



Providing access to cost-efficient, replicable,  
safe and flexible CCUS

# Potentials, concepts and improvements for inland CO<sub>2</sub> transport systems



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## About ACCSESS

If CO<sub>2</sub> capture and storage (CCS) is to become a relevant, large-scale technology for cutting carbon dioxide (CO<sub>2</sub>) emissions, several barriers need to be addressed, and its deployment must be accelerated.

ACCSESS works to address key challenges to the successful implementation of CCS across Europe: namely, challenges related to CO<sub>2</sub> capture, CCS chains, and societal acceptance. The project focuses on four industrial sectors with the potential to drastically reduce CO<sub>2</sub> emissions by implementing CCS: waste-to-energy, pulp and paper, cement, and biorefineries.

ACCSESS started in May 2021. Its consortium consists of 18 partners from eight different European countries.

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Abstract
<p>In this deliverable, we have aimed to shed light on the mechanisms driving the costs of CCS transport chains in order to guide and accelerate the development and implementation of CCS transport chains. The presented work has been divided into three parts, namely focusing on (i) deep-sea transport, (ii) inland transport, (iii) and the impact of impurities on transport.</p> <p>The first part of this report investigated the effect of CO<sub>2</sub> pressure on the costs of shipping using ships designed specifically for CO<sub>2</sub> transport as the basis in the technoeconomic analyses. Low-pressure shipping was shown to be more economical than medium-pressure shipping, especially if the current challenge of building large ships remains actual for medium-pressure ships, but not for low-pressure ones. There are opportunities to reduce the construction costs of low-pressure ships if less expensive tank materials are qualified for use at low temperatures, increasing the cost difference between low and medium pressure shipping to values beyond 30 %. The transported quantities and the ships' maximum achievable cargo capacity remain, however, some of the most important factors determining the shipping costs.</p> <p>In the second part, a technoeconomic assessment was carried out to study under which conditions transport options such as trucks, trains and barges are preferred. The analysis highlights the importance of capacity in the choice of transport vessels as the trend is towards increasing annual volumes of transported CO<sub>2</sub>. Consequently, pipelines are more economic than, in order, barges,</p>

trains and trucks at high annual volumes of CO<sub>2</sub> transported. At lower annual volumes, reuse of infrastructure such as roads and railways and lower investment costs become more important than capacity; this makes other transport options such as barges, trains and trucks economically favorable compared to pipelines. Importantly, the levelized cost of transport increases with a reduction in annual volumes. The same effect is seen on short time horizons when one assumes a delay in the availability of transport technologies such as pipelines and barges, where technology and/or infrastructure development are required, meaning that only train, truck and container-based barge transport are then available.

Finally, the third part investigated the impact of impurities in the CO<sub>2</sub> mixture on the transport chains, focusing on liquid CO<sub>2</sub> transport. We showed that non-condensable impurities have a large impact on the properties of the CO<sub>2</sub> mixture. Simultaneously, there are possibilities for optimizing the levels of non-condensable impurities to reduce the costs of post-capture purification while avoiding excessive costs in the transport chains. Similar opportunities were not observed in the case of water impurities. Thus, we conclude that further work on impurity levels for CO<sub>2</sub> mixtures should be focused on non-condensable impurities.

Together, part I and II highlight that large-scale transport chains must be realized alongside large-scale capture and storage to drastically reduce the costs of CCS value chains. To enable cost-efficient large-scale transport, early deployment of pipeline networks and low-pressure shipping is important. Simultaneously, optimizing the content of non-condensable impurities in the CO<sub>2</sub> mixture can reduce the costs across the CCS value chains. This can accelerate the deployment of large-scale CO<sub>2</sub> capture, which makes accessible the quantities of CO<sub>2</sub> necessary to further reduce the unitary costs of the CCS transport chains.

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# 1 INTRODUCTION

Carbon capture and storage (CCS) is a key technology to reach the ambitious target of net-zero emissions by 2050 set forth by the EU. Trajectories for CO<sub>2</sub> emissions worldwide reveal that we must capture, transport and store 230-430 MtCO<sub>2</sub>/yr by 2030 and 930-1200 MtCO<sub>2</sub>/yr by 2050 in Europe only to reach the net-zero target [1]. This involves an upscaling of CCS of a factor larger than 10 in the coming years [2]. Up to now, the implementation of CCS has not followed the trajectory required to meet the targets. Steps are made to intensify carbon capture and storage through carbon taxation (e.g. Emission Trading System) and the Net Zero Industry Act. Transport of CO<sub>2</sub>, on the other hand, has received less focus and is lagging behind the development of capture and storage. Nonetheless, the CO<sub>2</sub> transport is equally important for an accelerated implementation of CCS [3].

The EU H2020 project ACCSESS addresses the gap between capture and storage, and transport value chains by providing flexible and cost-efficient solutions for the complete CCS value chain from capture in European industries to permanent storage in the North Sea. Work package 11, "Enabling technologies for CCS chains", targets the transport chain in particular, investigating the potential for cost reductions in the CO<sub>2</sub> transport chain (e.g. through lower transport pressure) compared to the pioneering transport chains studied in WP9 in the ACCSESS project, and de-risking technical barriers associated with these improvements. Specifically, the objectives of WP11 are to:

- *Identify feasible, safe, and cost-efficient CO<sub>2</sub> transport solutions with the potential to reduce costs by 50%, both for inland transport (e.g. by rail, truck, river barge, etc.) as well as for coastal and large-scale deep sea ship transport*
- *Provide updated water specifications for CO<sub>2</sub> transport, specifically for low-pressure transport regimes.*
- *Understand the kinetics of potential dry ice formation and melting as CO<sub>2</sub> is handled along the transport chain.*
- *Define procedures for safe offloading/loading along the CO<sub>2</sub> transport chain.*

WP11 consists of four tasks working towards these objectives:

- *Task 11.1 CO<sub>2</sub> transport systems: Conditioning, logistics, design parameters*
- *Task 11.2 Safe, cost-efficient water specifications for CO<sub>2</sub> transport technologies*
- *Task 11.3 Dry ice formation, melting, and prevention*
- *Task 11.4 De-risking operational challenges of low-pressure containment systems and procedures for safe and reliable operations*

The work presented in this report is performed in the first two tasks of WP11, by investigating the transport value chains with the aim of identifying cost reduction measures and thereby of accelerating the deployment of CCS value chains.

## 1.1 Document Purpose

This report aims at identifying means to accelerate the deployment of CCS transport chains, including inland and deep-sea transport, by exploring ways to reduce the costs of the transport chains. One proposed measure is to move from medium to low pressure liquid CO<sub>2</sub> transport. For deep-sea transport, there are already indications to this effect, particularly in the scenarios where the annual volumes of CO<sub>2</sub> are large and the transport distances long. However, there is a lack of experience with designing and operating large-scale transport chains for CO<sub>2</sub>, which renders these cost estimates uncertain and impedes the deployment. Using new designs and construction costs of ships transporting CO<sub>2</sub> at low and medium pressure on a large scale, we are investigating and

optimizing deep-sea and inland transport chains. Thereby, we shed light on the conditions under which different transport options, whether train, truck, barge, ship or pipeline, are most economic.

Increasing the amount of allowed impurities in the captured and transported CO<sub>2</sub> is another proposed method to decrease the costs of CCS chains. This may reduce the costs of purification post-capture (and pre-transport), but can increase costs downstream in the transport chain due to corrosion or to altered operational conditions. The downstream costs are, however, highly dependent on which impurities are present in the mixture, but also on the combination of impurities. This in turn depends strongly on the emission source, capture method, and transport chain. The transport conditions influence the properties of the CO<sub>2</sub> mixture. For example, lower pressures and temperatures during transport of liquid CO<sub>2</sub> will generally decrease the solubility of impurities in the CO<sub>2</sub> mixture, which may favour corrosion. Since analysing the impact on the complete CCS value chain for all impurities and concentrations possible after capture is complex, we investigate in this report the thermodynamic limits of solubility of different impurities, under various conditions relevant to liquefaction and transport of CO<sub>2</sub>. Thus, we shed light on the critical impurities for which further purification, in addition to capture and liquefaction, may be needed.

## 1.2 Document structure

WP11 scopes the complete transport chain, from inland emitters to offshore permanent storage. To shed light on different measures as well as on how different measures affect different parts of the transport chains, the report is divided in three main parts:

1. Deep-sea LCO<sub>2</sub> transport
2. Inland CO<sub>2</sub> transport
3. CO<sub>2</sub>-mixture impurities' impact and criteria

The first part focuses on the deep-sea transport and the impact that lowering the pressure may have on the costs of large-scale shipping. The work presented herein is based on the scientific work performed in ACCSESS WP11, which is to be submitted as Røe, I. T., et al., *Shipping CO<sub>2</sub> at low- or mid-pressure: Revising current consensus with enhanced shipping engineering and cost knowledge*, <https://zenodo.org/communities/access>[4].

The second part discusses the optimal inland transport modalities and how these change with the transport conditions and implementation timeline. Here, the framework for the transport chains developed in WP9 is used to assess the LCO<sub>2</sub> transport. This comparison will be published and can be found in Oeuvray, P., et al., *Multicriteria assessments of inland and offshore carbon dioxide transport options*, <https://zenodo.org/communities/access>[5]. Additionally, the cost impact of lower pressure in truck transport is investigated in this second part.

The third and last part considers for the impurities the thermodynamic limits of solubility in CO<sub>2</sub> at different transport conditions. All parts include an introduction to the topic, an description of the methods used, then the results and the discussion thereof. Finally, the results of the different parts are contextualized and concluding remarks are given.

## 1.3 List of Acronyms and abbreviations

CCS	Carbon Capture and Storage
LCO <sub>2</sub>	Liquid CO <sub>2</sub>
LP	Low Pressure
PQL	P690QL2

MP  
NV  
NV Mn

Medium Pressure  
NV 9Ni/a  
NV Mn400

## 2 PART I – DEEP-SEA LCO<sub>2</sub> TRANSPORT

### 2.1 Introduction

Implementation of large-scale CO<sub>2</sub> capture and storage depends on an accelerated deployment of CO<sub>2</sub> transport solutions from the emitters to the offshore storage sites. Dense-phase pipeline transport has been intensively investigated and deemed the most cost-efficient method, particularly for high annual volumes and relatively short transport distances. However, offshore pipelines are associated with high capital costs and long implementation times [6]. Shipping of liquid CO<sub>2</sub> (LCO<sub>2</sub>) has been proposed to ease the implementation of CO<sub>2</sub> transport solutions by decreasing investment costs and deployment time compared to pipelines. This is already in operation commercially on small scales for food-grade CO<sub>2</sub>. Transport of LCO<sub>2</sub> at larger scales is also projected, e.g. in Northern Lights. Transport then occurs at medium pressure (MP), i.e. at 12-19 bar, and temperatures of -20 to -35°C. On the other hand, it has been reported that low pressure (LP) shipping will be more economical than MP shipping, particularly when the scales increase [7]. In LP shipping, LCO<sub>2</sub> is transported at 5-10 bar and -45 to -55°C, enabling larger cargo tanks compared to those for MP shipping. This reduces the costs of the cargo tanks per unit CO<sub>2</sub> transported. Furthermore, MP ships are assumed to have limited capacity compared to the LP ships because of the restriction not only on the total volume CO<sub>2</sub> the ship can contain, but also on the number of cargo tanks. Consequently, fewer ships are needed to transport the same annual volume if LP LCO<sub>2</sub> is transported rather than MP LCO<sub>2</sub>.

In Roussanaly et al., 2021 [7], both effects were observed. Yet, there are uncertainties associated with the technoeconomic assessments because the ship costs were based on literature. Due to the lack of experience with large-scale shipping of CO<sub>2</sub>, the literature values are often based on design of LNG ships, which are not necessarily representative of ships designed specifically for LCO<sub>2</sub> transport. In the ACCSESS project, Moss Maritime has contributed to closing this knowledge gap by designing and cost evaluating ships for transport of LCO<sub>2</sub>; these results can be used to compare the costs of LP versus MP shipping. The contributions from Moss Maritime include a design and cost estimate of large-scale MP ships, although not a detailed assessment of the technical feasibility of such MP ships. Thus, the maximum cargo capacity of the MP ships remains debated. Based on these contributions, we have investigated the effect of the specific designs and construction costs, as well as the MP ship capacity limit, on the overall economy of the shipping transport chains. The work will be published in [4]. Nonetheless, we will give a summary of the methodology, results and discussions in the following sections.

### 2.2 Methodology

The technoeconomic assessments presented in this part of the deliverable are based on the framework from Roussanaly et al., 2021 [7] First we will give a summary of the framework, before focusing on the ship construction costs as these are at the core of this study.

#### 2.2.1 Technoeconomic framework

The overall costs of the shipping value chain consist of multiple contributions apart from that of the actual shipping, as illustrated in Figure 2.1. Using the technoeconomic tool iCCS of SINTEF Energy, we can account for 1) liquefaction of CO<sub>2</sub>, 2) supplying terminal, including buffer storage and loading systems, 3) shipping, and 4) receiving terminal, including offloading systems, buffer storage and reconditioning.



To evaluate the impact of the shipping construction costs and capacity limits on the overall costs of the chain, we have kept steps 1, 2 and 4 identical to [7]. Further, the analyses have been simplified to consider only transport of pure CO<sub>2</sub> between harbours.

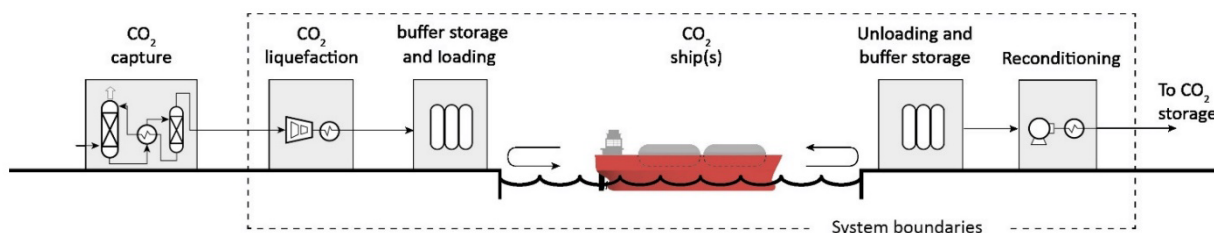


Figure 2-1 Illustration of CCS value chain with shipping-based transport between harbours along with the system boundaries used in the presented work. Adapted from Roussanaly et al., 2021 [7].

### 2.2.2 LCO<sub>2</sub> ship construction costs

Step 2 of the technoeconomic assessments where shipping is evaluated, accounts for ship investment costs as well as operational costs. The operational costs are as in [7] assumed to be 5 % of the CAPEX [7]. In Roussanaly et al., 2021, the ships' CAPEX was based on the regression curve given by Durusut and Joos, 2018 [8]. Particularly, the values for large-scale ships are based on estimations and retrofits from LNG ships which are not necessarily representative of LCO<sub>2</sub> ships. In contrast, we base the CAPEX herein on the designs and construction costs developed by Moss Maritime in the ACCSESS project for both LP and MP ships with 50 ktCO<sub>2</sub> cargo capacity. These account specifically for the conditions relevant to the LP and MP transport. The considerations include the choice of cargo tank material, geometry and configuration, which affect the ship hull design. For the MP case, the steel material P960QL2 (PQL) was chosen due to its high strength and low cost. PQL is qualified for MP LCO<sub>2</sub> transport and already in commercial use for small-scale MP transport but is not approved for LP LCO<sub>2</sub> transport due to the lower temperatures needed in the latter case. The alternative materials are more expensive, less strong, or both. There are therefore efforts to qualify PQL for LP shipping conditions in the CETO project [9], but no conclusions have been reached so far. In the meantime, the steel NV 9Ni/a (NV) was chosen for the LP tanks due to its high strength. Nevertheless, an alternative scenario using PQL as LP tank material was considered to shed light on the impact of a potential qualification of the MP materials for LP use on ship construction costs and overall transport costs of the LP transport chain.

The construction costs of the LP ship also include rates from shipyards collaborating with Moss Maritime, and thus reflect the real construction costs with 20% uncertainty. Nevertheless, ship prices generally depend on technical specifications and market conditions for the shipbuilding industry, including price fluctuations of materials and equipment, as well as financing and other aspects. Thus, prices taken from specific projects should be extrapolated with care. The construction costs of the MP 50 ktCO<sub>2</sub> ship only includes estimated shipyard costs based on the rates given for the LP ship. The reason for this is that the MP ship was not designed in detail. Importantly, this means that the technical feasibility of the ship, beyond simple considerations of e.g. buoyancy, is not verified herein. In fact, it is debated whether it is technically and mechanically feasible to construct large scale MP ships. This report does not shed further light on the technical aspects of such ships, but merely states an estimated cost of construction assuming that they are feasible.

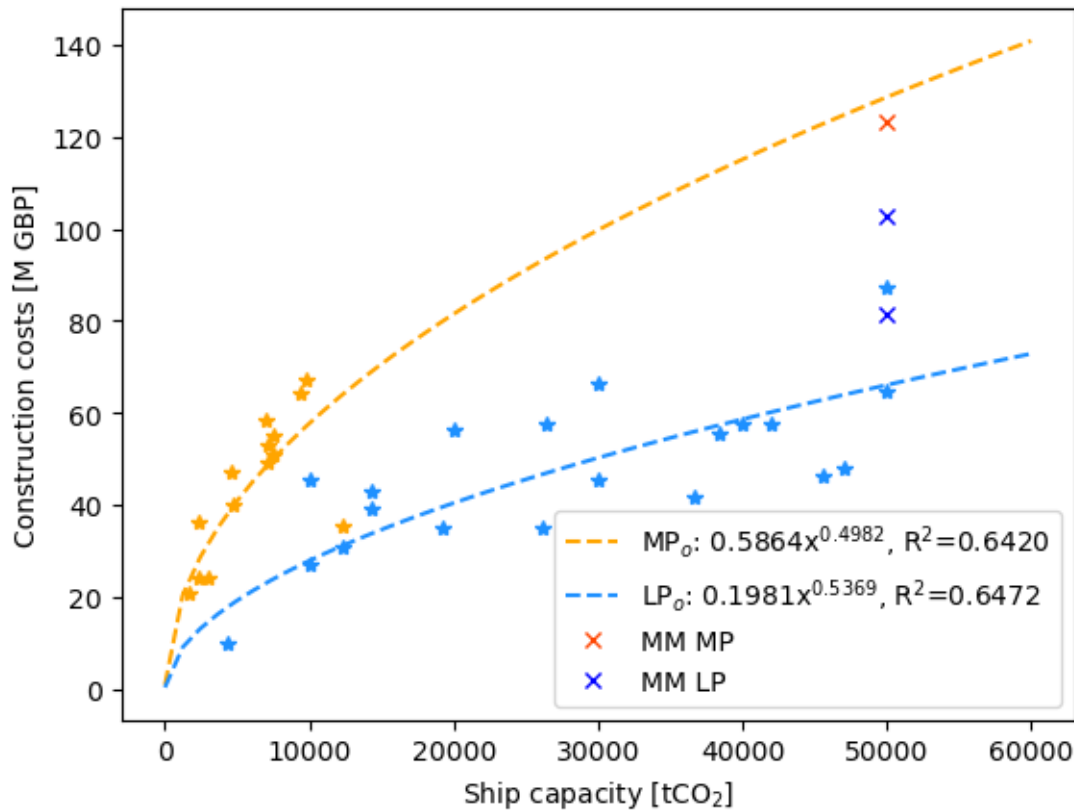


Figure 2-2 The construction costs as a function of ship capacity for LP (blue) and MP (orange) ship transport. The dotted lines are the cost curve fitted to the data points (stars) from [8]. Crosses (X) are the costs of the two LP alternatives (dark blue) and MP ship (dark orange) estimated by Moss Maritime in ACCSESS.

In Figure 2.2, the construction costs developed by Moss Maritime in this project are shown together with the literature values and the regression lines from [8]. We are assuming that the functional form of the regression,  $ax^b$ , is valid, but that the designs and costs developed by Moss Maritime are more correct for LCO<sub>2</sub> transport. Thus, new regression lines for the construction costs of MP ships, and LP ships with NV and PQL cargo tanks, respectively, were developed by keeping the exponential  $b$  at the same value as in Figure 2.2 and adjusting the coefficient  $a$  to fit the symbols for the MP and LP cases, i.e. the red and dark blue crosses, respectively. The parameters for the updated regression curves are shown in Table 1:

Table 1 The parameters in the cost regressions for LP and MP ship construction costs.

Case	a	b
MP [8]	0.5864	0.4982
MP	0.6931	0.4982
LP [8]	0.1981	0.5369
LP NV	0.3900	0.5369
LP PQL	0.3030	0.5369

The three new construction costs curves were then used to determine the CAPEX and OPEX of ships with different capacities.

### 2.2.3 Technoeconomic analysis and cases

In the present work, we perform the technoeconomic analyses using the updated construction cost regression curves. The results are compared to the technoeconomic analysis of transport of pure CO<sub>2</sub> between harbours using the construction cost curves from Durusut and Joos, 2018 [8] referred to as the base case (BC). There are two cargo tank material scenarios for the LP ships, which are evaluated in cases M<sub>NV</sub>C<sub>x</sub> and M<sub>PQL</sub>C<sub>x</sub>. In response to the recent discussion on the upper cargo capacity limit of the MP ships, three scenarios for the MP ship capacities, at 10, 15 and 30 ktCO<sub>2</sub>/ship, were evaluated. The cargo capacity of the LP ships was kept at 50 ktCO<sub>2</sub>/ship for all cases as in Roussanaly et al., 2021. An overview of the different scenarios is provided in Table 2. We notice that the upper bound of the MP ship cargo capacity was restricted to 30 ktCO<sub>2</sub>/ship based on discussions with the stakeholders within ACCSESS on the technical feasibility of such large-scale MP ships.

Table 2 The scenarios evaluated in the presented study.

Scenario	CO <sub>2</sub> conditions after capture			Tank material scenario		Maximum ship cargo capacity (ktCO <sub>2</sub> /ship)	
	CO <sub>2</sub> purity (%)	Pressure (bara)	Temperature (°C)	LP	MP	LP	MP
BC	100	1	40	(Durusut & Joos, 2018)(Durusut & Joos, 2018)	(Durusut & Joos, 2018)(Durusut & Joos, 2018)	50	10
M <sub>NV</sub> C <sub>10</sub>	100	1	40	NV 9Ni/a	P960QL2	50	10
M <sub>NV</sub> C <sub>15</sub>	100	1	40	NV 9Ni/a	P960QL2	50	15
M <sub>NV</sub> C <sub>30</sub>	100	1	40	NV 9Ni/a	P960QL2	50	30
M <sub>PQL</sub> C <sub>10</sub>	100	1	40	P960QL2	P960QL2	50	10
M <sub>PQL</sub> C <sub>15</sub>	100	1	40	P960QL2	P960QL2	50	15
M <sub>PQL</sub> C <sub>30</sub>	100	1	40	P960QL2	P960QL2	50	30

Since both transport distances and annual volumes of transported CO<sub>2</sub> impact the overall costs, ranges from 50 to 2000 km and 0.2 to 20 MtCO<sub>2</sub>/year, respectively, were considered for all cases. Furthermore, all cases of LP and MP shipping were compared to the costs of pipeline transport for the same distances and annual volumes. Details on the pipeline assessments can be found in [7].

## 2.3 Results and discussion

In this section, different scenarios of LP and MP shipping are compared to shed light on the mechanisms that impact the costs of the two transport modalities. Since the technoeconomic analyses are performed for a wide range of transport distances and annual volumes, the results are

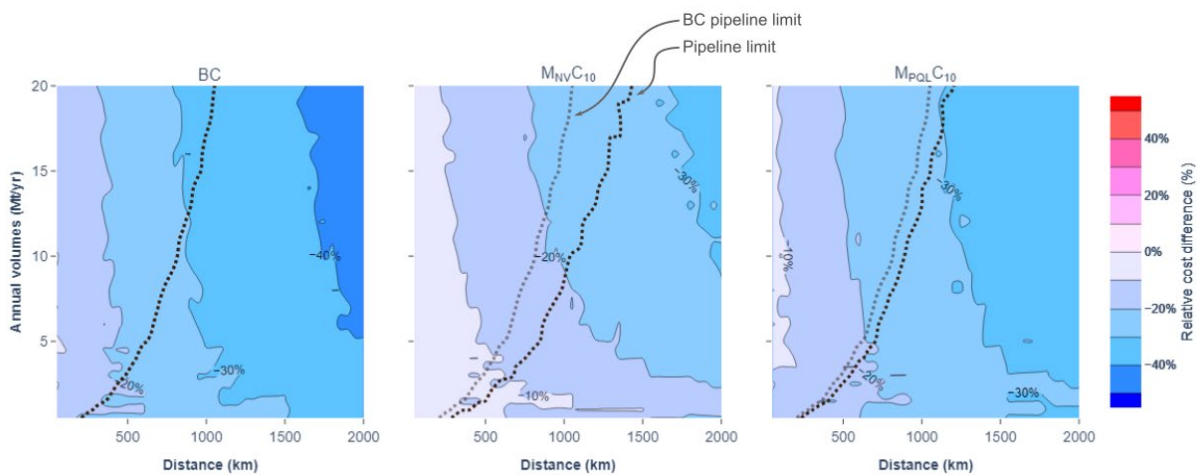
presented as a series of cost comparison maps, where the cost difference between LP and MP shipping is calculated as:

$$\delta = \frac{(cost_{LP} - cost_{MP})}{cost_{MP}}$$

The cost limits of pipeline transport relative to the LP shipping are shown as dotted lines in the cost comparison maps, meaning that in the volume-distance-region left of the lines, pipeline is more economic than LP shipping.

### 2.3.1 Impact of tank material

Figure 2.3 shows the relative costs of LP versus MP shipping using the two different construction cost curves for LP ships reported in Table 1 reflecting the cargo tank material choice. The tank materials vary from left to right from the original in Durusut and Joos, 2018 [8], the NV and the PQL. We see that both updated cost curves (middle and right) involve a decreased cost difference between LP and MP shipping compared to the base case, BC. This is because the updated construction costs exceed the original cost estimates, as depicted in Figure 2.2. Higher cost benefit will of course be achieved if the PQL material is approved for use at -55°C, but the figure shows that there is no step change cost benefit of the LP shipping depending on the qualification of PQL. That is, even if the cost of the tanks for LP shipping increases compared to the tank costs of the MP ships, LP shipping is likely to remain significantly less expensive. This is particularly true for the region where pipeline is not relevant, i.e. to the right of the brown dotted curve in the figures.



*Figure 2-3 The relative cost difference of LP and MP shipping as a function of transport distance and annual volumes CO<sub>2</sub> for (from left to right) the base case, the NV tank material and PQL tank material scenario. The MP ship capacity is 10 ktCO<sub>2</sub>/ship in all three cases. The dotted brown lines show the pipeline cost limit compared to the LP case (i.e. compared to the LP BC,  $M_{NVC10}$  and  $M_{PQLC10}$  in the left, middle and right panels, respectively). The transparent dotted lines in the middle and right panels show the pipeline cost limit compared to the LP BC. To the left of the dotted lines are the volume-distance regions where pipelines are more economic than LP shipping.*

We notice that increased LP ship construction costs reduce the cost difference more for low annual volumes than for high annual volumes, particularly for long transport distances. This is because the LP ships at 50 ktCO<sub>2</sub> capacity become more expensive to manufacture than the MP ships at 10 ktCO<sub>2</sub> capacity. When the annual volume is low, fewer ships are needed in the fleet to transport the LCO<sub>2</sub>, resulting in a smaller difference between LP and MP in total construction costs of the



fleet. The reduced fleet CAPEX at low annual volumes, increases the importance of the OPEX on the overall transport costs, which is similar for LP and MP ships, and further reduces the total transport cost difference between LP and MP shipping at low annual volumes and for long distances. Thus, the smaller the annual volume and the longer the transport distance, the more important it becomes to reduce the OPEX of the ships. For LP shipping, it becomes important to qualify less expensive materials for LP LCO<sub>2</sub> containment under these conditions.

Another aspect related to the slightly increased LP ship costs compared to the BC is that the range (in terms of transport distance and annual volumes) where the pipeline transport is beneficial over shipping increases. This is seen by the shift of the pipeline limit rightwards in the middle and right panels of Figure 2.3. In fact, when NV steel alloy is used for the LP tanks, the relative shift in the pipeline curve is up to 40%. That is for any annual volume, the maximum distance for which pipeline is still beneficial increases of 25-40% in the  $M_{NV}C_{10}$  scenario compared to BC. Since pipeline transport scales better with annual volumes, the shift becomes larger for increasing annual volumes. The  $M_{PQL}C_{10}$  scenario exhibits similar trends, but obviously the effect is less pronounced for the PQL material.

We see that LP shipping remains less expensive than MP shipping for all ranges of annual volumes and distances even if the construction costs of LP ships are higher than what has been estimated in literature. This conclusion holds also if the qualification of less expensive materials for LP LCO<sub>2</sub> containment is not obtained. Nonetheless, qualifying less expensive materials significantly increases the region where LP shipping is more economic than pipelines, and thus increases the long-term relevance of shipping.

### 2.3.2 Impact of medium pressure cargo capacity

In the previous section, the cargo capacity of the MP ships was kept at 10 ktCO<sub>2</sub>/ship in accordance with the base case, BC, and with common practice. However, this capacity limit arises from engineering and mechanical features of the ship construction and design, which have recently been questioned. Therefore, we have analysed the impact of increasing the MP ships' cargo capacity to shed light on their potential impact, should it prove to be practically possible.

Figure 2.4 shows the relative cost difference between LP and MP shipping with maximal MP ship cargo capacities of (from left to right) 10, 15 and 30 ktCO<sub>2</sub>/ship. The NV material is used for the LP tanks, and the dotted line signifies the pipeline cost limit relative to LP shipping with NV tank materials. The figure clearly shows the decrease in cost difference between the LP and MP shipping as the MP ship capacities are increased. The decrease is a consequence of the reduced number of ships needed to transport the same annual volume when the ship capacity is increased. The number of MP ships needed in the fleet is reduced, diminishing the difference between LP and MP shipping to around 10% or less in the case where the MP ship capacity is increased to 30 ktCO<sub>2</sub>/ship.

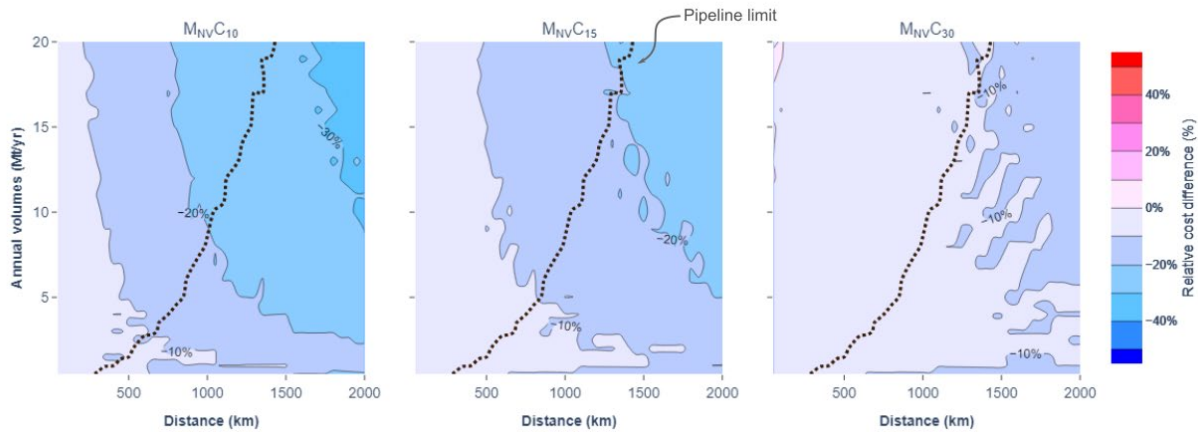


Figure 2-4 The relative cost difference of LP and MP shipping as a function of transport distance and annual volumes CO<sub>2</sub> for MP ship capacities of (from left to right) 10, 15 and 30 ktCO<sub>2</sub>/ship. The NV tank material is used in all three scenario. The dotted lines show the pipeline cost limit compared to the LP shipping scenario. To the left of the dotted lines are the volume-distance regions where pipelines are more economic than LP shipping.

Yet, the costs of LP shipping remain lower because of the lower construction costs of LP ships compared to MP ships of the same capacity, as seen in Figure 2.4. Thus, the construction costs of the ships become more important as the cargo capacities equalize. This is also illustrated in Figure 2.5, showing the cost comparison of the two LP material scenarios to the MP shipping with 30 ktCO<sub>2</sub>/ship capacities. We see that reducing the tank costs by qualifying PQL for LP shipping increases the cost difference between LP and MP shipping to more than 10 % in the region relevant for shipping (i.e. to the right of the dotted line).

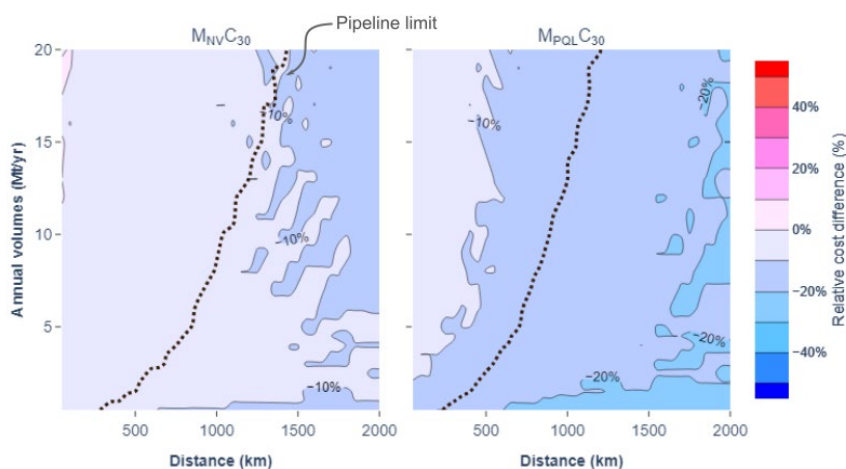


Figure 2-5 The relative cost difference of LP and MP shipping as a function of transport distance and annual volumes CO<sub>2</sub> for the NV tank material (left) and PQL tank material scenario (right) when the MP ship capacity is 30 ktCO<sub>2</sub>/ship. The dotted lines show the pipeline cost limit compared to the LP shipping scenario. To the left of the dotted lines are the volume-distance regions where pipelines are more economic than LP shipping.

## 2.4 Conclusions

In this part of the work, we have investigated how construction costs of ships designed for LCO<sub>2</sub> impact the overall costs of the shipping transport chains at low and medium pressure. The technoeconomic assessments are performed using the iCCS tool of SINTEF Energy, accounting for liquefaction, loading, offloading and buffer storage in addition to shipping. The design and cost evaluations of the large-scale LP and MP ships were performed by Moss Maritime in the ACCSESS project. Two ship construction cost scenarios have been developed for the MP ship; one assuming that only the currently qualified materials for LP CO<sub>2</sub> containment are available, and one assuming that the efforts to qualify less expensive materials are successful. In the first scenario, NV 9Ni/a was chosen for the cargo tank material, while the second assessed the P690QL2 material. Additionally, increasing the MP ship capacity beyond the 10 ktCO<sub>2</sub>/ship standard has been investigated in response to the recent questioning of the upper limit of MP ship capacities.

The technoeconomic assessments showed that the qualification of less expensive materials, such as P690QL2, is not critical for the economic benefit of LP shipping compared to MP shipping given that the MP ship capacity cannot exceed 10 ktCO<sub>2</sub>/ship. That is, although the cost difference increases in case P690QL2 is qualified for LP shipping conditions, our results show that LP ships constructed with currently available materials remain less costly than MP ships. Increasing the MP ship capacity could, however, significantly reduce the cost difference between LP and MP shipping. Nevertheless, LP shipping remains slightly less expensive even in the extreme case where 30 ktCO<sub>2</sub>/ship capacities are possible and only the current material selection for LP tanks is available.

In conclusion, the assessments presented herein show that LP shipping remains less expensive than MP shipping in all evaluated scenarios. The largest cost difference exceeds 30 % and is found for the scenario where less expensive materials are qualified for LP LCO<sub>2</sub> containment and the LP ship capacity remains five times higher than that of the MP ships. Qualification of less expensive materials for LP LCO<sub>2</sub> containment may increase the long-term relevance of shipping compared to pipeline transport, but we found that increasing the ship capacities impacts the shipping costs more than reducing the tank costs. Nonetheless, the costs of LP shipping will always be significantly smaller than those of MP shipping, except for the case where both MP ships with the same capacity as LP ships can be constructed and the qualification of LP tank materials fails. We emphasize that this work has not evaluated the technical feasibility of ships with larger cargo capacities than the current standard. Thus, this question remains open.

## 3 PART II – INLAND CO<sub>2</sub> TRANSPORT

### 3.1 Introduction

While most European storage sites are located on the northern continental shelf, many of the CO<sub>2</sub> emitters are located inland. Their access to the permanent storage sites is complicated and difficult, requiring the development of large-scale transport chains from inland locations to coastal areas with access to the infrastructure for transport to the permanent storage sites. Similar to the deep-sea transport discussed in part I, pipelines are considered to be the most cost-efficient for large-scale inland transport of CO<sub>2</sub>, but come with a high investment cost and a long implementation time [6]. Since shipping is not an alternative for inland emitters, LCO<sub>2</sub> transport on trucks, trains and barges has been suggested for accelerated implementation of transport value chains compared to value chains based on pipeline transport. Today, however, dedicated LCO<sub>2</sub> transport occurs only on trucks and trains at medium pressure (MP), i.e. at 12-19 bar (15 bar average) and at temperatures from -20 to -30°C, and on small scales with container-based transport, for use of CO<sub>2</sub> in the food and beverage industry [11]. Dedicated barge transport is to the best of our knowledge not yet operational. Neither has there been much attention on optimal designs of inland transport value chains using other transport modes than pipelines before the contributions from the ACCSESS project [3]. This is particularly true when considering multiple criteria such as technical performance, implementation horizon, reliability and scalability in addition to cost. Providing insights into how different transport options relate and should be combined to make an optimal inland transport chain is critical for early mover emitters, and an accelerated implementation of CCS. In part II of this report, we therefore first summarise the work performed within ACCSESS on the optimisation of medium pressure (MP) and pipeline inland transport chains. This work has resulted in a scientific contribution which will be published in Oeuvray, P., et. al, *Multicriteria assessments of inland and offshore carbon dioxide transport options*, <https://zenodo.org/communities/access>, and where further details on the methodology and results can be found. Secondly, we have extended the assessments to low pressure (LP) truck transport to investigate the cost impact of transitioning from the MP to LP regime for complete inland transport chains.

### 3.2 Methodology

#### 3.2.1 Technoeconomic assessment of inland transport

In the work presented in this part, the technoeconomic approach developed by ETH in connection with ACCSESS was used to evaluate the transport options. A detailed description of the technoeconomic framework can be found in Oeuvray, P., et. al, *Multicriteria assessments of inland and offshore carbon dioxide transport options*, <https://zenodo.org/communities/access>. The technoeconomic assessments are built on specific connections and quotes made for six emitters within ACCSESS and the project DemoUpCARMA:

1. ARA Bern (waste-water treatment plant in Bern, Switzerland)
2. KVA Linth (waste-to-energy plant in Niederurnen, Switzerland)
3. KVA Hagenholz (waste-to-energy plant in Zurich, Switzerland)
4. Jura Cement (cement plant in Wildegg, Switzerland)
5. Heidelberg Cement Hannover
6. Heidelberg Cement GóraŹdŹe (cement plant in GóraŹdŹe, Poland)



Three main transport categories were considered:

- Container-based transport
- Dedicated transport
- Pipeline transport

**Container-based transport** is a batch-wise solution relying on the use of an ISO tank container, referred to as *isotainer*, with capacity of approx. 20 tCO<sub>2</sub>. The isotainers can be loaded on various transport modes such as trucks, trains, barges (on rivers) and ships (on the sea), and are transferred between transport modes by the means of a crane throughout the transport chain. In contrast, **dedicated transport** relies on tanks permanently attached to specific transport vessels, such as trucks, trains, barges and ships, and transfer between modalities (e.g. from truck to train) occurs by off- and onloading of LCO<sub>2</sub>. The dedicated tanks are larger than the isotainers, with capacities of 26, 50 and 3000-5000 tCO<sub>2</sub> for truck, train and barges, respectively. Off- and onloading of LCO<sub>2</sub> requires intermediate storage capacity and possibly reconditioning. Since the isotainers act as intermediate storage tanks, a 20 % surplus of isotainers has been assumed in the assessments to ensure continuous operation of the transport chains. For the dedicated transport, however, ancillary storage tanks with a buffer time of 5 days are accounted for in each connection between transport modalities (i.e. whenever LCO<sub>2</sub> is transferred from one modality such as a truck to another such as a train). **Pipeline transport** occurs in the vapour phase at 15 to 30 bar pressure or in dense phase at 90 to 350 bar pressure. The temperature is ambient in both cases. Herein, the pipeline pressure is not determined a priori, but results from the design of each case in the technoeconomic assessment.

The cost assessment comprises (1) capital investments and (2) operational and maintenance expenses. The costs of both container-based and dedicated transport are derived from quotes obtained from service providers in 2021. As pipeline transport has been abundantly studied, the cost numbers are based on literature [12]. We notice that depending on the transport option, specific items were handled differently, such as whether to rent or to buy transport vessels, which may affect the allocation between capital and operational expenses.

The other criteria used to evaluate and to compare the technologies are given as constraints to the model. One example is the time horizon for implementation of a specific transport option; constructing a pipeline infrastructure takes more time than implementing container-based transport. Thus, on a short time horizon, pipeline transport will not be available (and thus not part of the optimisation). We notice that also the maturity level of dedicated transport is lower than the container-based, particularly for barge and ship transport, and that construction of infrastructure for intermediate storage is needed. Dedicated transport has a longer implementation time than container-based transport, although shorter than pipelines. Further details on the cost equations and constraints used in the optimisation can be found in Oeuvray, P., et. al, *Multicriteria assessments of inland and offshore carbon dioxide transport options*, <https://zenodo.org/communities/access>.

### 3.2.2 Low-pressure truck transport

To assess the potential for cost reduction by further decreasing the inland transport pressure to the low pressure (LP) region, i.e. at 5-10 bar (7 bar average) and -40 to -55 °C, we assessed the cost of truck transport in the transport chains described in the previous section. The same framework

was used for the technoeconomic assessment, but the costs of the LCO<sub>2</sub> carriers were replaced by estimations of tank geometries for LP and MP containment, calculated according to the procedures described in Appendix A.

As the tank size is limited by the truck, the size does not change from MP to LP transport. Thus, only the material selection and the wall thickness impact the tank costs. For the MP tank, the P690QL2 steel material was used for the same reasons as explained in Part I. For the LP tank, the NV Mn 400 (NV Mn) steel material was used. We notice that the material selection here is different compared to that in Part I where the NV 9Ni/a steel alloy was found most suitable. Both materials are qualified for low temperatures. The manganese alloy has lower tensile strength but is less expensive. Since the truck's tank size is smaller than the ship's, NV Mn 400 was chosen for the containment in the inland LP transport chain. Similar to Part I, the scenario where the P690QL2 is qualified for LP transport was investigated. The overall transport costs of the two scenarios of LP transport for the six emitters were calculated using the technoeconomic assessment and compared to the MP transport chain calculations described in the previous subsection. Notice that the cost data for the MP trucks collected from the service providers did not detail the different components. Consequently, the MP tank costs are deduced from material cost data and the relations between tank geometry and cost as described in Appendix A. In the assessments presented in section 3.3.2, the truck transport using updated tank costs for MP and LP tanks are used to assess the relative costs of LP compared to MP truck transport.

### 3.3 Results and discussions

#### 3.3.1 Technoeconomic assessment of inland medium pressure transport

The technoeconomic assessments are performed for specific combinations of transport options for each individual emitter. In this section, we analyse the aggregated transport costs resulting from the individual calculations. By *aggregated*, we mean that we have generalized the transport costs calculated for individual emitters and specific transport options to cases that are independent of emitters and location. That is, we have extracted each transport option in the specific chains with their belonging transport distance, annual volume and cost, and deduced the cost of that transport option as a function of distance and annual volume. *Figure 3.1* shows the aggregated cost of transport as a function of transport distance and annual volumes for short, medium and long time-horizons and scenarios without and with waterway accessibility. Offshore transport is also included in the last row of *Figure 3.1*.

On the short term, we have assumed that existing infrastructure and technologies are used, and therefore only dedicated truck and container-based transport options are available. Dedicated train transport is not included in the short-term options, because train infrastructure is not available for several of the emitters studied herein, making a generalization difficult. The left row in *Figure 3.1* shows the costs of the different transport options assumed to be available. We see that waterway transport is preferred over land-based (truck and train) in most cases. This is because the barges have higher capacities than trucks and trains. Thus, fewer voyages are needed to transport the same annual volume. In other words, barges can easier access economies of scales than truck and trains, which greatly reduce the transport costs as seen in the middle compared to the top row of *Figure 3.1*. Whenever waterways are inaccessible, trains are preferred over trucks for the same reason. We notice that the costs at fixed transport distance do not change with annual volume for

container-based transport and dedicated trucks (and trains). This is because the capacity of these transport options does not allow for economies of scale.

In the medium term, dedicated trains, barges and ships are included. They are associated with higher capacities, meaning that they are economically more efficient than container-based options and dedicated trucks apart in special cases, e.g. for short transport distances or low amounts. For example, dedicated truck transport will be preferred over dedicated trains on short transport distances (up to 150 km) in chains where waterways are inaccessible as seen in the top, middle panel in *Figure 3.1*. Whenever waterways are available, barges are preferred over trains in most cases due to the higher capacity of the barges compared to the trains. We notice that the barge costs are not constant with annual volume because the barge capacity is scalable. Thus, higher capacities can be used when the annual volume is increased, reducing the costs per unit CO<sub>2</sub> transported.

On the long-term horizon, we assume that pipeline transport is established. Since the pipeline transport scales better with CO<sub>2</sub> flow rate, the other transport options are more economic only at low annual volumes. This is particularly true for the cases without waterway access. With waterway access, dedicated barges can be preferred for low to medium annual volumes since the barges have relatively high and scalable capacity.

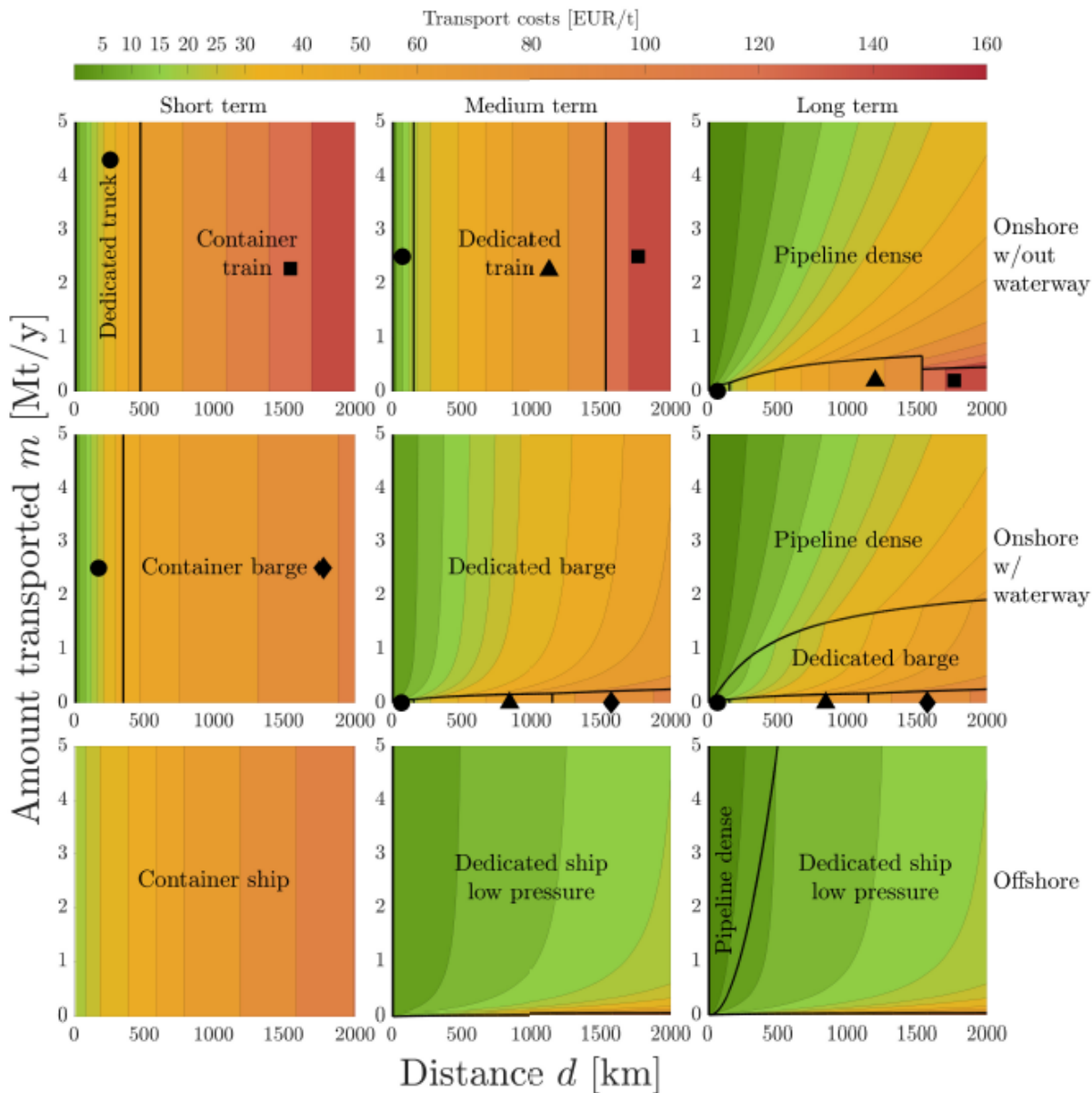


Figure 3-1 Most economical single transport option and transport cost as a function of the distance and of the CO<sub>2</sub> mass flow transported for different time horizons and terrains. Left column: short-term deployment time horizon, middle column: medium-term, right column: long-term. Upper row: onshore terrain without waterway, middle row: onshore terrain with waterway, lower row: offshore terrain. The cost-efficient transport option is directly described in the figure, unless when there is no space to write, in which case symbols are used:  $\bullet$  for dedicated truck,  $\blacksquare$  for container train,  $\blacktriangle$  for dedicated train, and  $\blacklozenge$  for container barge. From Oeuvray, P., et. al, <https://zenodo.org/communities/access> [5].

The results from the technoeconomic assessment of the inland transport chains highlight the importance of capacity on the transport vessel to reduce costs. Since different transport options inherently have different capacities, the transport costs range from, in general, trucks at the highest to pipelines at the lowest costs. Nonetheless, the inland transport chains are more complex than deep-sea shipping since not all transport options will be available everywhere, and particularly not



on the same time horizon. The presented results show how different transport options have their use on different time horizons, and for different transport distances and annual volumes.

### 3.3.2 Technoeconomic assessment of low-pressure truck transport

In part I, lowering of the transport pressure resulted in reduced shipping transport costs. To investigate if the same effect can be observed in inland transport chains, we have calculated the costs of truck transport at LP compared to MP. At low pressure, two tank steel materials are used; the NV Mn400 and the P690QL2 as described in section 3.2.2, reflecting the tank materials currently and prospectively available for LP containment. The technoeconomic calculations show that the cost difference between MP and LP truck transport is less than 1%, and therefore insignificant, independent of the transport distance and annual volumes as well as the LP tank material.

We recall from Part I that the major cost benefit of LP shipping arose from two major contributions; 1) Larger containers are possible for LP compared to MP resulting in lower cost of containment per unit CO<sub>2</sub> transported, and 2) Larger containers enable higher transport capacities on each LP ship (since the number of containers is limited) which results in better economies of scale. For truck transport, however, we cannot profit of such economies of scale. The sole cost benefit is that the LP tank can be constructed with thinner walls than the MP tanks, making them around 50 % cheaper. Since the tank costs are only a small part of the total chain cost, where the truck operational costs dominate, this benefit is diluted to less than 1% with an insignificant improvement in qualifying the P690QL2 steel for LP transport.

We remark that this analysis is only performed for dedicated truck transport. The results are expected to be similar for train transport as the constraints with respect to tank dimensions are the same, i.e. there is no room for increasing the size of the tanks and decreasing the number of tanks. The dedicated barge transport may, on the other hand, exhibit better scalability since the size of the tanks can be varied. Thus, there may be an opportunity to increase the size of the tanks for LP barges beyond what is possible for MP. If in addition, higher barge capacities can be achieved for LP barges compared to MP barges due to the reduced number of tanks required, the dedicated barge transport may show properties similar to shipping. This can decrease the cost of dedicated barge transport in the medium-term scenario shown in the middle row and column of *Figure 3.1*. Furthermore, it can increase the region in the middle right panel in *Figure 3.1* where dedicated barge transport is beneficial over pipeline transport.

## 3.4 Conclusions

In part II, we have analysed the technoeconomic implications of utilising different inland transport options such as trucks, trains, barges, and pipelines. The calculations were performed using a technoeconomic approach where not only the costs of the various transport options, but also the technology maturity and the consequent implementation timeline for six emitters in Europe were accounted for. Optimal transport value chains have been explored for each emitter, and then aggregated to shed light on techno-economics of different transport options for varying transport distances and annual volumes. Container-based and dedicated truck, train, and barge transport solutions were investigated for the inland value chains. The implementation of these options was divided into three time horizons in which the availability of the transport options differs.

On the short term, use of existing technology and infrastructure is assumed to be the only possibility, thus making the container-based transport modes most appropriate. The dedicated transport modes are, however, associated with lower costs and will replace the container-based transport modes on medium time horizons except for in special cases such as at very small annual volumes and long distances. On the long term, dense pipeline transport is expected to be the cost-effective solution, although dedicated barges will have their place in the long-term transport chains wherever waterways are available. In fact, waterway transport is in general preferred, particularly over truck and train transport, independent of time horizon.

Reducing the costs of inland transport is of course important to accelerate the implementation of CCS. Although part I shows that moving towards LP reduces the costs of deep-sea shipping, this part reveals that no significant benefits can be achieved by changing from MP to LP truck transport. We hypothesize that the barge transport may benefit more from LP solutions as higher degrees of economies of scale may be achieved. Nevertheless, facilitating construction of pipeline infrastructure for inland transport seems to be the best way to swiftly drive down the costs of inland transport.

## 4 PART III – IMPACT OF IMPURITIES AND RELATED CRITERIA

### 4.1 Introduction

The properties of the transported CO<sub>2</sub> mixture affect the transport costs. In part I and II, we have explored, amongst others, how the transport pressure affects the costs of the value chains: from high pressure pipeline transport to medium- and low-pressure liquid CO<sub>2</sub> transport. There are, however, other properties of the CO<sub>2</sub> mixture, such as corrosivity, triple point and dew line, that can affect the transport costs by e.g. increasing maintenance due to corrosion or compression demand due to changed dew line. Impurities present in the mixture are the reason for these undesirable chemical and thermodynamic properties. Normally, captured CO<sub>2</sub>, which will inevitably contain impurities, is processed and purified before entering the transport value chain. In the case of liquid CO<sub>2</sub> (LCO<sub>2</sub>) transport, this processing involves liquefaction and removal of additional impurities that are not removed during the liquefaction process. This processing can be costly. Allowing higher impurity contents has therefore been proposed as a method to reduce the costs of the CCUS value chains, but without negatively impacting the costs downstream. However, different impurities and, notably, different combinations of impurities impact the downstream value chain differently. Thus, a comprehensive view is needed to determine the cost impact of increased impurity content in the CO<sub>2</sub> mixture.

Roughly we can classify the impurities as either condensable or non-condensable. Non-condensable impurities are volatile components which, when pure, are in the vapor phase at the operating conditions. Examples include nitrogen, oxygen, argon, helium, and hydrogen. The most important condensable impurity is water, and it is a problematic impurity for several reasons. It has extremely low solubility in CO<sub>2</sub>, and an aqueous phase can thus separate out at low concentrations. The dissolved CO<sub>2</sub> in such an aqueous phase will form carbonic acid which is corrosive for carbon steel, a cheap and widely used material [13]–[16]. Water concentration must be kept low enough to avoid such corrosion. For medium-pressure (MP) and low-pressure (LP) shipping, however, the temperature is so low that the main problem is associated with the deposition of *solid* aqueous phases, such as ice or hydrates. Hydrates are solids similar to ice, but where the frozen water forms cage-like structures with interstitial, small guest molecules such as CO<sub>2</sub>. Solids can clog transfer lines [17], [18], and the accepted approach is thus to keep the water level low enough to inhibit all solids. Since hydrates are extremely stable at low temperatures, they easily form during handling of CO<sub>2</sub> for LCO<sub>2</sub> transport, where temperatures can be as low as -50°C, even if only small amounts of water are present.

Another solid phase that can occur is dry ice. The process design always ensures that temperature stays above dry ice formation temperatures, which is approximately equal to the triple point temperature of CO<sub>2</sub>, namely -56.6°C. However, in the event of a sudden pressure loss below the triple point pressure of 5.2 bar, dry ice will form due to the Joule-Thomson cooling effect. Impurities impact this issue through freezing point depression, meaning that the presence of impurities has the beneficial effect of lowering the freezing temperature [19], [20]. In practice the amount of impurities will be so small that this depression will be negligible, and as a conservative approach one designs the processes to never drop into the solid regime of pure CO<sub>2</sub>. But since the presence of more impurities generally yields a lower liquefaction temperature, this sets a thermodynamic limit on the amount of allowable impurities to ensure a safe margin from the dry ice regime.

Since impurities complicate both the analysis and the operation of CCS chains, in a start-up phase it is advisable to have strict purity requirements, although this may be not cost-optimal. This is the

strategy adopted by Northern Lights, whose CO<sub>2</sub> specification is given in Table 3 [21]. Northern Lights has opted for the MP shipping, in part due to its maturity.

*Table 3 CO<sub>2</sub> specification in the Northern Lights project [21].*

Component	Concentration (ppm)
Water	$\leq 30$
Oxygen	$\leq 10$
SO <sub>x</sub>	$\leq 10$
NO <sub>x</sub>	$\leq 10$
Hydrogen sulfide	$\leq 9$
Carbon monoxide	$\leq 100$
Amine	$\leq 10$
Ammonia	$\leq 10$
Hydrogen	$\leq 50$
Formaldehyde	$\leq 20$
Acetaldehyde	$\leq 20$
Mercury	$\leq 0.03$
Cadmium and Thallium	$\leq 0.03$ (sum)

We notice that the Northern Lights requirements are not general for all CCS value chains. The necessary purity requirements both depend on the transport options (i.e. inland pipeline transport is less sensitive to impurities than LCO<sub>2</sub> transport) and are debated [22]. Yet, the requirements of Northern Lights illustrate the conservative approach often adopted by providers of CO<sub>2</sub> transport and storage to reduce risks downstream of the capture plant. On the other hand, stricter purity requirements involve higher costs of capture and purification, in practice making the CCS technology less available, particularly to small-scale emitters. To reduce costs of the CCS value chains, and accelerate their deployment, it has been proposed to enforce higher impurity limits than those indicated e.g. by Northern Lights. Allowing higher impurity contents must be balanced by the technical and economic risks induced downstream of the capture. Arriving at general purity requirements therefore involves complex process simulations across all steps of the CCS value chain. To simplify the analyses, and as a first step, this part addresses the thermodynamic limits for the level of impurities. Assuming that liquid CO<sub>2</sub> transport will be necessary on short time horizons, in accordance with part I and II, we aim to shed light on the maximum level of impurities present in the CO<sub>2</sub> after capture and liquefaction for LP transport chains compared to MP ones. Furthermore, we analyse the impact that these impurity levels may have on the technical and economic performance of the LP and MP LCO<sub>2</sub> transport chains. Thus, we aim at highlighting the most challenging impurities and at guiding the continued investigation of impurities' impact on the CCS value chains.

## 4.2 Methodology

Thermodynamic calculations using REFPROP v.10 and the thermodynamic toolbox Thermopack [23] were performed to investigate the impact of impurities on the properties of CO<sub>2</sub>-rich mixtures, focusing on non-condensable impurities. In the case of water, hydrate formation experiments performed within the ACCSESS WP11 by Heriot-Watt University and tuned to Cubic-Plus-Association equation of state to predict the thermodynamic conditions of hydrate formation [24].

## 4.3 Results and discussions

### 4.3.1 Non-condensable impurities

In this section we analyse the impact of non-condensable impurities on the thermodynamic properties of CO<sub>2</sub> at conditions relevant for LP and MP transport, and relate these properties to the composition of the CO<sub>2</sub>-mixtures.

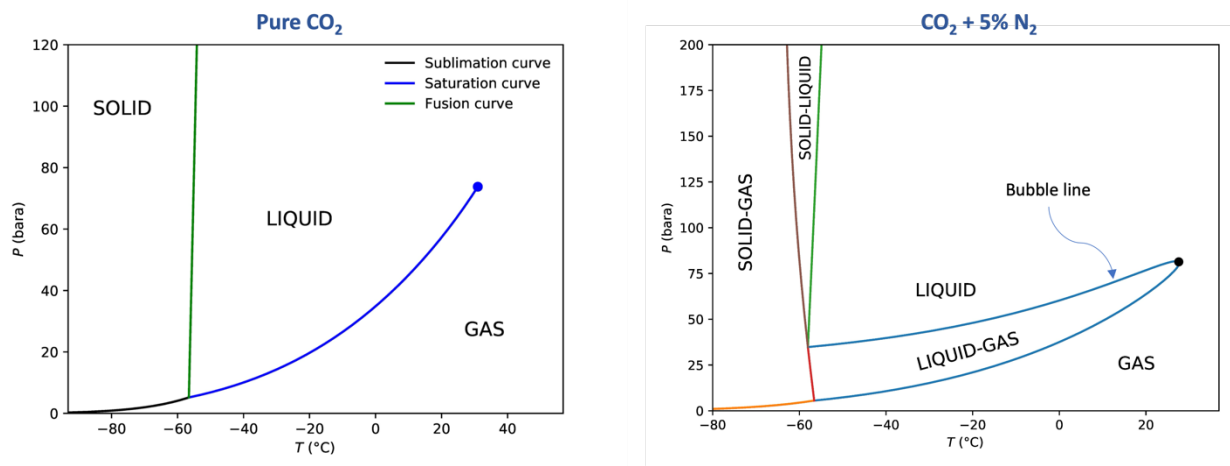


Figure 4-1 Phase diagram of pure CO<sub>2</sub> (left) and a CO<sub>2</sub>-N<sub>2</sub> mixture (right) in temperature-pressure space. Generated using REFPROP v.10.

Non-condensable impurities make a CO<sub>2</sub> stream harder to fully condense. This effect is illustrated in Figure 4-1, where the phase diagram of pure CO<sub>2</sub> changes significantly upon introducing 5 % nitrogen. Whereas the dew point line, i.e. the temperatures and pressures where a gas just begins condensing, is quite insensitive to composition, the bubble point line moves to lower temperatures and higher pressures. Note that for pure CO<sub>2</sub>, as for any pure component, the dew point line and the bubble point line coincide and correspond to the liquid-vapor equilibrium curve.

Table 4 Liquefaction temperatures for pure CO<sub>2</sub> at different pressures. The lowest pressure corresponds to the triple point.

Pressure	Liquefaction temperature	Comment
15 bar	−28.5 °C	MP transport
7 bar	−49.4 °C	LP transport
5.2 bar	−56.6 °C	Triple point

One key motivation for transporting liquid CO<sub>2</sub> at low pressures is that the tank walls can be made thinner, reducing CAPEX. However, the lower pressure is accompanied by lower temperature as seen in Table 4, inevitably increasing the cost of the liquefaction process [25].



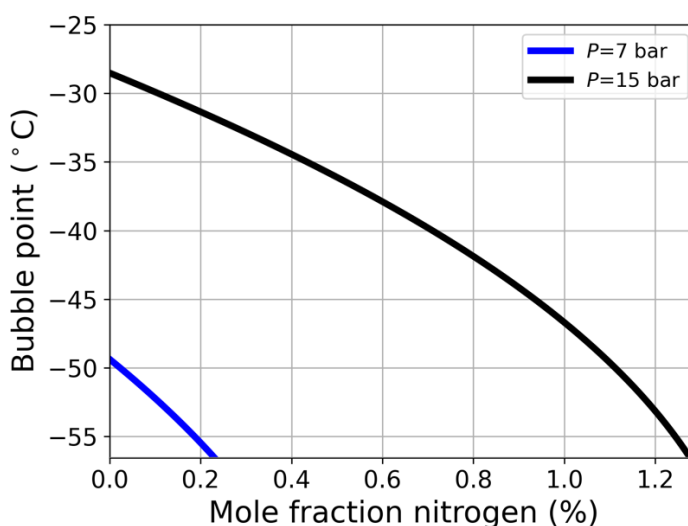


Figure 4-2 Isobaric bubble point curve of  $\text{CO}_2$ - $\text{N}_2$  mixtures at 7 bar (blue) and 15 bar (black). The mixture is fully liquid to the left of the curves, whereas a vapor phase enriched in nitrogen appears to the right of the curves.

The liquefaction temperature for a given mixture at a given pressure is thermodynamically given by the bubble point temperature. Figure 4-2 shows these bubble point temperature for  $\text{CO}_2$ - $\text{N}_2$  at LP (7 bar) and MP (15 bar). The middle column of Table 5 shows the slope at 0 % impurity, whereas the rightmost column yields the impurity level at an assumed minimum temperature of  $-52^\circ\text{C}$ . This minimum temperature incorporates a certain margin to the triple point, as recommended by the report produced by the CCUS Forum Expert Group [22].

Table 5 Thermodynamic impact of impurities on the liquefaction process at 7 bar and 15 bar, as computed from the equations of state in REFPROP. Middle column: Required lowering of liquefaction temperature (linearized) per 100 ppm of each impurity, as compared to pure  $\text{CO}_2$  (Table 4). Rightmost column: the maximum amount of an impurity assuming a lower temperature limit of  $-52^\circ\text{C}$ .

Component	Decreased liquefaction temperature (K/100 ppm)	Impurity limit (ppm)
<b>7 bar</b>		
Helium	-9.0	25
Hydrogen	-1.3	187
Nitrogen	-0.27	927
Argon	-0.20	1329
Oxygen	-0.19	1304
Carbon monoxide	-0.17	1522
Methane	-0.098	2597
<b>15 bar</b>		
Helium	-2.0	283
Hydrogen	-0.54	2382
Nitrogen	-0.14	11698
Argon	-0.11	16178
Oxygen	-0.100	16392

Carbon monoxide	-0.92	18537
Methane	-0.055	33740

Several conclusions are apparent from Table 5. First, it is clear that at 7 bar the liquefaction temperature is much more sensitive to impurities than at 15 bar. Second, different non-condensable impurities have very different effects on the required liquefaction temperature. As a rule of thumb, the lower the critical temperature of an impurity the more volatile it is and the more it reduces the liquefaction temperature. Helium, with the extremely low temperature of 5.2 K, thus has the strongest effect.

The volatile impurities will be partially removed in the liquefaction process. The last step in such a process is usually throttling down to the desired pressure, which will produce liquid CO<sub>2</sub> that is purer than the feed, as well as a vapor phase enriched in the volatile impurities. At some stage the impurities in the vapor phase will be purged to the atmosphere, together with some amount of CO<sub>2</sub>. The amount of purged CO<sub>2</sub> increases with the amount of volatile impurities present in the feed stream. If this vapor is vented to the atmosphere, the capture rate goes down, while energy consumption, footprint, and cost per ton liquefied CO<sub>2</sub> go up significantly [25].

### 4.3.2 Water

#### Hydrate formation boundaries

The amount of water present in liquified CO<sub>2</sub> must be limited to prevent water-rich phases from forming, and out of all such phases hydrates are the most challenging to predict. More specifically, what we need to predict are the *hydrate formation boundaries*, i.e. the temperatures, pressures and water concentrations at which an incipient hydrate phase first appears. This is illustrated by the contour plot in Figure 4-3. In this plot, each temperature and pressure has been assigned a color, and this color corresponds to the maximum ppm amount of water that the CO<sub>2</sub> can hold before hydrate formation. The red dotted curve shows all temperatures and pressures for which this amount is 150 ppm.

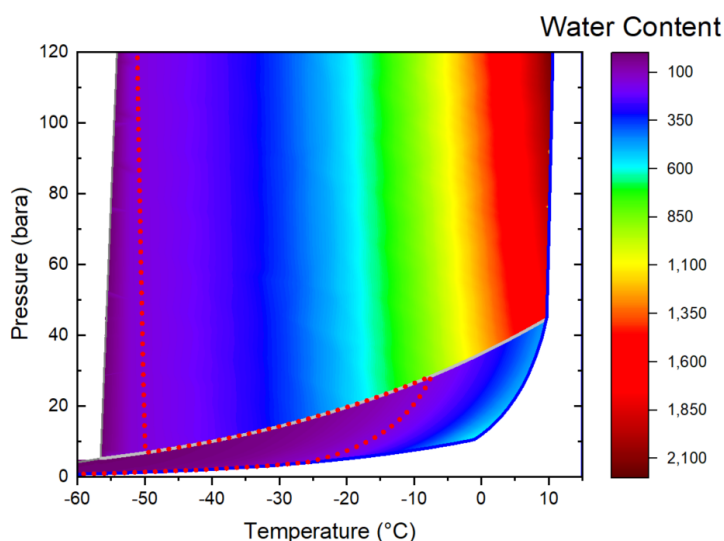


Figure 4-3 Water content (ppm) needed to form CO<sub>2</sub> hydrate calculated using the CPA equation of state – Dotted red lines: edge of hydrate stability zone for CO<sub>2</sub> with 150 ppm water. The thin

grey line is the vapor pressure curve for pure CO<sub>2</sub>. Source: Prof. Antonin Chapoy, Heriot-Watt University.

Figure 4-3 shows that ppm levels of water can result in hydrate formation, and less water is needed to form hydrate as temperature decreases. Especially notable is that, for a given temperature, a much higher water content is permissible in the liquid phase (above the grey line) than the vapor phase (below it). The implication for CCS is that, if one is able to keep the CCS stream predominantly in the liquid phase, then around 150 ppm of water is permissible at -50°C (corresponding to 7 bar shipping). The Northern Lights specifications of 30 ppm, however is necessary if a complete vaporization of (a portion of) the stream will be performed, since in that case one will be below the gray line in the figure. Clearly, having the option to vaporize the stream is prudent in the context of pioneering chains, although innovative chains can choose to relax this demand if the cost savings are significant.

### Cost reduction potential of relaxing water specifications

The key issue is therefore whether the drying of the CO<sub>2</sub> to 30 ppm induces a large cost. Molecular sieve and TEG systems are the main candidate technologies for drying. Table 6 shows indicative costs for the two technologies from a 2014 study, comparing prices from one TEG vendor and two molecular sieve vendors [26], [27].

Table 6 Cost of drying with molecular sieve and TEG systems, for a large CO<sub>2</sub> stream of 265 t/hr. [26], [27]

		Molecular Sieve			TEG
		Vendor 1	Vendor 2	Average	
CO <sub>2</sub> flow	t/h	265	265	-	265
	Mt/y	1,97	1,97	-	1,97
CAPEX	M€	1,05	2,60	-	1,60
OPEX	M€/y	0,43	1,34	-	0,71
Drying cost per ton on CO <sub>2</sub>	€/tCO <sub>2</sub>	0,27	0,80	0,53	0,44

The cost for both drying technologies is on the order of 0.5 €/t. These costs are fraction of the total cost of CCS, where a liquefaction process alone amounts to roughly 20 €/t [25]. On thermodynamic grounds this is perhaps surprising, since one expects that an increasing amount of reversible work is needed to remove an increasingly dilute impurity. However, the actual cost is also a strong function of technological maturity, and drying of process streams is of course a mature unit operation.

We emphasize that the CAPEX is indicative as it depends on a range of factors such as operating pressures, amount and types of impurities, and choice of monitoring equipment. In any case, the capital costs for drying are a minor part of the overall costs for a CCS plant [27]

A molecular sieve is quite robust to the operating conditions [27]. The optimal operating pressure is in the range 25-30 bar, but going five bar above or below this only increases costs by roughly 10%. High amounts of NO<sub>x</sub>, SO<sub>2</sub> and H<sub>2</sub>S requires use of an acid-resistance molecular sieve, but

this also increases cost by only 10%. There is no difference between the capital costs for target humidities of 550 ppmv or 10 ppmv, and it is normal to design any sieve to achieve <1 ppmv water. Drying down to these levels also reduces operational risk due to corrosive reactions, due e.g. bulk-phase reactions and adsorbed water on equipment walls.

The cost impact and the risk of relaxing water specifications of a CCS chain will be treated in further detail in an upcoming journal article.

## 4.4 Conclusions

Non-condensable impurities are detrimental to CCS efficiency for several reasons. First, they reduce the necessary liquefaction temperature, which decreases the allowable water content and yields less margin with the respect to the region of the phase diagram where dry ice may form. At 7 bar, one ppm of He reduces the necessary liquefaction temperature about 30 times more than one ppm nitrogen. Thermodynamic considerations imply that, at 7 bar, the liquefied CO<sub>2</sub> must reach a purity level of about 99.9% (1000 ppm impurities) if the impurities are nitrogen, oxygen or argon; 99.98% if it the only impurity is hydrogen, and 99.998% if it is only helium.

These volatile impurities will generally partition to the vapor phase during the isenthalpic throttling step of a liquefaction process, along with some CO<sub>2</sub>. If this vapor is purged to the atmosphere, the capture rate decreases, and the energy consumption, carbon footprint, and cost per ton liquefied CO<sub>2</sub> increases significantly. Optimizing the handling and the allowable amount of non-condensable impurities thus has a significant cost-saving potential.

As the evidence stands, relaxing water specifications from the Northern Lights specifications of 30 ppm will not save significant cost. In addition, it will increase risk since it limits the allowable operations one can apply to the streams without risking hydrate formation. Using a molecular sieve as the final drying step seems especially attractive, since it is both cheap and can dry the stream down to 1 ppm water if desired, significantly decreasing operational risk due to corrosion.

## 5 CONCLUDING REMARKS

This report has been developed in the EU H2020 project ACCSESS and has aimed at shedding light on the mechanisms driving the costs of CCS transport chains in order to guide and accelerate the development and implementation of CCS transport chains. The presented work has been divided into three parts discussing (i) deep-sea transport, (ii) inland transport, and (iii) the impact of impurities on transport, respectively.

The first part of this report investigated in particular the effect of CO<sub>2</sub> pressure on the costs of shipping using ships designed specifically for CO<sub>2</sub> transport. Low-pressure shipping was shown to be more economical than medium-pressure shipping, especially if the current challenge of building large ships remains actual for medium-pressure, but not for low-pressure ships. There are opportunities to reduce the construction costs of the low-pressure ships if less expensive tank materials are qualified for use at low temperatures, increasing the cost difference between low and medium pressure shipping. The transported quantities and the ships' maximum achievable cargo capacity remain, however, some of the most important factors determining the shipping costs.

Unsurprisingly, the technoeconomic assessment in part II on the inland transport chains also highlights the importance of capacity in the choice of transport vessels as we look towards increasing annual volumes of transported CO<sub>2</sub>. Consequently, pipelines are more economic than, in order, barges, trains and trucks at high annual volumes. At lower annual volumes, reuse of infrastructure such as roads and railways and reduced investment costs become more important than capacity and makes other transport options such as barges, trains and trucks economically favorable compared to pipelines. Importantly, the levelized costs of transport decrease with increasing annual volumes. Similarly, the transport costs increase on short compared to long time horizons when we assume a delay in the availability of transport technologies such as pipelines and barges, where technology and/or infrastructure development are required, meaning that only container-based transport is available.

Together, part I and II highlight that large-scale transport chains must be enabled alongside large-scale capture and storage to drastically reduce the costs of CCS value chains. To enable cost-efficient large-scale transport, early deployment of pipeline networks and low-pressure shipping is important. However, sufficiently high capture capacities may not be achieved unless CO<sub>2</sub> from all sorts of emitters, including those with small-scale emissions, is captured. For these emitters, transport by truck, train or barge may be important, implying that the sole focus cannot be on pipeline development, but also on how to further reduce costs in the other transport options. In this respect, and especially for small-scale emitters, increasing the amounts of allowed impurities in the CO<sub>2</sub> mixture compared to current standards is suggested. This may reduce the costs of post-capture purification and thereby reduce overall costs of CCS.

On the other hand, increasing the impurity levels may have detrimental effects downstream of the capture and of the purification steps. In the third part of this report, we discuss the technical and economic effects of increased impurity levels, focusing on water and on non-condensable impurities. We saw that while the water content may be increased, it comes at high technical uncertainties and risks downstream particularly in (low pressure) liquid transport chains. We concluded that these risks outweigh the relatively small cost reduction potential indicated for relaxed water specifications. On the contrary, we found that the levels of non-condensable impurities affect both the costs and the conditions of the CCS value chains, and that optimization of these levels could yield cost reductions across the value chain.



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## APPENDIX

### A APPENDIX A

The calculations of the required design pressure and wall thickness of storage tanks for liquid CO<sub>2</sub> containment are described in the following. In this work, cylindrical storage tanks with spherical end caps were considered. The maximum size of a single tank is limited by the CO<sub>2</sub> pressure, the tank material strength and the maximum allowed tank wall thickness. The tank design pressure for a tank of length,  $L$ , and diameter,  $D$ , is calculated as<sup>1</sup>:

$$P_{eq} = P_0 + P_{gd}$$

where  $P_0$  is the maximum overpressure. The maximum overpressure is taken as the largest of either the allowed overpressure of the tank design or the minimum vapour pressure. The minimum vapour pressure is calculated according to:

$$P_{0,min} = 0.2 + AC(\rho_r)^{1.5},$$

$$A = 0.00185 (\sigma_m / \Delta\sigma_A)^2$$

$$C = \max(D, 0.45L)$$

The liquid pressure,  $P_{gd}$ , is a function of the liquid height and the tank acceleration. It is calculated along the points of the tank perimeter considering an acceleration vector  $\mathbf{a} = a_x\mathbf{x} + a_y\mathbf{y} + (a_z+g)\mathbf{z}$ . assuming that the acceleration in the x- and y- directions are independent of one another, the liquid height can be calculated for the yz- and xz-plane for each point along the perimeter of the tank within the boundaries  $\beta \in [0, \beta_{\max}]$  as:

$$Z_{\beta-y} = z \cdot \cos\beta + y \cdot \sin\beta + \frac{D}{2}$$

$$Z_{\beta-x} = z \cdot \cos\beta + x \cdot \sin\beta + \frac{D}{2}$$

The resulting pressure was taken as the maximum liquid pressure at any point in any of the planes according to:

$$P_{gd} = \max(a_{\beta-y} \cdot Z_{\beta-y} \cdot \rho, a_{\beta-x} \cdot Z_{\beta-x} \cdot \rho)$$

where  $a_{\beta-x/y}$  and  $Z_{\beta-x/y}$  are the acceleration and corresponding liquid height in the z-x/y-plane, and  $\rho$  is the liquid density. The equilibrium pressure influences the plate thickness along with the tank diameter,  $D$ , and the tank material strength, measured through the maximum allowable stress,  $\sigma_m$  and the joint efficiency,  $v$ . The minimum plate thickness is then given for cylindrical part,  $s_{cyl}$ , and the spherical part,  $s_{sph}$ , separately.

$$s_{cyl} \geq \frac{P_{eq} \cdot D}{20 \cdot \sigma_m \cdot v + P_{eq}}$$

$$s_{sph} \geq \frac{P_{eq} \cdot D}{40 \cdot \sigma_m \cdot v + P_{eq}}$$

Here, the joint efficiency is assumed to be 1.0. For steel materials apart from nickel steel, a corrosion margin of 1 mm is added to the plate thicknesses.

<sup>1</sup> DNV-RU-SHIP Pt.5 Ch. 7