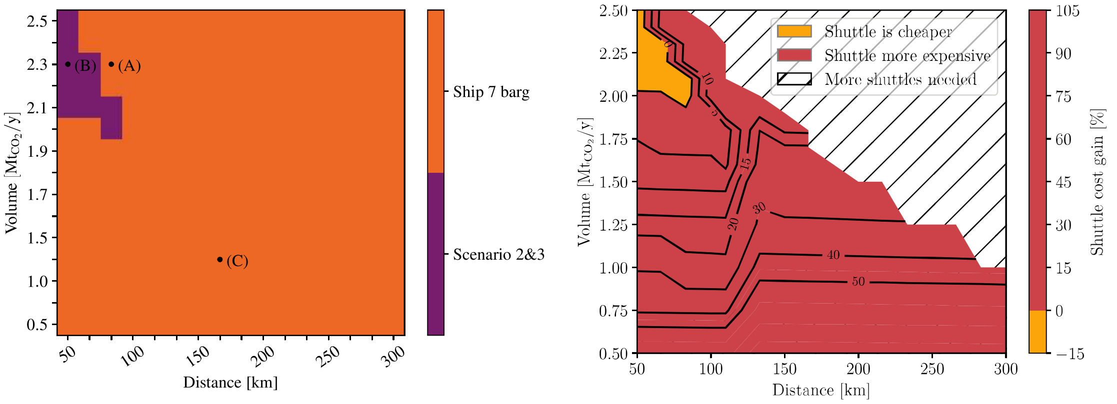
(b) Relative cost gain in % with using a shuttle (S1 or S2) as compared to 15 barg shipping.



(c) Optimal transport strategy (S1-S3 or 15 barg shipping).

(d) Relative cost gain in % with using a shuttle (S1-S3 as compared to 15 barg shipping.

Figure 7: Results of the comparison in-depth cost comparison of the subsea shuttle concept (S1-S3) is compared to 15 barg-based shipping as a function of the transport distance (X-axis) and annual volume (Y-axis). The points marked in (a) and (c) refer to the detailed cases studied in Figure 6. The diagonal striped area marks infeasible combinations of annual volume and distance due to the restriction of having maximum 2 subsea shuttles.



(a) Optimal transport strategy

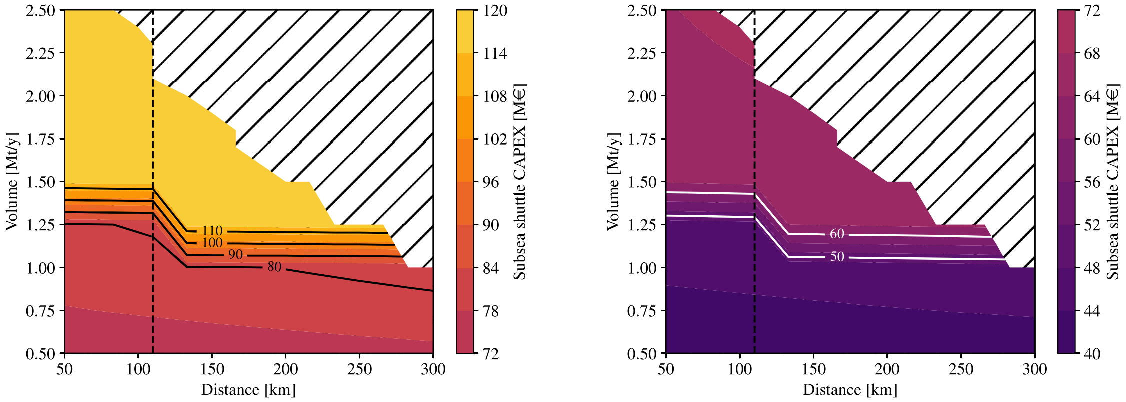
(b) Relative cost gain in % with using a shuttle as compared to shipping.

Figure 8: Results of the comparison in-depth cost comparison of the subsea shuttle concept (S1-S3) is compared to 15 and 7 barg-based shipping as a function of the transport distance (X-axis) and annual volume (Y-axis). The points marked in (a) and (c) refer to the detailed cases studied in Figure 6. The diagonal striped area marks infeasible combinations of annual volume and distance due to the restriction of having maximum 2 subsea shuttles.

cost-competitiveness of the subsea shuttle concept. Indeed, results show that the subsea concept can outperform ship-based transport in only a few cases (on the upper left part of the figures). When looking at the required subsea shuttle logistical approach, the result emphasizes that only single-shuttle logistical concepts can achieve competitiveness. Furthermore, in any case, the cost-reduction potential enabled by the subsea shuttle concepts is very limited (less than 5.0 %, 4.2 % on average). Considering these aspects, and under the assumptions adopted here, subsea shuttle transport is unlikely to become a significant solution for the transport of CO_2 to offshore storage.

4.3. Uncertainty in shuttle investment costs

As highlighted in Section 4.1, the high investment costs (CAPEX) of a subsea shuttle are a key driver of the concept cost and hinder its capacity to be cost-competitive. Indeed, the CAPEX of a subsea shuttle of 11.6 kt$_{CO_2}$ was here assumed to be 120 M€ based on [17]. In comparison, the CAPEX of a ship of the same capacity would be 76 M€ and 37 M€ for, respectively, a 15 barg (mid-pressure) and a 7 barg (low-pressure) ship according to [21]. However, while the CAPEX of a carrier (ship or shuttle) is expected to be higher as the transport pressure increases [21] and the CAPEX of a subsea shuttle is expected to be higher than the one of a ship of the same capacity (at equal transport pressure), the CAPEX of a subsea shuttle remains a significant uncertainty. In order to understand the impact of this uncertainty on the cost comparison, this study also seeks to back-calculate for the subsea shuttle's CAPEX required for the subsea shuttle to be on-par with the cost of a ship-based approach (Figure 9), as well as to be 10 % cheaper than the ship-based approach (see Figure B.1 in Appendix B). These comparisons are made with regard to only 15 barg shipping, as well as when considering both 15 and 7 barg shipping. In the on-par scenario compared to 15 barg-based shipping, the base case subsea shuttle's CAPEX enables a significant area of cost competitiveness, as earlier shown. More interestingly, it highlights that even if the CAPEX of the subsea shuttle concept were to be significantly lower (for example, 80 M€ per shuttle), the set of distances and annual volumes in which the subsea shuttle is more cost-efficient than shipping does not increase drastically. In the on-par scenario compared to both mid- and low-pressure shipping, the results show that subsea shuttle's CAPEX would need to be halved compared to the base case assumption in order for the subsea shuttle to be cost-competitive for a significant set of distances and annual volumes. This would thus mean that a subsea shuttle's CAPEX would have to be 22 % lower than the CAPEX of a 15 barg ship of the same capacity, which is highly unlikely considering that higher transport pressures increase carrier's CAPEX significantly and that a subsea shuttle is expected to be more expensive than a ship of the same capacity. Considering these results, it is thus extremely unlikely that uncertainties in the subsea shuttle CAPEX could lead to a cost-competitive concept compared to shipping considering both mid- and low-pressure options. Finally, it is important to note that these



(a) Relative cost gain in % with using a shuttle as compared to shipping.

(b)

Figure 9: Subsea shuttle CAPEX required for the subsea shuttle concept to result in an on-par CO_2 conditioning and transport compared to (a) 15 barg-based and (b) 7 barg-based shipping transport. The dotted line marks the maximum distance for scenario S2. The diagonal striped area marks infeasible combinations of annual volume and distance due to the restriction of having maximum 2 subsea shuttles.

trends are further exacerbated if one seeks to achieve a 10 % cost reduction compared to shipping, as highlighted in Figure B.1.

5. Conclusion

The necessity of storing CO_2 offshore in Europe due to social acceptance brings several challenges (technology maturity, cost, high investment, uncertainties on rollout) in terms of CO_2 transport, especially in early deployment phases when volumes are expected to remain low. To reduce these hurdles, several concepts have been proposed and matured over the past decade, such as CO_2 shipping with a receiving terminal, shipping with a receiving offshore floating facility, shipping with direct injection, or even subsea shuttles. The present study seeks to understand the potential of the latter approach, which emerged in the past few years.

The result shows that the shuttle concept could be cost-competitive to currently mature 15 barg-based shipping, although this is for a rather limited range of transport volume. If the subsea suttle could connect to a receiving pipeline, the shuttle concept would outperform 15 barg-based shipping for annual volume between 0.8 and 2.3 $\mathrm{Mt_{CO_2}}$/y and distances between 50 and 300 km, depending on the transport volume. However, if the shuttle has to connect directly to a reservoir, this window of cost-competitiveness is significantly reduced (between 1.25 and 2.6 $\mathrm{Mt_{CO_2}}$/y and distances between 50 and 275 km depending on the transport volume). More importantly, it is unlikely that this concept would be able to be cost-attractive compared to the upcoming 7 barg-based shipping. These higher costs can be explained by, especially, the high investment costs in the subsea shuttle. Sensitivity analyses highlight that the subsea shuttle cost would need to fall to unlikely low levels so that the concept can become cost-attractive with upcoming 7 barg-based shipping.

Thus, although the subsea shuttle also presents other advantages (flexibility, low-manning, operability, and insensibility to weather), this study concludes that it is unlikely to become a significant solution for the transport of CO_2 to offshore storage.

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CRediT author statement

S.R. and S.H. have undertaken Conceptualization, Methodology, Validation, Formal analysis, Writing - Original, Draft Writing - Review & Editing. A.S. has contributed to the Methodology and Draft Writing - Review & Editing.

Appendix A. Further details on the liquefaction process for subsea shuttles

See Table A.1 and Table A.2.

Table A.1: Operating compression power and heat exchanger cooling duty of liquefaction process for an annual volume of 1.3 $\mathrm{Mt}_{\mathrm{CO}_2}/\mathrm{y}$.

	Stage 1	Stage 2	Stage 3	Total
Compressor power [kW]	4.5	4.5	3.60	12.60
Heat exchanger cooling duty [kW]	4.70	5.56	6.37	16.63

Table A.2: Characteristic of the CO_2 stream through the liquefaction process for an annual volume of 1.3 $\mathrm{Mt}_{\mathrm{CO}_2}/\mathrm{y}$.

	To liquefaction process	After compression stage number[7]			After liquefaction process
		1	2	3	
Mass flow [t/h]	176.1	175.4	174.9	174.8	174.6
Pressure [bar]	1.93	6.43	21.5	62.5	62.5
Temperature [°C]	28	38	38	38	20
Density [kg/m^3]	3.4	11.2	40.9	170	774
Composition [%vol]					
CO_2	98	98.88	98.58	99.66	99.99
H_2O	2	1.11	0.42	0.34	50 ppm
N_2	0.01	0.01	0.01	0.01	0.01

Appendix B. Uncertainty in shuttle investment costs - 10% cost reduction target

In Figure B.1 the shuttle CAPEX required to achieve 10 % cost reduction compared to the shipping alternatives is shown. Figure B.1(a) compare the shuttle scenarios to 15 barg shipping, while in Figure B.1(b) the shuttle is compared against 7 barg shipping.

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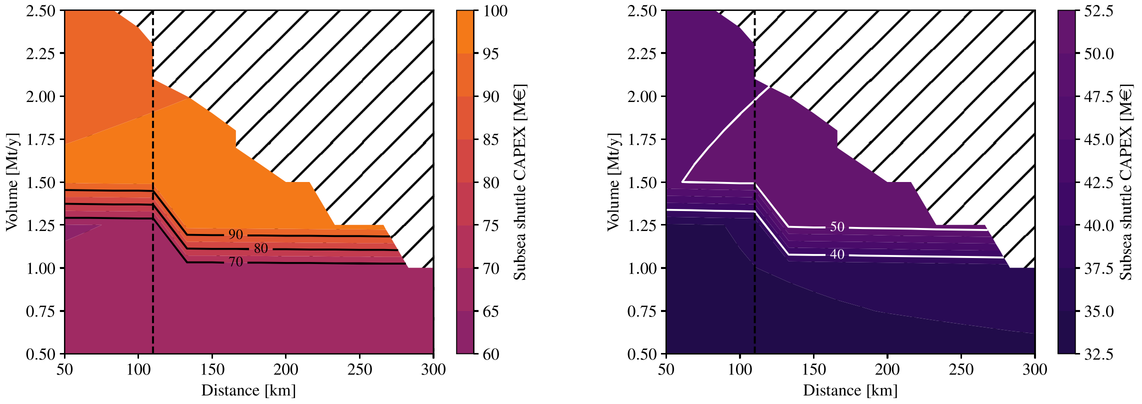
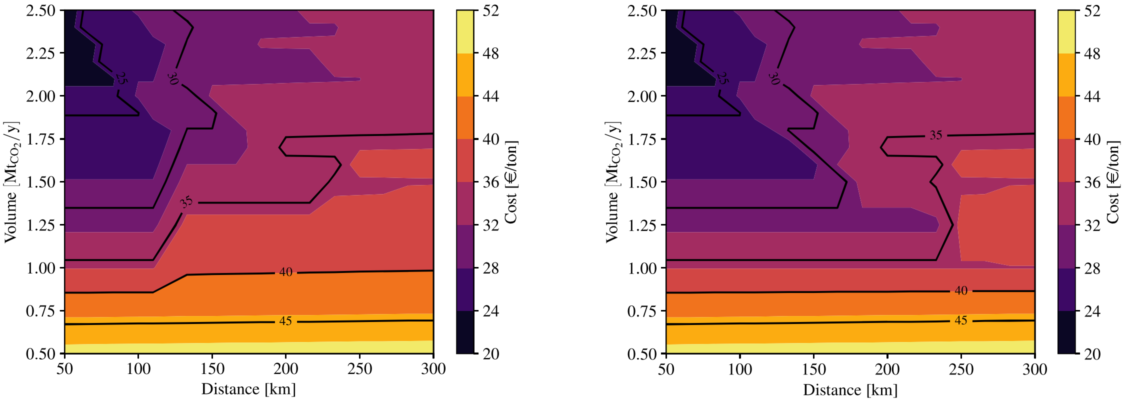
[7] Include the intercooling and the flash separator.

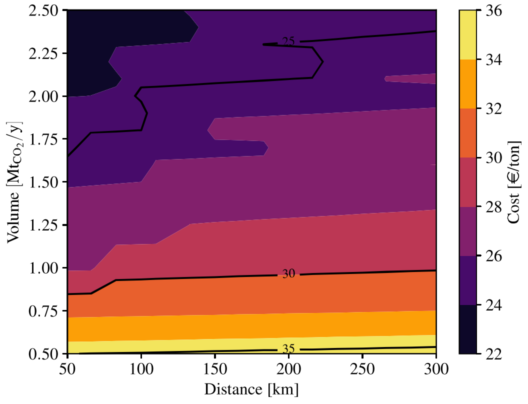


(a) (b)

Figure B.1: Subsea shuttle CAPEX required for the subsea shuttle concept to result in a 10 % cheaper CO_2 conditioning and transport compared to (a) 15 barg-based and (b) 7 barg-based shipping transport. The dotted line marks the maximum distance for scenario S2. The diagonal striped area marks infeasible combinations of annual volume and distance due to the restriction of having maximum 2 subsea shuttles.



(a) Cost of the cheapest strategy in Figure 7(a). (b) Cost of the cheapest strategy in Figure 7(c).



(c) Cost of cheapest strategy in Figure 8(a).

Figure B.2: Cost of cheapest strategy. Cost is given in €/ton.

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