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Multi-criteria assessment of inland and offshore carbon dioxide transport options

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ABSTRACT

Transport is a key element of carbon dioxide (CO_2) capture, transport, and storage (CCTS) supply chains. Early movers, particularly inland emitters (e.g., in continental Europe), do not yet have access to a fully developed CO_2 network infrastructure connecting them with the offshore storage hubs (e.g., in the European northern seas, as these belong to the first wave of storage infrastructure that will be developed in Europe). Therefore, specific source-to-sink CCTS supply chains combining and integrating different transport options must be developed and deployed first. In this work we analyse such transport options, which include (i) tank containers that can be transported by trucks, trains, barges, or ships, (ii) dedicated tanks permanently integrated into trucks, trains, barges, or ships, and (iii) pipelines. We develop general and portable methods, criteria, and correlations to determine the cost of transport through any given connection between two nodes in a CO_2 network infrastructure, using any of the modes of transport above, as a function of distance and capacity. In particular, the correlations are based on real data collected through interviews with service providers and stakeholders. Based on the associated techno-economic assessment and the consideration of additional performance indicators of a more holistic nature, we carry out a multi-criteria assessment of the different transport options. Such multi-criteria approach allows for a holistic and transparent comparative assessment of the different alternatives for a whole CCTS supply chain, as illustrated with reference to a very specific connection.

1. Introduction and scope

The increase in the concentration of greenhouse gases caused by human activities in the atmosphere has led to unprecedented changes in the climate system (IPCC, 2021). Among greenhouse gases, carbon dioxide is the most abundant and has the largest contribution to radiative forcing (Forster et al., 2007; IPCC, 2022). From 280 ppm during the pre-industrial era, its concentration in the atmosphere rose to 410 ppm in 2021. According to the Paris Agreement, there is a necessity for a strong, rapid, and sustained reduction of greenhouse gas emissions to limit global warming and to contain the harmful effects of climate change (IPCC, 2021). Carbon capture and storage technologies belong to the portfolio of instruments needed to achieve this climate target by decarbonising hard-to-abate industry sectors and by providing negative emissions when applied to bio-energy production plants (BECCS) (IPCC, 2022; Der Bundesrat, 2022).

In Europe, most of industrial emitters are spread all over the continent, while most of the sites for permanent underground CO_2 storage are under development in the northern region, especially in and around the North Sea (see Fig. 1). Therefore, it is a key challenge for the deployment of carbon capture and storage to connect efficiently such emitters to the storage site through a dedicated transport network. Locating new CO_2 underground storage sites closer to point-source emitters may need years to succeed, thus the need for a CO_2 transport network remains. Transport of CO_2 has attracted attention only in recent years, despite its crucial role in the implementation of carbon capture, transport and storage (CCTS) technologies. In this study, the acronym CCTS will be used to underline the importance of transport for the successful deployment of carbon emissions reduction technologies.

Numerous studies have addressed the design of CCTS supply chains and networks for the long-term time horizon, focusing mostly on CO_2 transport via ship and pipeline (Bjerketvedt et al., 2022; d'Amore et al., 2021; d'Amore et al., 2021; Elahi et al., 2014; Nie et al., 2017; Kalyanarengan Ravi et al., 2017; Leonzio et al., 2019; Zhang et al., 2020; Luo et al., 2014; Alhajaj and Shah, 2020; Morbee et al., 2012; Knoope et al., 2014; Roussanaly et al., 2013, 2014, 2021). Among them, Knoope et al. (2014) have assessed the costs of gaseous phase

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Nomenclature

AIC	Annualised investment costs
AOC	Annualised operating costs
b_c	Boolean expression indicating if customs are traversed
b_{cy}	Boolean expression indicating if country cy is traversed
C_{adm}	Administration cost
C_{c}	Customs cost
C_{cg}	Congestion supplement cost
C_{dg}	Dangerous goods supplement cost
C_{el}	Electricity cost
C_{f}	Fuel cost
C_{h}	Harbour cost
$\mathrm{C}_{\text{HGVT,cy}}$	Heavy good vehicle tax (HGVT) in country cy
C_{inf}	Infrastructure cost
C_{ins}	Insurance cost
c_l	Cost of loading
c_{lab}, C_{lab}	Cost of labour
C_{lw}	Low-water supplement cost
C_M	Maintenance cost
c_{ROW}	Right-of-way cost
c_{st}	Cost of intermediate storage
$\mathrm{C}_{\text{steel}}$	Steel cost
C_{t}	Transport and service cost
C_{tax}	Vehicle tax
C_{tyr}	Tyres cost
C_{ts}	Transshipment cost
C_{w}	Weighing cost
C_{wg}	Wagon rent cost
CRF	Capital recovery factor
d	Distance (one-way)
d_{cy}	Distance (one-way) in country cy
d_{ref}	Reference distance
D_{pipe}	Pipe diameter
f	Frequency of transport
I_c	Investment cost for a carrier
I_{iso}	Investment cost for an isotainer
I_l	Investment cost for a loading station
I_{lab}	Investment cost for labour
I_{mat}	Investment cost for pipe material
I_{misc}	Investment cost for miscellaneous
I_{pump}	Investment cost for one pumping station
I_{ROW}	Investment cost for right-of-way
IC	Investment cost for a component
LC	Levelised costs
L_{pipe}	Pipe length
m_{CO_2}	Mass flow of CO_2 transported
$m^c_{\text{CO}_2}$	Mass of CO_2 transported by a carrier
m_c	Mass of the empty carrier (incl. isotainer if applicable)
m_{ref}	Reference mass flow
m_{tot}	Total mass of the carrier and CO_2 transported ($m^c_{\text{CO}_2} + m_c$)
n_c	Number of carriers
n_{iso}	Number of isotainers
n_l	Number of loading stations
n_{lab}	Number of labour forces
n_s	Number of shipments
n_{pump}	Number of pumping stations
OC	Operational cost for a component
r	Discount rate
S	Capacity
t	Duration of a roundtrip
t_l	Duration of loading
t_{op}	Operating hours within a year
UC	Unitary costs
V_{pipe}	Volume of a pipe
W_{pump}	Power capacity of a pumping station
γ_{f}	Specific fuel consumption
ϵ_{st}	Ratio of isotainers dedicated to intermediate storage
μ_{misc}	Miscellaneous cost ratio
μ_{OM}	Operation and maintenance cost ratio
ρ_{steel}	Density of steel
τ	Lifetime of a component
C_1	Set of countries with yearly HGVT
C_2	Set of countries with kilometric HGVT

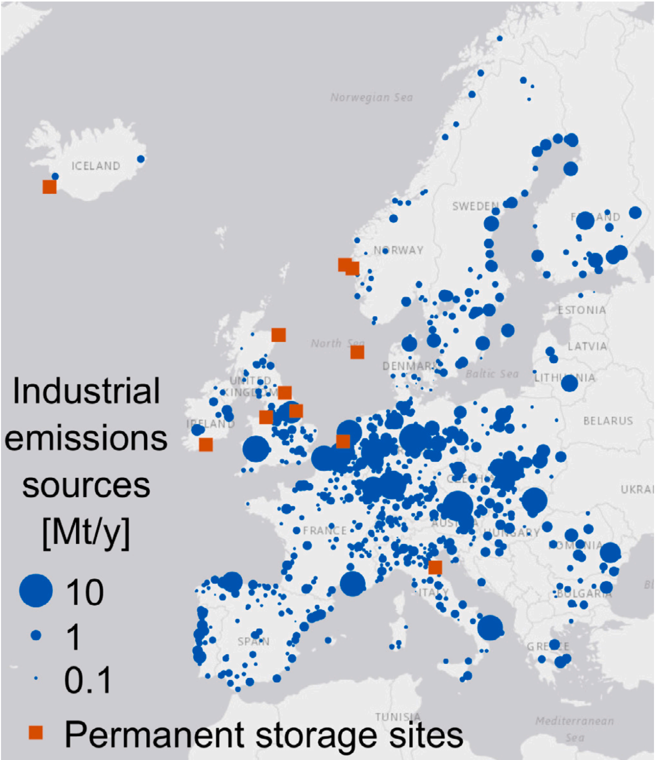

Fig. 1. Industrial hard-to-abate emission sources (chemical, food, iron and steel, manufacturing and transformation, non-ferrous metals, non-metallic minerals, pulp and paper, waste sectors) and CO_2 storage sites in operation, under development or announced in Europe (Endrava, 2022).

and dense phase pipelines on different terrains (Knoope et al., 2014). Roussanaly et al. (2013) have conducted a detailed numerical study of transport and conditioning costs of onshore and offshore CO_2 transport by ship and by dense phase pipeline for different distances and capacities (Roussanaly et al., 2013, 2014). A subsequent study has concluded that for offshore transport, pipelines are preferred for shorter

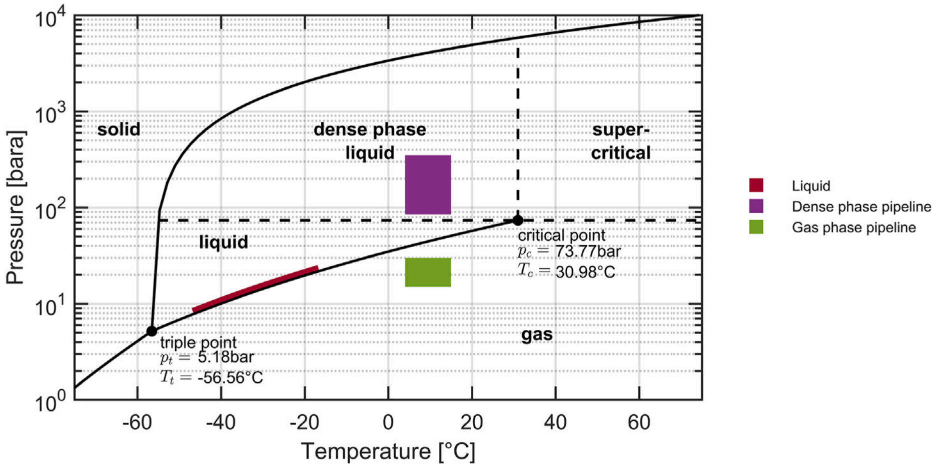

Fig. 2. Phase diagram for pure CO_2 adapted from Span and Wagner (1996). Transport conditions are represented by the red, purple and green areas for liquid, dense and gas phase, respectively.

distances and larger mass flows, while ships offer more flexibility and are thus used for transporting over longer distances but with smaller mass flows (Roussanaly et al., 2021). However, both these transport modes require years to be developed and implemented. In fact, while many projects are under development (AirLiquide, 2022; DNV, 2022; Mitsubishi, 2022; TGE, 2022; SWZ Maritime, 2022; Man Energy Solutions, 2022; Dan-Unity CO_2, 2021), there are currently no dedicated CO_2 ships with a capacity larger than 1800 t_{CO_2}, as the existing ones are mainly used for the food and beverage industry (Brownsort, 2015; Yara, 2015; Haugen et al., 2017). Similarly, CO_2 pipelines would require years to be constructed (Becattini et al., 2022). Furthermore, substantial investments are required for a pipeline network. It is therefore reasonable to assume that such a network will only be built if both storage capacity and volumes of CO_2 captured are guaranteed at the necessary scale. At the same time, emitters will only capture CO_2 if the transportation to a storage site is assured. This deployment dilemma between the different stages of the CCTS chain might make the development process unsustainably slow. Nevertheless, it is urgent to act against global warming (Pörtner et al., 2022; IPCC, 2022), and early mover emitters are willing to implement CCTS in the near-term time horizon (Brevik CCS, 2022; ACCSESS, 2021; DETEC, 2022). For these emitters, alternative transport options could be attractive as they allow to accelerate the effective start-up of CCTS projects. Beside relying on technologies available nowadays, inland emitters need solutions to transport CO_2 to the coast before having access to maritime transport. As of today, the transport of CO_2 via road or via rail has only been considered for specific applications such as BECCS or a coal power plant with post-combustion capture (Stolaroff et al., 2021; Roussanaly et al., 2017). Some studies consider additional metrics besides the techno-economic assessment, such as Becattini et al. (2022), who have studied an optimal infrastructure rollout for Switzerland considering techno-economic and environmental performance (Becattini et al., 2022) and a resilient network (Gabrielli et al., 2022). Zanobetti et al. (2023) have performed a multi-objective optimisation of economic and environmental aspects for point-to-point pipelines (Zanobetti et al., 2023). While focusing on ship transport only, Bjerketvedt et al. (2020) have studied the consequences of operational fluctuations and uncertainties on the design and expected cost of ship-based CO_2 transport for a single-source single-sink CCTS supply chain (Bjerketvedt et al., 2020). In Demir et al. (2015), a review has been conducted to examine the negative externalities of freight transportation organised by mode (road, rail, maritime, and air) in a general sense, but the study does not specifically address CO_2 transport (Demir et al., 2015).

In this article, we propose a comprehensive multi-criteria assessment of CO_2 transport options including road, railway, barge, ship, and pipeline transport. Based on data gathered in most cases directly from service providers and logistics companies, we provide a techno-economic assessment and derive correlations that can be used to evaluate the performance of each transport option for any distance and amount of CO_2 to be transported. Additionally, the technical and environmental performance, the implementation horizon, the reliability, and the scalability of the transport options are considered. The overarching goal of this study is to identify existing and future transport options, to provide a holistic comparative analysis of these options and to design promising pathways for CO_2 transport by combining the components of the supply chain and by using the portable tools provided in this study. In particular, we provide an overview of transport options for the near-term that allow for a rapid implementation, thus bridging the gap to large-scale deployment. Ultimately, this paper will benefit institutional and industrial early movers, who aim to deploy these solutions in the near, medium, or long term, as well as researchers, who want to explore quantitatively the complexity of CO_2 supply chains and their deployment.

The article is structured as follows. Section 2 introduces and describes all potential transport options for CO_2 transport. Section 3 describes the methodology used for the techno-economic assessment of the transport options and defines the criteria later used for the holistic assessment. Section 4 presents the outcomes of the techno-economic assessment and investigates the trade-offs associated with each transport option. Section 5 deals with the implementation of a supply chain for a specific case study. Finally, Section 6 summarises findings and draws conclusions.

2. Transport options

There are various options available to transport CO_2, both now and in the future. Among them, we distinguish between three main categories: (i) container-based transport, which implies the transport of CO_2 in ISO (International Organisation for Standardisation) tank containers; (ii) dedicated transport, which is based on carriers designed to transport CO_2 using tanks that cannot be removed from the carrier itself; (iii) pipeline transport, which provides a continuous transport solution.

Fig. 2 shows the phase diagram of CO_2, which indicates under which conditions CO_2 is in solid, liquid, dense, gas, or supercritical state. With the coloured regions, we identify conditions of interest for the different transport options.

As illustrated in Fig. 2, pipeline transport is possible either in the dense phase at ambient temperature and above the critical pressure of 74 bar, or in the gas phase at ambient temperature and below the vapour pressure. Note that pipeline transport is not carried out in the supercritical state, as this requires temperatures above 31 °C and consequently either insulation or heating of the pipes (Knoope et al., 2014; Zhang et al., 2012, 2006). The inlet conditions are not defined a priori, but they represent a key decision variable for the optimisation of the pipeline configuration (e.g., the inlet pressure is selected based on factors such as the distance to be covered and the pressure to be maintained upon transport), together with the pipe diameter and the steel grade. The inlet pressure is selected within the optimisation ranges indicated by the purple and green shaded areas for dense and gas phase pipeline transport, respectively. For container-based and dedicated transport, the CO_2 is transported as a liquid, indicated in red in Fig. 2. Liquid transport is carried out along the vaporisation line, as pressure and temperature increase during transport. The industry typically specifies standard loading conditions, either medium pressure or low pressure. While container-based transport is carried out at medium pressure only, dedicated transport can be done at low or medium pressure. Medium pressure requires loading at 16 bar and −27 °C, while for low-pressure transport the loading conditions are 8 bar and −46 °C. In these cases, the conditioning requirements are known.

In the following, we refer to transport mode as the method or means of transporting CO_2 from one place to another. Examples of transport modes include road, rail, inland waterway, maritime waterway, and pipeline. With transport technology, we indicate the specific technology used to transport CO_2. Examples of transport technologies can be container-based, dedicated, and pipeline. With transport option, we indicate a specific combination of transport mode, technology, and phase used to transport CO_2. Examples of transport options are container-based truck, dedicated train, low-pressure dedicated ship, or gas pipeline.

2.1. Container-based transport

The container-based transport is a batch-wise, hence discontinuous transport solution. It relies on the use of an ISO tank container (see Fig. 3), here simply referred to as ‘isotainer’, which consists of a cylindrical vacuum-insulated pressurised vessel surrounded and protected by a frame (International Tank Container Organisation (ITCO), 2011). The capacity of an isotainer is approximately 20 t_{CO_2}. It is identical in dimensions to a 20’ ISO freight container, and can be loaded onto a variety of transport modes including truck, train, barge, and ship. It can be transferred between means of transport at particular transshipment terminals. In this way, no reconditioning or intermediate storage of CO_2 is needed at transport exchanges, as the CO_2 remains within the container. Isotainer transport is a mature technology (Meeberg, 2023), which can be employed on a near-term basis. It transports CO_2 at medium pressure and can withstand a pressure of up to 22 bar. Usually, a holding time between 60 and 200 days is guaranteed by the isotainer manufacturers. It means that during this time period, the pressure increase is small enough that no release of CO_2 is necessary to avoid exceeding the maximal operating pressure.

Fig. 3. ISO tank container (TCC1, 2010).

Fig. 4. Dedicated wagons for railway transport, also known as rail tank cars (NorthWoodsHiawatha, 2007).

Certain considerations must be taken into account when using specific forms of transportation. Generally, railway, barge and ship isotainer transport is delivered by a service provider, which is considered to be the case in this study. In terms of barge transport, it can be performed on suitable inland waterways. Since the Rhine is the only river relevant to the cases studied and since the Rhine corridor accounts for more than two thirds of freight transport on inland waterways in Europe, all findings in this study are applicable to the Rhine (Kelderman et al., 2016). The transport by ship studied in this report concerns connections to Northern Europe, where the storage sites currently considered are located. Air transportation is not considered in this study as it is deemed too expensive (Prata and Arsenio, 2017) and emission intensive for a climate change mitigation effort (Horvath, 2006).

2.2. Dedicated transport

Dedicated transport options rely on tanks permanently built and attached onto specific means of transport such as trucks, trains (see Fig. 4), barges, and ships. Generally, those tanks have a larger capacity than isotainers (see Table A.8 in the *Supplementary Material*) and can transport CO_2 in liquid form at medium or low pressure depending on their design. As opposed to container-based transport, these tanks cannot be moved, such that they have to be filled or emptied in case of a transport mode exchange. This discontinuity makes intermediate storage necessary for the use of dedicated transport options. Reconditioning might also be needed in some specific transport exchanges, to cope with the different transport loading specifications. The maturity of the technologies differs: dedicated road and railway transport already exist, while dedicated barges and ships are still under development. Nonetheless, the filling process of rail tank cars for dedicated railway transport requires additional infrastructure that is possibly unavailable in a standard rail freight station. For example, in Switzerland, this process is only permitted in private railway stations due to the classification of CO_2 as dangerous good, which restricts the range of suitable stations where such goods can be handled. This could delay the implementation of dedicated railway transport in certain cases. The characteristics of the dedicated transport options such as the capacity, the loading and operating conditions, and the holding time are described in the *Supplementary Material*. It is important to note that the loading capacity of dedicated barges is limited by the water level, which fluctuates during the year. Dedicated transport options are mainly insulated with layers of polyurethane of different widths; however, they could also be vacuum insulated, as in the case of isotainers. This choice is a trade-off between an increase in holding time with a better insulation and a decrease in the available space for CO_2 within the vessel.

2.3. Pipeline

Pipelines have been thoroughly studied in several analyses (Knoope et al., 2014; Roussanaly et al., 2013, 2014; National Energy Technology Laboratory (NETL), 2022; McCoy and Rubin, 2008). This transport technology is characterised by a continuous operation mode. The CO_2 is transported at ambient temperature either as a gas or in the dense phase depending on the operating pressure. Generally, they are used to transport large volumes at low costs and can be used for long distances. However, they require a long lead time due to the planning, permitting, and construction of the infrastructure. As of 2015, about 6500 km of CO_2 pipelines existed, mainly in North America (Global CCS Institute, 2015; Knoope et al., 2013). In Europe, such long pipelines do not exist yet, one exception is the 160 km long submarine pipeline connecting the offshore Snøhvit storage site with the onshore capture facilities in the northern part of Norway (Equinor, 2023).

3. Multi-criteria approach

In this study, a multi-criteria approach is adopted to evaluate the transport options. The techno-economic assessment is presented in Section 3.1, and the other criteria metrics are introduced in Section 3.2.

The work presented in this study is based on real-world analyses that have been carried out for six representative emitters listed in Section 3.1. Those emitters are located within a certain geographical area for which it makes sense to consider storage in the vicinity of the North Sea, and can be generalised for Europe.

3.1. Techno-economic assessment

The cost evaluation presented in this study is built on specific connections and quotes that have been made for six emitters selected for potential pioneering chains within the projects DemoUpCARMA[1] and ACCSESS[2]:

(i) the wastewater treatment plant ARA Bern in Bern (CH), which separates approximately 6 kt of CO_2 yearly from methane through its biogas upgrading process. A demonstration chain currently connects it to storage in Iceland;
(ii) the waste-to-energy plant KVA Linth, located in Niederurnen (CH). It emits approximately 150 kt_{CO_2} per year. It has been chosen due to its relatively small size, its geographical interest, as there is no access to sea in Switzerland, and the willingness of the Swiss waste sector to rapidly decarbonise;
(iii) the waste-to-energy plant KVA Hagenholz in Zurich (CH). It is located within the city, thus posing a challenge for access to the point-source. Beside the readiness in the Swiss waste sector to decarbonise, its larger emissions as compared to other waste-to-energy plants – estimated to 400 kt_{CO_2} per year in the future – enable to estimate the potential economies of scale;
(iv) the cement plant Jura Cement in Wildegg (CH). With ca. 650 kt_{CO_2} per year, it is one of the largest point sources in Switzerland, and has a private railway station;

Table 1
Aspects considered for each transport option (equation numbers refer to Tables 3 and 4).

		Container-based				Dedicated				Pipeline
		Truck	Train	Barge	Ship	Truck	Train	Barge	Ship	
Capital	Isotainer	(6)	(6)	(6)	(6)					
	Intermediate storage					(7)	(7)	(7)	(8)	
	Loading stations					(9)	(9)	(9)	(10)	
	Carrier (tractor, trailer, barge, ship)	(11)				(11)		(11)	(11)	
	Pipe									(12)
	Pumping stations									(17)
Operational	Intermediate storage					(18)	(18)	(18)	(18)	
	Loading stations					(19)	(19)	(19)	(18)	
	Fuel	(20)				(20)		(20)	(20)	
	Carrier maintenance	(21)				(21)			(18)	
	Heavy goods vehicle tax	(22)				(22)				
	Labour	(23)				(23)				
	Administration, insurances, tax and infrastructure	(24)				(24)				
	Tyres	(25)				(25)				
	Transshipment		(26)	(26)						
	Weighing		(27)	(27)						
	Customs		(28)	(28)	(28)		(28)			
	Transport & service		(29)	(29)	(29)		(29)			
	Low-water supplement			(30)						
	Congestion supplement			(31)						
	Dangerous goods supplement			(32)	(32)					
	Harbours				(33)			(34)	(35)	
	Wagon rent						(36)			
	Pipe									(18)
	Pumping stations									(18) + (37)

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[1] DemoUpCARMA (Demonstration and Upscaling of CARbon dioxide MAnagement solutions for a net-zero Switzerland) is a Swiss pilot project lead by ETH Zurich. It aims at demonstrating the implementation and scale-up of pathways leading to negative emissions, among which the demonstration of the technical feasibility of using and storing CO_2 captured at a Swiss industrial site by implementing a carbon capture, transport and storage (CCTS) value chain based on CO_2 transport and permanent storage in a geological reservoir abroad (DemoUpCARMA, 2022).

[2] ACCSESS is a European project aiming at providing access to cost-efficient, replicable, safe, and flexible CCUS. One of the goals of the project is to develop and improve CCUS chains from continental Europe and the Baltic area to the North Sea (ACCSESS, 2023).

Table 2
Supporting equations for the cost calculations.

Capital recovery factor	$\mathrm{CRF}\,[-] = \dfrac{r}{1-(1+r)^{-\tau}}$	(1)
Number of shipments	$n_s\,[\mathrm{y}^{-1}] = \left\lceil \dfrac{m_{\mathrm{CO_2}}\,[\mathrm{ty}^{-1}]}{m^c_{\mathrm{CO_2}}\,[\mathrm{t}]} \right\rceil$	(2)
Number of carriers	$n_c\,[-] = \left\lceil \dfrac{n_s\,t\,[\mathrm{h}]}{t_{\mathrm{op}}\,[\mathrm{h}]} \right\rceil$	(3)
Number of isotainers	$n_{\mathrm{iso}}\,[-] = \left\lceil \left(n_c + \left\lceil \dfrac{m_{\mathrm{CO_2}}\,[\mathrm{ty}^{-1}]}{m^c_{\mathrm{CO_2}}\,[\mathrm{t}]\,f\,[\mathrm{y}^{-1}]} \right\rceil \right) (1+\epsilon_{\mathrm{st}}) \right\rceil$	(4)
Number of loading stations	$n_l\,[-] = \left\lceil \dfrac{n_s\,t_l\,[\mathrm{h}]}{t_{\mathrm{op}}\,[\mathrm{h}]} \right\rceil$	(5)

(v) the Heidelberg Cement plant in Hannover (DE), which has direct railway and waterway access, emits approximately 700 $\mathrm{kt_{CO_2}}$ per year;

(vi) the Heidelberg Cement plant in Górażdże (PL), which emits 3.6 $\mathrm{Mt_{CO_2}}$ yearly, of which half is expected to be captured. It is located far from the coast and the nearby waterway is not navigable.

In Section 5, the case study based on KVA Hagenholz will be presented more in detail, highlighting the potential transport pathways for this plant.

The techno-economic assessment of each transport option is based on data and information gathered, whenever possible, directly from industry in 2021 (i.e., not covering the inflationary pressures observed since for energy and materials (Russell and Smialek, 2022)).

Assumptions. In the following, we present the main assumptions used in the analysis. For container-based transport, the isotainers can directly act as intermediate storage tanks. Therefore, we assume a 20% surplus of isotainers for each connection with a container-based transport option to ensure continuous operation. For dedicated transport, ancillary intermediate storage tanks are needed, and those are sized for a buffer time of 5 days and the specific CO_2 mass flow from the emitter. The capacity of container-based transport options as well as dedicated trucks and trains is a fixed standard value indicated by manufacturers and service providers. The size of dedicated barges, ships, and pipelines is selected within a range based on the specified CO_2 quantity and distance to be covered. For dedicated barge transport, we consider a discrete number of tanks in the hull, ranging from the smallest to the largest alternative offered by the manufacturer.

For dedicated ship transport, we use the discrete range of sizes from 2500 up to 50 000 m^3 suggested by (Roussanaly et al., 2021). As few existing industry data are available, the techno-economic assessment of dedicated ship and pipeline transport is based on literature (Roussanaly et al., 2021; Knoope et al., 2014). In both cases, the costs have been adapted to 2021 with cost indices according to the best practices (van der Spek et al., 2019). In this study, we differentiate between onshore and offshore terrain, as well as between gas phase and dense phase transport. Knoope et al. (2014) delivers a comprehensive study of all four types of pipeline transport for point-to-point pipelines, which transport CO_2 from one source to one sink, as opposed to trunk pipelines, which is a gathering system (Knoope et al., 2014). The algorithm and equations proposed by Knoope et al. have been adapted in this study as described and discussed in the *Supplementary Material*.

The cost assessment for transport comprises (i) capital investments, i.e., containment, carriers, pipes, intermediate storage, loading and pumping stations, and (ii) operational and maintenance expenses, i.e., labour, energy, infrastructure, administration, insurance and taxes, customs, material rent, specific supplements. It is worth mentioning that the allocation of expenses between capital and operational costs was determined based on the service providers' proposals. In other words, the emitter has the freedom to decide how to manage specific items. For example, a dedicated ship can be either purchased or rented. Cost equations for each transport option can be found in Table 1. Supporting equations can be found in Table 2. The equations related to capital investment can be found in Table 3, while the equations related to operational expenses are in Table 4.

For the number of isotainers described in Eq. (4), the first term is accounting for a periodical delivery, while the second term adds the number of isotainers due to lag time between two connections, which depends on the frequency at which specific connections are operated.

Supporting equations for the computation of pipeline investment and operating costs can be found in Appendix B in the *Supplementary Material.*

Cost metrics for transport. In this work, the cost of CO_2 transported is expressed as Levelised Cost (LC) per unit mass of CO_2 transported $[\mathrm{EUR\,t^{-1}_{transp}}]$:

$$\mathrm{LC} = \frac{1}{m_{\mathrm{CO_2}}}(\mathrm{AIC}+\mathrm{AOC}) = \frac{1}{m_{\mathrm{CO_2}}} \sum_{t\in\mathcal{T}} \mathrm{CRF}_t \cdot \mathrm{IC}_t + \mathrm{OC}_t \tag{38}$$

where AIC and AOC are the Annualised Investment Costs and the Annualised Operating Costs, respectively $[\mathrm{EUR\,y^{-1}}]$, $\mathcal{T}$ being the set of equations applying to a certain transport option, i.e., the equation

Table 3
List of equations for the capital expenditures as investment items.

Isotainer	$\mathrm{IC}\,[\mathrm{EUR}] = n_{\mathrm{iso}} I_{\mathrm{iso}}\,[\mathrm{EUR}]$	(6)
Intermediate storage	$\mathrm{IC}\,[\mathrm{EUR}]$ Linear inter– or extrapolation of data[a]	(7)
Intermediate storage (Roussanaly et al., 2021)	$\mathrm{IC}\,[\mathrm{EUR}] = S[\mathrm{t}]c_{\mathrm{st}}\,\left[\mathrm{EUR\,t^{-1}}\right]$	(8)
Loading stations	$\mathrm{IC}\,[\mathrm{EUR}] = n_l I_l\,[\mathrm{EUR}]$	(9)
Loading stations (Roussanaly et al., 2021)	$\mathrm{IC}\,[\mathrm{EUR}] = \dfrac{m_{\mathrm{CO_2}}\,[\mathrm{t\,y^{-1}}]c_l[\mathrm{EUR\ t^{-1}_{CO_2}}]}{\mathrm{CRF}}$	(10)
Carrier[b]	$\mathrm{IC}\,[\mathrm{EUR}] = n_c I_c\,[\mathrm{EUR}]$	(11)
Pipe (Knoope et al., 2014)	$\mathrm{IC}\,[\mathrm{EUR}] = I_{\mathrm{mat}}\,[\mathrm{EUR}] + I_{\mathrm{lab}}\,[\mathrm{EUR}] + I_{\mathrm{ROW}}\,[\mathrm{EUR}] + I_{\mathrm{misc}}\,[\mathrm{EUR}]$	(12)
Material	$I_{\mathrm{mat}}\,[\mathrm{EUR}] = V_{\mathrm{pipe}}\,[\mathrm{m^3}]\rho_{\mathrm{steel}}\,[\mathrm{kg\,m^{-3}}]\mathrm{C_{steel}}\,[\mathrm{EUR\,kg^{-1}}]$	(13)
Labour	$I_{\mathrm{lab}}\,[\mathrm{EUR}] = c_{\mathrm{lab}}\,[\mathrm{EUR\,m^{-2}}]D_{\mathrm{pipe}}\,[\mathrm{m}]L_{\mathrm{pipe}}\,[\mathrm{m}]$	(14)
Right-of-way	$I_{\mathrm{ROW}}\,[\mathrm{EUR}] = c_{\mathrm{ROW}}\,[\mathrm{EUR\,m^{-1}}]L_{\mathrm{pipe}}\,[\mathrm{m}]$	(15)
Miscellaneous	$I_{\mathrm{misc}}\,[\mathrm{EUR}] = \mu_{\mathrm{misc}}\left(I_{\mathrm{mat}}\,[\mathrm{EUR}] + I_{\mathrm{lab}}\,[\mathrm{EUR}]\right)$	(16)
Pumping stations[c] (Knoope et al., 2014)	$\mathrm{IC}\,[\mathrm{EUR}] = n_{\mathrm{pump}} I_{\mathrm{pump}}\,[\mathrm{EUR}]$	(17)

[a] The minimal size of intermediate storage is considered to be an isotainer, while there is no upper bound.

[b] For truck transport, tractor and trailer have different lifetimes and thus need to be considered separately. For dedicated barges, the investment cost is a second-degree polynomial of the barge capacity obtained from industrial data. For dedicated ships, the investment cost is a power function of the ship capacity (Roussanaly et al., 2021).

[c] A detailed equation for the investment costs for pumping stations is given in Appendix B in the *Supplementary Material.* It accounts for the lower outlet pressure required at the last pumping station.

Table 4
List of equations for the operational expenditures associated with a certain category.

Operation & maintenance	$\mathrm{OC}\ [\mathrm{EUR\,y^{-1}}] = \mu_{\mathrm{OM}} I\ [\mathrm{EUR}]$	(18)
Loading stations	$\mathrm{OC}\ [\mathrm{EUR\,y^{-1}}] = n_{\mathrm{lab}} \mathrm{C}_{\mathrm{lab}}\ [\mathrm{EUR\,y^{-1}}]$	(19)
Fuel	$\mathrm{OC}\ [\mathrm{EUR\,y^{-1}}] = n_s 2d\ [\mathrm{km}] \gamma_{\mathrm{f}}\ [\mathrm{t\,km^{-1}}] \mathrm{C}_{\mathrm{f}}\ [\mathrm{EUR\,t^{-1}}]$	(20)
Maintenance	$\mathrm{OC}\ [\mathrm{EUR\,y^{-1}}] = n_s 2d\ [\mathrm{km}] \mathrm{C}_M\ [\mathrm{EUR\,km^{-1}}]$	(21)
Heavy goods vehicle tax	$\mathrm{OC}\ [\mathrm{EUR\,y^{-1}}] = n_c \sum_{\mathrm{cy} \in \mathcal{C}_1} b_{\mathrm{cy}} \mathrm{C}_{\mathrm{HGVT,cy}}\ [\mathrm{EUR\,y^{-1}}]$ $+ n_s \sum_{\mathrm{cy} \in \mathcal{C}_2} d_{\mathrm{cy}}\ [\mathrm{km}] \left(\mathrm{C}_{\mathrm{HGVT,cy}}(m_{\mathrm{tot}}) + \mathrm{C}_{\mathrm{HGVT,cy}}(m_c) \right)\ [\mathrm{EUR\,km^{-1}}]$	(22)
Labour	$\mathrm{OC}\ [\mathrm{EUR\,y^{-1}}] = n_s t\ [\mathrm{h}] \mathrm{C}_{\mathrm{lab}}\ [\mathrm{EUR\,h^{-1}}]$	(23)
Administration, insurances, taxes, and infrastructure	$\mathrm{OC}\ [\mathrm{EUR\,y^{-1}}] = n_c \left(\mathrm{C}_{\mathrm{adm}} + \mathrm{C}_{\mathrm{ins}} + \mathrm{C}_{\mathrm{tax}} + \mathrm{C}_{\mathrm{inf}} \right)\ [\mathrm{EUR\,y^{-1}}]$	(24)
Tyres	$\mathrm{OC}\ [\mathrm{EUR\,y^{-1}}] = n_c \mathrm{C}_{\mathrm{tyr}}\ [\mathrm{EUR\,y^{-1}}]$	(25)
Transshipment	$\mathrm{OC}\ [\mathrm{EUR\,y^{-1}}] = 2 n_s \mathrm{C}_{\mathrm{ts}}\ [\mathrm{EUR}]$	(26)
Weighing	$\mathrm{OC}\ [\mathrm{EUR\,y^{-1}}] = n_s \mathrm{C}_{\mathrm{w}}\ [\mathrm{EUR}]$	(27)
Customs	$\mathrm{OC}\ [\mathrm{EUR\,y^{-1}}] = b_c f\ [\mathrm{y^{-1}}] \mathrm{C}_{\mathrm{c}}\ [\mathrm{EUR}]$	(28)
Transport & service[a]	$\mathrm{OC}\ [\mathrm{EUR\,y^{-1}}] = n_s \mathrm{C}_{\mathrm{t}}\ [\mathrm{EUR}]$	(29)
Low-water supplement	$\mathrm{OC}\ [\mathrm{EUR\,y^{-1}}] = n_s \mathrm{C}_{\mathrm{lw}}\ [\mathrm{EUR}]$	(30)
Congestion supplement	$\mathrm{OC}\ [\mathrm{EUR\,y^{-1}}] = 2 n_s \mathrm{C}_{\mathrm{cg}}\ [\mathrm{EUR}]$	(31)
Dangerous goods supplement	$\mathrm{OC}\ [\mathrm{EUR\,y^{-1}}] = n_s \mathrm{C}_{\mathrm{dg}}\ [\mathrm{EUR}]$	(32)
Harbours	$\mathrm{OC}\ [\mathrm{EUR\,y^{-1}}] = f\,[\mathrm{y^{-1}}] \mathrm{C}_{\mathrm{h}}\ [\mathrm{EUR}]$	(33)
	$\mathrm{OC}\ [\mathrm{EUR\,y^{-1}}] = n_c \mathrm{C}_{\mathrm{h}}\ [\mathrm{EUR\,y^{-1}}]$	(34)
	$\mathrm{OC}\ [\mathrm{EUR\,y^{-1}}] = 2 n_s m^c_{\mathrm{CO_2}}\ [\mathrm{t_{CO_2}}] \mathrm{C}_{\mathrm{h}}\ [\mathrm{EUR\ t^{-1}_{CO_2}}]$	(35)
Wagon rent	$\mathrm{OC}\ [\mathrm{EUR\,y^{-1}}] = n_s \left\lceil \frac{t\,[\mathrm{h}]}{24\mathrm{h\,d^{-1}}} \right\rceil \mathrm{C}_{\mathrm{wg}}\ [\mathrm{EUR\,d^{-1}}]$	(36)
Pumping stations energy[b] (Knoope et al., 2014)	$\mathrm{OC}\ [\mathrm{EUR\,y^{-1}}] = n_{\mathrm{pump}} W_{\mathrm{pump}}\ [\mathrm{MW_e}] t_{\mathrm{op}}\ [\mathrm{h}] \mathrm{C}_{\mathrm{el}}\ [\mathrm{EUR\,MWh^{-1}}]$	(37)

[a] For train transport, the cost of transport is a linear interpolation of roundtrip costs obtained from industrial data as a function of the distance.

[b] As for the pumping stations investment costs, refer to Appendix B in the *Supplementary Material* for a more detailed equation.

numerators listed in the corresponding column of Table 1. The AIC consider the costs associated with the purchase of pieces of equipment with investment costs IC [EUR], as listed in Table 3, and CRF is the capital recovery factor [-], which annualises the investment costs IC based on the interest rate r and the lifetime of the equipment τ, as described in Eq. (1) in Table 2. In a similar manner, the Annualised Operating Costs are the costs associated with the operation and maintenance of the equipment, where OC are the operating costs [$\mathrm{EUR\,y^{-1}}$], as listed in Table 4.

The Unitary Cost (UC) per unit mass of $\mathrm{CO_2}$ transported and per unit distance covered [$\mathrm{EUR\,t^{-1}_{transp}\,km^{-1}}$] are obtained by dividing the Levelised Costs by the transport distance; $\mathrm{UC} = \mathrm{LC}/d$.

3.2. Multi-criteria assessment

The goal of the multi-criteria assessment is to evaluate the performance of transport options by analysing the costs along with additional practical aspects, requirements, and repercussions described thereafter. This holistic approach including several features enables a better appraisal of the performance of the available transport options.

3.2.1. Criteria and comparison metrics

The criteria defined in this section aim to evaluate and compare transport options with each other. To this end, comparison metrics are based on the best-in-class approach, which sets the benchmark according to the highest performance in each category.

Costs. The transport options carry diverse volumes and cover different distances; hence they have to be compared based on a unitary transport cost, which includes all elements described in Section 3.1. The comparison is based on the value at a generic distance of 1000 km and mass flow of 1 Mt $\mathrm{y^{-1}}$. More information about the cost analysis is provided below.

Conditioning energy requirement. The conditioning energy requirement for a specific transport option comprises the liquefaction or the compression from capture to the specifications required by the transport phase, that is liquid, gas, or dense. It is worth noting that the conditioning energy requirement excludes the energy consumed by pumping stations along the pipelines, which is included in the transport category and the energy consumed by reconditioning units, which have not been considered.

For the liquefaction, we use the results from Roussanaly et al. (2021), while the compression energy requirement for pipeline transport in dense or gaseous phase is obtained from the data of Knoope et al. (2014).

Global warming impact (GWI). The direct and indirect greenhouse gas emissions associated with a transport option have been modelled based on the aforementioned case studies (Burger et al., 2024) and calculated with life-cycle assessment methods from the Ecoinvent database 3.8 (system model: cut-off by classification) for each specific application, accounting for leakages and empty return trips (Wernet et al., 2016). One obtains the global warming impact accounting for the infrastructure and the carrier emissions over the lifetime of the carrier. Thus, the GHG emissions reported here are not merely direct emissions but include life-cycle emissions. The values obtained contain regional differences depending on the local energy mixes and are based on conventional technologies.

Holding time. The holding time is the period during which a container can carry $\mathrm{CO_2}$ before a leakage or pressure release occurs, the latter occurring when the maximal operating pressure is reached (see also Section 2.1). In this study, we consider the holding times corresponding to the current design and insulation of transport options. A longer holding time is preferable to avoid a limitation on the geographical range on which the transport option can be used. However, for shorter connections, a longer holding time might not be required, thus resulting in lower costs due to the use of less expensive insulation and higher capacity.

Duration variability. Connection duration variability refers to the degree of variation in the potential length of time a connection can last compared to its average duration. The duration variability for a transport mode is defined as the average over all connections included in this analysis and is based on historical data. Its impact on the logistics may be critical, as it could result in delays and missed connections.

Table 5

Impact matrix based on the number of weeks per year concerned and the according loss in capacity. *Very (v.) low* affects less than 0.5% of the total yearly capacity, *low* between 0.5 and 1%, *medium* between 1 and 2%, *high* between 2 and 4%, and *very (v.) high* more than 4%.

	Duration in weeks						
Decrease in capacity [%]	<1	1–2	3–4	5–8	9–12	13–16	17–26
0–4	V. low	V. low	V. low	V. low	V. low	Low	Low
5–9	V. low	V. low	V. low	Low	Medium	Medium	High
10–14	V. low	V. low	Low	Medium	High	High	V. high
15–19	V. low	V. low	Medium	High	High	V. high	V. high
20–29	V. low	Low	Medium	High	V. high	V. high	V. high
30–49	V. low	Medium	High	V. high	V. high	V. high	V. high
⩾50	Low	Medium	V. high	V. high	V. high	V. high	V. high

Seasonal fluctuations. The seasonal fluctuations in the availability and capacity of a transport option have a major impact on the sizing of the carrier or transport fleet and intermediate storage tanks. Optimally, CO_2 should be delivered to the storage site in a regular manner. An example of delivery fluctuations is the water level of the Rhine river for barges (SRF, 2022). During dry summers, the maximum loading of barges is reduced, leading to lower capacity utilisation of each barge and potentially supply chain disrupting backlogs. The decrease in capacity due to a lower loading or a recurring delay of the connections play a role, as well as the number of weeks per year over which it happens. Table 5 shows a multidimensional matrix with the impact of seasonal fluctuations. The columns of the matrix represent the number of weeks within a year during which a transport option is affected by a seasonal fluctuation, and the rows represent the decrease in capacity caused by this fluctuation. The outcome of the matrix is the impact on the total yearly capacity.

Time horizon. The deployment time horizon gives an indication of the maturity of a technology and the time needed to deploy it, i.e., the time needed to bring a given technology into operation. In this study, we consider near-term deployment time horizon as referring to existing transport options and ongoing projects, medium-term deployment time horizon for projects under development with a lead time of less than five years, and long-term deployment time horizon for transport options that may be implemented in five years time from now.

Greenfield infrastructure needs. This criterion defines the extent to which a greenfield infrastructure is needed to implement a transport option, such as all-new constructions of loading stations, intermediate storage tanks, greenfield pipelines. Potential refurbishment of brownfield pipelines and additional rail tracks are not considered.

Economies of scale. This criterion evaluates the potential for economies of scale with an increasing volume of CO_2 transported. It comprises infrastructure and equipment sized for larger mass flows, as well as discounts on service purchases for larger mass flows.

3.2.2. Other criteria

In addition to the criteria described above, there are several other qualitative aspects to consider when selecting a suitable CO_2 transport mode. These aspects, although outside the scope of our analysis, can greatly influence the overall effectiveness and acceptability of the transportation method.

The *frequency* of transport is an important factor as it affects the reliability of the chosen option. The availability and regularity of connections between the emitter and the storage site play a key role in ensuring consistent and timely transport. This can be influenced by factors such as the number of carriers available or the operating schedule of a specific transport supplier.

The *land footprint* of the transport option should also be evaluated. With increasing demands and limited land availability (Lambin and Meyfroidt, 2011), it becomes essential to assess the overall land requirements of the chosen transport mode, considering not only the construction of greenfield infrastructure but also any existing land use conflicts.

Safety and risk procedures should be established to guarantee the safe handling of CO_2 upon transport. Safety standards must be in place for all CO_2 transport options; nonetheless, so far they have been studied in literature only for pipelines (Gale and Davison, 2004; Koornneef et al., 2010). Similarly, risk assessments should be carried out taking into account the likelihood of a risk event (e.g., a failure or an accident) as well as the severity of a risk, i.e., the amount of CO_2 that could be released which depends on the capacity of a transport option.

Resilience is a criterion that reflects how quickly a connection can be restored after a disruption (Gabrielli et al., 2022). The ability to recover and resume operations promptly after an incident, such as a pipeline rupture or a transport system failure, is crucial to guaranteeing a reliable CO_2 transport infrastructure.

Public acceptance is a vital factor for the successful implementation of CCTS projects. It can be influenced by various socio-economic, historical, cultural, institutional, infrastructural and geographical characteristics of the communities involved (Anderson et al., 2012; Heiskanen et al., 2008; Wüstenhagen et al., 2007). The proximity of the transport mode to inhabited areas, as well as the frequency of journeys, may impact public acceptance and should be taken into consideration during the decision-making process (Dütschke et al., 2016; Wallquist et al., 2012).

4. Results and discussion

The performance of the transport options introduced in Section 2 is analysed from a techno-economic perspective in Section 4.1. In Section 4.2, the multi-criteria assessment of the transport options is presented in a holistic context.

4.1. Techno-economic assessment

This section focuses on the techno-economic assessment of single transport options. First, the objective is to calculate costs as a function of the transport distance and the amount transported and to provide functional relationships. Second, we draw guidelines for the selection of a transport option for specific settings. Third, we conduct a sensitivity analysis to consider the impact of varying parameters on our results.

We particularly invite the reader to focus on comparative trends and to refer to the above-mentioned section concerning the boundaries and limitations of this study.

4.1.1. Cost assessment of transport options

In this section, we show the fitting of the data for different transport options, distances, and mass flows, we provide cost functions for each transport option, and we generalise the results by extrapolation.

Fig. 5 shows data points, fitting curves and functions, and coefficients of determination for three selected transport options: container-based truck transport, container-based train transport, and dense phase offshore pipeline transport. The p-value of the models is smaller than the pre-defined threshold of 5% in all cases, indicating that the curves closely match the observed data points and provide accurate predictions.

For the transport options with data stemming from industrial quotes, the data points refer to the specific connections assessed for the selected emitters described in Section 3.1, while for the transport options modelled according to literature (dedicated ship and pipeline), the costs have been computed for a grid of data points with distances ranging from 50 to 2000 km and mass flows ranging from 1 kt y^{-1} to 2 Mt y^{-1}. In order to obtain widely applicable results, these data points have been fitted with a range of functional forms. The goodness of fit of a functional form is evaluated using the coefficient of determination R^2_{adj}, the p-value of the model under a constant null hypothesis, and

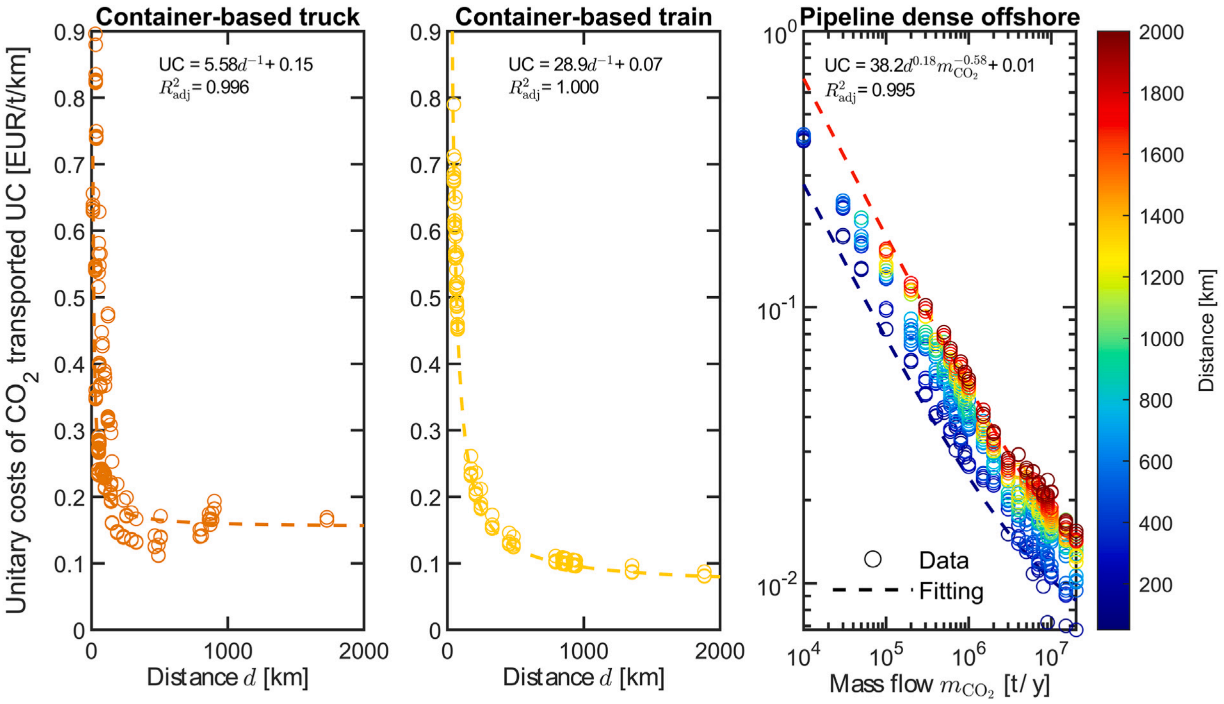

Fig. 5. Unitary cost data points and selected fitting curve as a function of the distance for container-based truck transport and container-based train transport, and of the mass flow for dense phase offshore pipeline transport. For the last plot on the right, the colour of the data points indicates the distance covered.

the p-values of the fitted coefficients. These measures are useful for determining the appropriateness of a functional form and the overall fit of the model. In case two functional forms perform equivalently for fitting the data of a certain transport option, the simplest model with the smallest number of variables has been chosen.

Table 6 describes the best functional forms for the fitting of the data points for all transport options. The fitting parameters can be found in the *Supplementary Material*.

Based on the fitting functions shown above, Fig. 6 compares the unitary costs of the different transport options by category: container-based transport, dedicated transport, and pipeline transport. The unitary costs of each transport option are plotted (on a logarithmic scale) as functions of the distance for three different CO$_2$ mass flows. It is worth noting that unitary costs of container-based transport options are independent of the mass flow; hence, there is a single plot for this category. Solid lines indicate the interpolation of data points, while dotted lines are extrapolations from the fitting. In the case of pipeline transport, the increase of labour costs for distances below 50 km is not accounted for.

The unitary costs of transport of carriers with a relatively small capacity (up to 50 t) are not influenced by the mass flow transported, but only by the distance covered. All container-based transport options as well as dedicated truck and train are thus best fitted by Eq. (39) in Table 6. Dedicated vessels both reveal a distance and a mass flow-dependency and are therefore best fitted by Eq. (40). Finally, pipeline unitary costs are mainly driven by the mass flow transported according to the fitting performed on the simulated data points grid with Eq. (41). The length of the pipeline has a relatively small influence on onshore pipelines, while it impacts more severely the unitary costs of transport for offshore pipelines. This is due to the assumption that no pumping stations are installed offshore, thus requiring larger pipeline diameters and higher pressure. It also seems counter-intuitive that offshore pipeline transport is relatively less expensive than onshore pipeline transport for short distances and small amounts. As right-of-way costs are independent of the diameter of the pipeline and thus of the mass flow, they have a significant impact in those cases. Dedicated trains are limited in their geographical range of use because of their short holding time; this explains why the corresponding curve of unitary cost is provided only up to 1500 km.

As described in Section 3.1, container-based transport costs are based on the quotes obtained for the transport of a single isotainer, thus not considering potential reductions for large transported mass flows. Those are nonetheless not expected to be high enough to significantly decrease the unitary costs of transport. It is also important to note that the frequency of transport, which is represented by the second term in Eq. (4), has a significant impact on the logistics, especially for the transport options with a low frequency such as ships. Moreover, the costs gathered for already existing transport options are based on implementation projects, while those for dedicated vessels and pipelines are based on predictions from the industry or literature.

4.1.2. Transport costs as a function of distance and volume transported

Ultimately, the selection of the most economical transport option depends on the distance and the CO$_2$ mass flow transported. The availability and accessibility of a transport option in a certain time horizon

Table 6
Fitting functions for transport options unitary costs.

Distance dependent	$\mathrm{UC}\left[\frac{\mathrm{EUR}}{\mathrm{t\,km}}\right]=\alpha_1\left[\frac{\mathrm{EUR}}{\mathrm{t\,km}}\right]+\frac{\alpha_2\,[\mathrm{EUR\,t^{-1}}]}{d[\mathrm{km}]}$	(39)
Distance and mass flow dependent	$\mathrm{UC}\left[\frac{\mathrm{EUR}}{\mathrm{t\,km}}\right]=\alpha_1\left[\frac{\mathrm{EUR}}{\mathrm{t\,km}}\right]+\frac{\alpha_2\,[\mathrm{EUR\,t^{-1}}]}{d[\mathrm{km}]}+\frac{\alpha_3\,[\mathrm{EUR\,km^{-1}\,y^{-1}}]}{m_{\mathrm{CO_2}}\,[\mathrm{t\,y^{-1}}]}$	(40)
	$\mathrm{UC}\left[\frac{\mathrm{EUR}}{\mathrm{t\,km}}\right]=\alpha_1\left[\frac{\mathrm{EUR}}{\mathrm{t\,km}}\right]+\alpha_2\left[\frac{\mathrm{EUR}}{\mathrm{t\,km}}\right]\left(\frac{d[\mathrm{km}]}{d_{\mathrm{ref}}\,[\mathrm{km}]}\right)^{\alpha_3}\left(\frac{m_{\mathrm{CO_2}}\,[\mathrm{t\,y^{-1}}]}{m_{\mathrm{ref}}\,[\mathrm{t\,y^{-1}}]}\right)^{\alpha_4}$	(41)

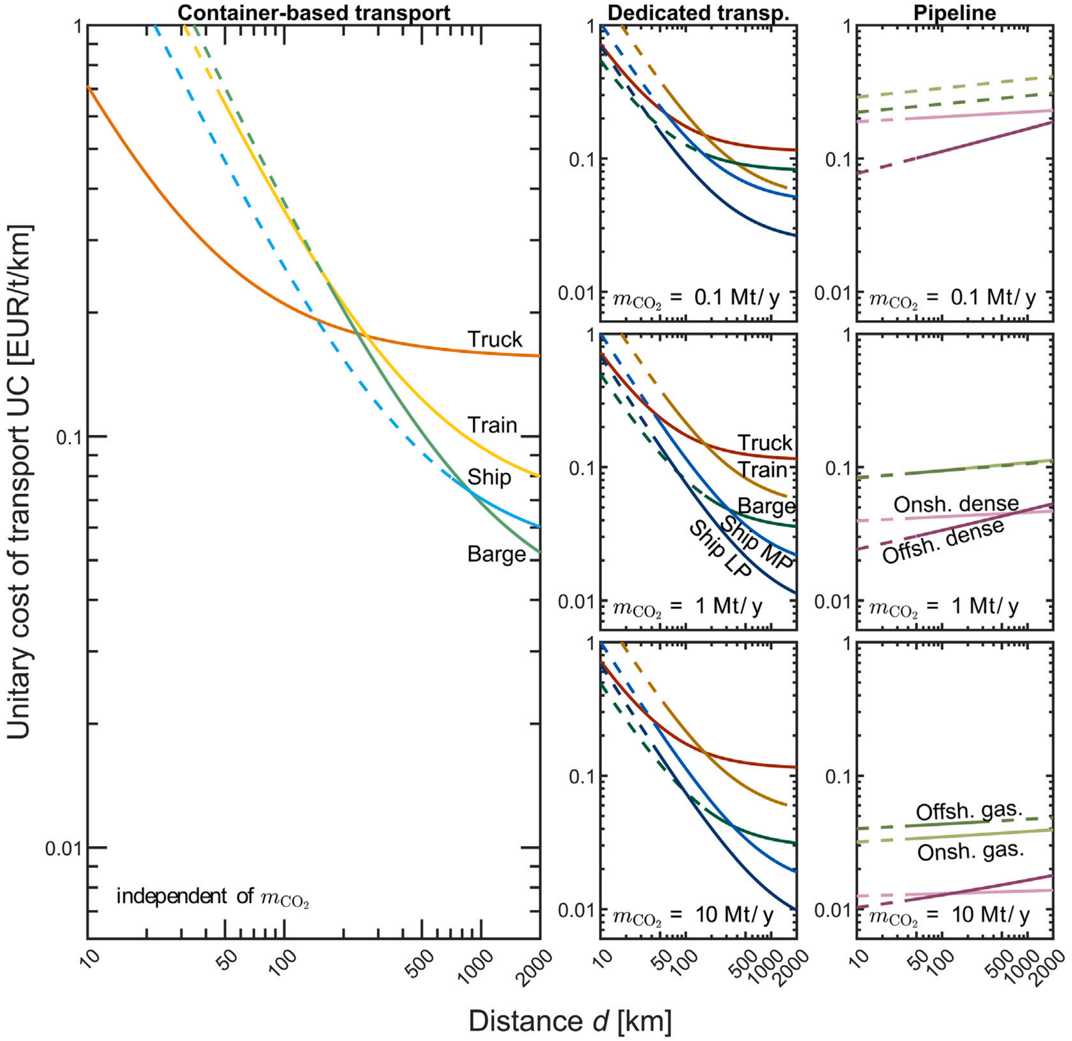

Fig. 6. Unitary cost of transport as a function of the distance. Each colour represents a different transport option, while the full lines are interpolated from selected connections, the dotted lines are extrapolations from the fitting. The left plot represents container-based transport options, the middle column dedicated transport options, and the right column pipeline transport. The unitary costs of transport are displayed for different quantities: the upper row is for $0.1\,\mathrm{Mt\,y^{-1}}$, the middle row is for $1\,\mathrm{Mt\,y^{-1}}$, and the lower row is for $10\,\mathrm{Mt\,y^{-1}}$.

and on a specific terrain will also affect such choice. Fig. 7 displays the most cost-effective transport option at a specific distance and mass flow transported. It distinguishes between near-, medium- and long-term time horizons as well as between onshore terrain with and without waterway, and offshore terrain. Note that the y-axis is upper-bounded at 5 Mt y^{-1}, as results stay unchanged above this threshold.

As already observed in Fig. 6, in the near-term, the most economical transport option depends only on the distance, and it is not affected by the mass flow transported. Onshore, dedicated truck transport is the most economical transport option for short distances, while container train and container barge are preferred for longer distances. Offshore, the only available transport option is container ship. In the medium term, the use of dedicated transport options enables a decrease in transport costs. Once again, the limitation in the range of use of dedicated railway transport requires the complementary use of container-based railway and barge transport over larger distances for relatively small mass flows. Dedicated barges are the preferred transport option whenever an inland waterway is available for larger amounts and longer distances. For offshore transport, low-pressure dedicated ship transport is the most cost-efficient transport in all cases, as suggested by Roussanaly et al. (2021). In the long-term, pipeline transport in the dense phase appears an attractive transport option, especially for the transport of large quantities. Offshore, dedicated ship remains the most economical option for smaller amounts and longer distances, which is consistent with the conclusions drawn by Roussanaly et al. (2021). While in Fig. 6, there is no indication that gaseous $\mathrm{CO_2}$ transport by pipeline is more cost-effective than dense phase transport for short distances and low mass flow rates, this trend, previously described by Knoope et al. (2014), can be partially observed in Fig. C.1 in the *Supplementary Material*. This Figure shows the costs of transport combined with the conditioning, giving a different perspective.

In practice, the topology of the terrain might induce different distances for different means of transport between two locations. Furthermore, combinations of transport options might be more appropriate for certain cases. A specific application is presented in Section 5.

4.1.3. *Sensitivity analysis*

The input data used for the techno-economic assessment are inherently uncertain; this section aims at assessing the sensitivity of the levelised costs to variations in the input data. Fig. 8 shows the impact of selected parameters on the levelised costs of transport for each transport option. It should be noted that in some cases, the impact of certain parameters in a quote cannot be accurately measured due to a lack of cost breakdown. For example, while the discount rate may affect the purchase of isotainers in container-based transport, its impact on

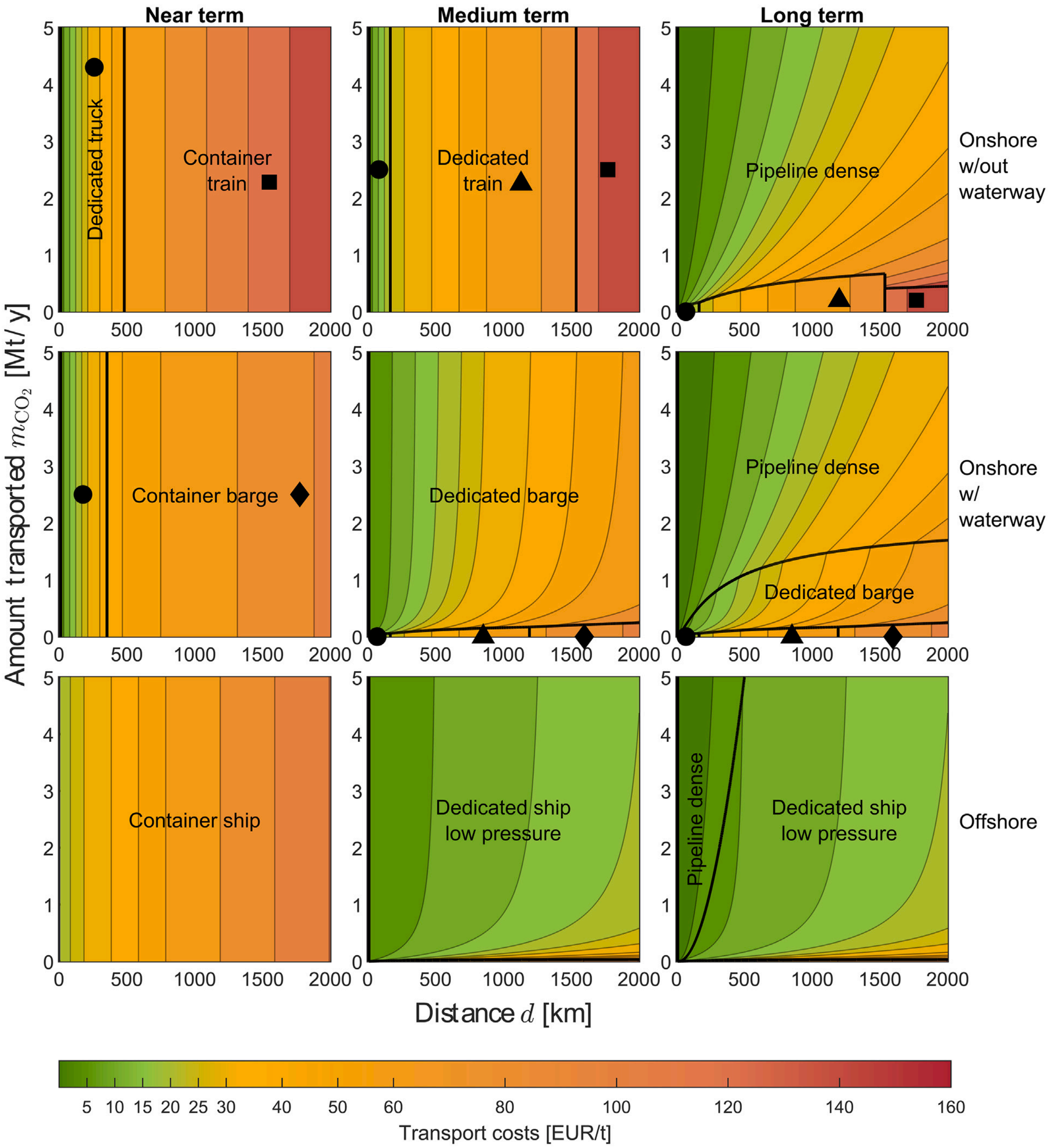

Fig. 7. Cost-effective single transport option and transport cost as a function of the distance and of the CO_2 mass flow transported for different time horizons and terrains. Left column: near-term deployment time horizon, middle column: medium-term, right column: long-term. Upper row: onshore terrain 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: • for dedicated truck, ■ for container train, ▲ for dedicated train, and ⧫ for container barge.

wagon purchases or track construction by the service provider remains uncertain and undisclosed.

In Fig. 8 we compare the influence of several parameters. For instance, a change in the discount rate would affect mainly transport options requiring a high investment, while transport options dominated by operational expenses are not strongly affected. As reference, according to Knoope et al. (2014), the levelised costs for CO_2 transport by pipeline on flat sparsely populated terrain would increase by roughly 40% if the interest rate increased by 50% (Knoope et al., 2014), which is in agreement with the results of our study. Similarly, the labour costs are an important factor for truck and pipeline transport. Regional variations in labour costs can greatly vary, e.g., being approximately double in Switzerland than the European average. As container-based transport is a modular solution, the net mass of CO_2 transported by a carrier linearly influences the number of shipments and the number of isotainers required; hence, also strongly affects the costs. The net mass of CO_2 transported by a carrier can vary depending on the remaining amount on board chosen by the operator of a supply chain, whether they choose to transport back the carrier filled only with gaseous CO_2 at equilibrium pressure, or if some liquid CO_2 is also transported back to ensure that the carrier is kept cooled. To a lesser extent, an increased velocity allows for a larger number of roundtrips per carrier and thus decreases the number of carriers required and the associated investment or renting costs. The fuel cost is an important operational

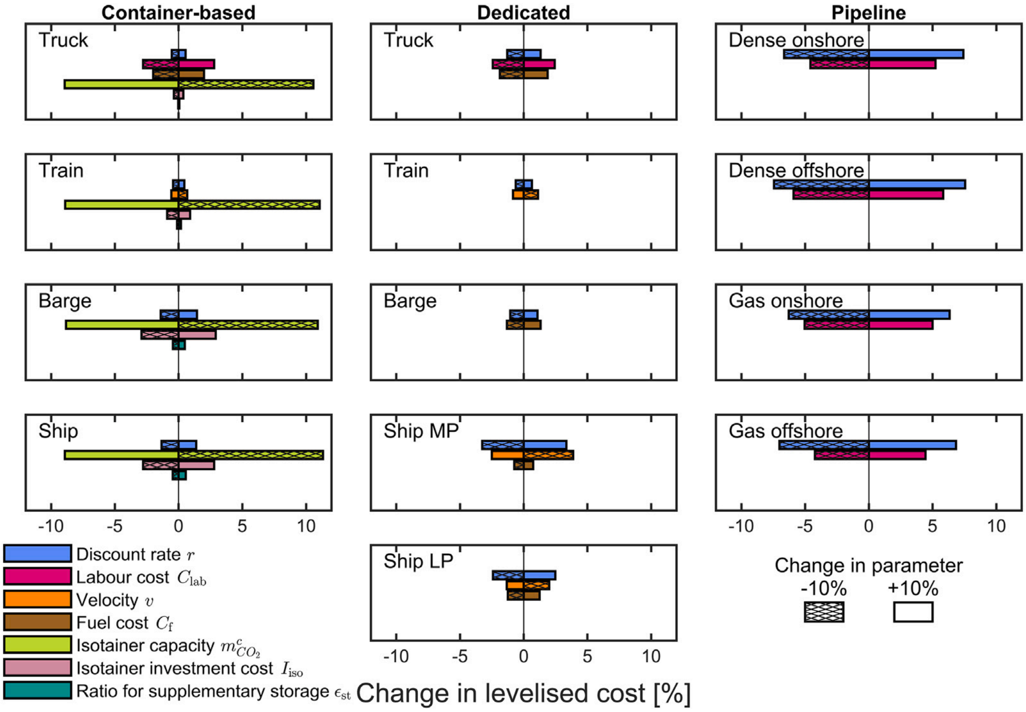

Fig. 8. Sensitivity analysis of the levelised costs of transport towards selected parameters for affected transport options.

expense for fuelled transport modes, especially for truck transport. The recent fluctuations in the price of fossil fuels have a certain impact on the transport costs for the relevant modes. Finally, we assume 20% of supplementary isotainers in this study to ensure continuity along the chain in case of delays or missed connections. In Fig. 8, one can observe that the variation of this parameter on the costs of transport is negligible.

4.2. *Multi-criteria assessment*

In the following, we assess the considered transport options through the multi-criteria approach described above (Section 3.2). The quantitative or qualitative value for each criterion is translated into a grade that rates from ++ (best-in-class) to − − (poor performance) through 0 (average). In Fig. 9, the lines represent results obtained for reference conditions, while the shaded areas indicate variability ranges. For example, for the unitary costs, the reference line describes the costs for a distance of 1000 km and an amount transported of $1\,\mathrm{Mt\,y^{-1}}$, and the shaded region describes the potential range when varying the amount between 0.1 and $10\,\mathrm{Mt\,y^{-1}}$ for the same distance. For the conditioning energy, the reference result describes the energy needed to condition pure CO_2 to the average specifications for transport in a certain physical state, and the shaded region describes the range according to an impurity scenario or to the range of potential pressures for gaseous or dense phase pipeline transport. For the global warming impact, the reference result is the impact corresponding to the average European electricity mix and/or number of isotainers, and the shaded area describes the variation that can be linked with CO_2-intensive energy mixes. These three criteria are quantitative and the scale is linear and continuous, with the limits corresponding to the rounded best and worst cases observed. The other criteria are only qualitatively assessed, hence through a single value, except if they are linked with a high uncertainty.

Since the grades in the spider graphs of Fig. 9 increase from the centre outwards, a larger polygon area indicates a better overall performance of the transport option.

Costs and economies of scale. The unitary costs have been extensively discussed in Section 4.1. Generally, the dedicated transport options are economically more competitive than container-based transport, and the development of pipeline networks will lead to a noticeable reduction of transport costs. Additionally, pipeline transport allows for substantial economies of scale, as the cost of a pipe does not increase linearly with its diameter. Dedicated vessels with large capacities such as barges and ships also exhibit significant economies of scale, whereas discontinuous transport options with limited transport capacities have little to no economies of scale, because the amount of manufactured objects increases linearly with the increasing amount of CO_2 transported.

Conditioning energy requirement. The specific conditioning energy is the lowest for compression for gas phase pipeline transport. The conditioning to the dense and liquid phases requires substantial energy, especially in the case of low-pressure transport. Potential impurities in the CO_2 stream from the capture plant lead to higher energy requirements.

Global warming impact. The global warming impact is based on conventional technologies and prevailing energy mixes, and transport can have a relative contribution of up to 40% of the GWI of a supply chain in the near-term (Burger et al., 2024). Therefore, it is important to compare the GWI of the different transport options. In the future, traditional fuels could be replaced by fuels with a smaller carbon footprint (e.g., biofuels, ammonia, hydrogen, or LNG) or by electrified systems (Herdzik, 2021; Borlaug et al., 2021; Çabukoglu et al., 2019). In parallel, energy decarbonisation is anticipated in the next years and decades, such that the GWI of all transport modes is expected to improve. Currently, the greenhouse gas emissions from trucks are the highest per unit amount transported, especially because they have the highest weight-to-payload ratio. Barges and trains exhibit an average performance, and ship transport exhibits a low global warming impact compared to other transport modes. Pipeline transport also performs well in this domain, with its impact largely dictated by the carbon intensity of electricity, resulting in significant variability among countries due to the GHG intensity of their corresponding electricity mix.

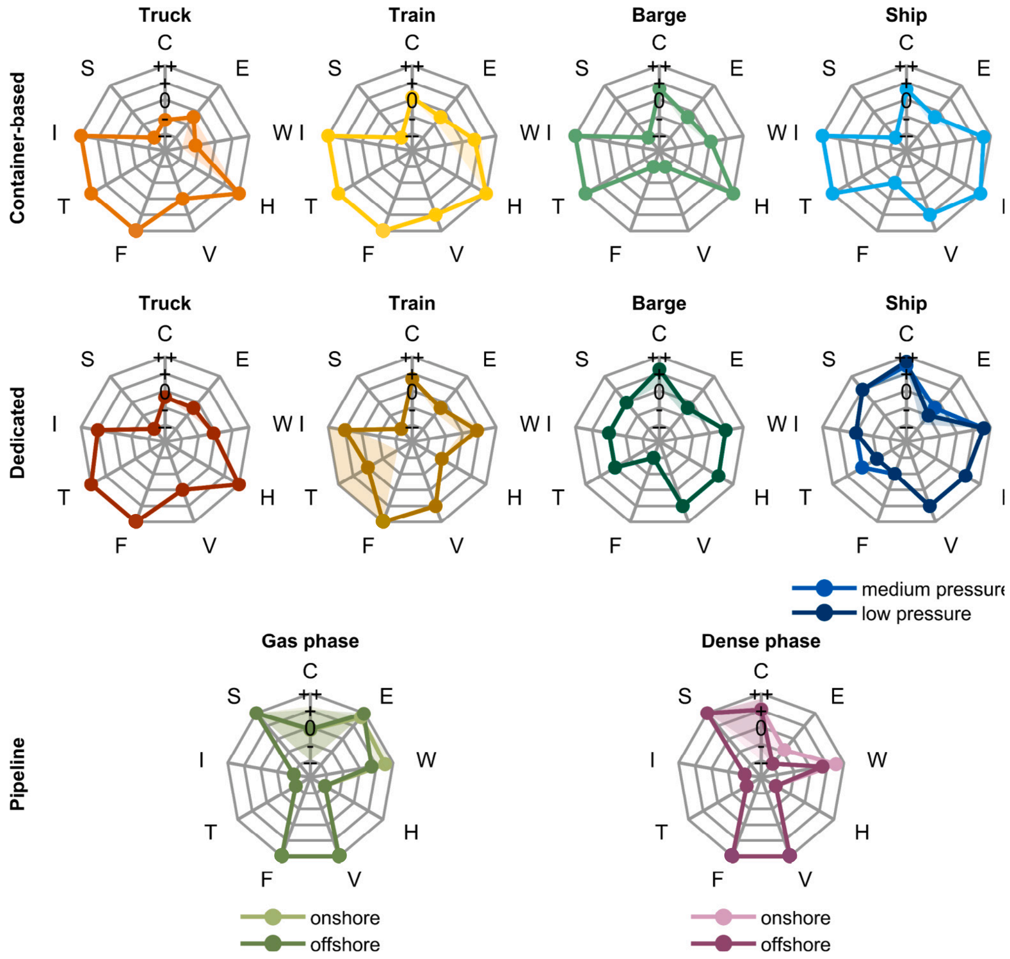

Fig. 9. Spider graph of the multi-criteria assessment for different transport options: in the first row, container-based transport, in the second, dedicated transport, and in the third row, pipeline transport. The abbreviations stand for: C — unitary costs, E — conditioning energy requirement, W — global warming impact, H — holding time, V — duration variability, F — seasonal fluctuations, T — time horizon, I — greenfield infrastructure, S — economies of scale.

Holding time. The holding time of the transport technologies largely depends on the insulation type. Little to no data is available concerning leakages of ISO tank containers and dedicated tanks, such that it is assumed that they are perfectly tight as long as no pressure release occurs. The isotainers are vacuum-insulated, so that all container-based transport options share a holding time of at least 60 days, which allows for their transport to destinations up to more than 10 000 km away. Dedicated transport options are insulated with polyurethane layers of different widths, with the exception of dedicated trucks, which are vacuum-insulated. For example, the rail tank cars used for dedicated railway transport have a holding time of five days only, which limits the geographical range on which this transport technology can be used to approximately 1500 km. Dedicated barges have a holding time of 23 days, which is sufficient for all connections on the Rhine river. For dedicated ships we assume a similar holding time as for dedicated barges, because their structure is similar. The larger size of dedicated ships might even confer a longer holding time. It is difficult to transfer the concept of holding time to the pipelines since their working principle is different from the other transport options. In this study, the holding time of pipelines is defined to be zero, as they are subject to leakages and thus continuously release small amounts of CO_2.

Duration variability and seasonal fluctuations. The duration variability depends mostly on the congestion, which is considerable in certain harbours, e.g., along the Rhine river; therefore, the container-based barge performance is very poor, while the purposely built terminal for dedicated barges avoids this issue. Truck transport is also subject to traffic jams, while delays are proportionately less frequent for train and ship transport, consistent with the work of Demir et al. (2015). The duration variability does not matter for pipeline transport which is operated continuously. Seasonal fluctuations affect mainly waterway transport modes. Ship transport can be slowed by unfavourable weather conditions in the winter, while the water level determines the loading of barges. The situation is expected to worsen for most rivers in the future decades because of climate change (Internationale Kommission zum Schutz des Rheins (IKSR), 2015; Nilson et al., 2020). The warm temperatures in the summer might also influence the holding time of all vessels, as their temperature will tend to increase faster. While this is not a real issue for isotainers, which have a high holding time in all cases, this will especially affect transport options with limited insulation.

Time horizon. The time horizon of the implementation of transport options is closely linked to the greenfield infrastructure needs. Indeed, all technologies transporting CO_2 in isotainers are mature and thus available in the near term. The infrastructure is existing, and the required additional component are the isotainers. Similarly, dedicated road and railway transport is already existing; however, the loading of dedicated rail tank cars requires railway stations with a specific loading terminal. For example, in Switzerland, the loading process can take place only in a private railway station. Therefore, the time horizon of this transport option entirely depends on the availability of such infrastructure. Dedicated vessels are not yet existing at scale, although their production could start soon and be available within a few years (Dan-Unity CO_2, 2022). The deployment of a pipeline requires several preparation steps such as planning, engineering, permitting, constructing the infrastructure, which results in long lead times. It is here assumed that carbon dioxide pipelines will be built from scratch. Nonetheless, there is a need to clarify if the refurbishment of existing natural gas pipelines might be an option, similar to suggestions made for hydrogen (European Union Agency for the Cooperation of Energy Regulators (ACER), 2021; Entsog, 2021; van Rossum et al., 2022; Klopčič et al., 2022).

In summary, container-based transport will be convenient to start deploying CCTS at larger scale, as the infrastructure is already existing. However, dedicated transport will be preferred in the medium term despite the need for specific facilities. Indeed, as the dedicated options have a higher capacity than the corresponding container-based options, their efficiency increases in terms of costs, economies of scale and global warming impact, while they show a similar performance in other categories. Concerning the different means of transport, trucks appear to be flexible and allow to reach any facility, but they are connected with higher costs, high specific emissions, and congestion, so that generally other options will be preferred when they are available. For inland transport, barge is the most economic option, but its reliability and load fluctuate considerably, while train transport is more reliable, but connected to higher costs and little to no economies of scale. In the long run, transport via pipeline appears to be the most promising transport option for onshore transport, as they perform very well in terms of costs, economies of scale, global warming impact, and are very reliable, as they are not subject to any congestion or seasonal fluctuations. Offshore, dedicated ships are approximately as efficient as pipeline transport and would be the choice for longer distances, while pipelines remain interesting for very large amounts and shorter distances.

5. Supply chain for a specific source-to-sink connection

The transport options described in the previous sections are combined and applied to a case study to design CCTS chains linking a specific emitter with a permanent storage site. The performance of those chains is examined considering different aspects.

KVA Hagenholz is a waste-to-energy (WtE) plant that treats municipal solid waste from the city of Zurich to deliver district heating and electricity (Stadt Zürich - Tiefbau- und Entsorgungsdepartement, 2014). From 2027, the plant will have three incineration lines, which will emit 405 kt of CO_2 per year, corresponding to a yearly amount of 365 kt_{CO_2} captured at a 90% rate. In this study, we assume the mass flow of CO_2 captured to be constant throughout the year, although in reality, it might be fluctuating because of the planned shutdowns for maintenance and depending on the available heat for capture (Otgonbayar and Mazzotti, 2024). In this case study, we focus on possible transport paths from this point-source emitter site in inland Europe to a selected storage site in the North Sea. We consider three different scenarios with respect to costs (optimistic, average, and conservative) based on reasonable upper and lower bounds for selected parameters. We examine exclusively point-to-point options and are looking at the near- and medium-term possibilities. We anticipate that the pipeline networks developed in the long-term will be the most efficient solution, but they are not within the scope of this case study.

We assume capture, conditioning, and storage to be pre-defined based on state-of-the art technologies. For the capture, we assume mature amine-scrubbing technology and 90% capture rate. Eliasson et al. (2022) report a range for the specific costs of capture from industrial processes with excess heat. Subtracting the conditioning costs from this range, estimating the costs for a first-of-a-kind (FOAK) plant with the learning-curve method (van der Spek et al., 2017; National Energy Technology Laboratory (NETL), 2013), and adapting the costs to 2021, we estimate a specific capture cost of 100 EUR t^{-1} to be representative. The conditioning plant design is based on the studies of Deng et al. (2019) and Roussanaly et al. (2021) for liquefaction, and Knoope et al. (2014) for compression. It is worth noting that conditioning is considered only once in the design of the supply chains. It is assumed that when transferring CO_2 from medium- to low-pressure carriers, the expansion is sufficient to ensure the temperature decrease.

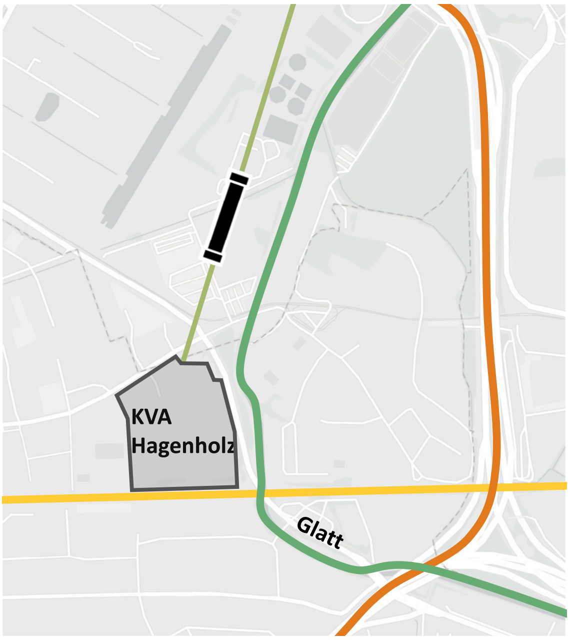

Fig. 10. Map of the geographical situation of KVA Hagenholz (OpenStreetMap, 2023). The orange line represents a highway, the yellow line a railway line, the turquoise line the Glatt river, and the green line an approximate path for a pipeline.

Furthermore, we select storage in a saline aquifer at the Northern Lights facility. The CO_2 is injected in a reservoir 2000 m to 3000 m under the seabed, at a pressure of 200 bar to 300 bar and a temperature of 100 °C (equinor, 2019). The Northern Lights project is planning to offer CO_2 storage in the near term. Closer storage sites might develop in the future, which would also significantly decrease the transport costs.

The levelised costs of avoided CO_2 are obtained by considering the greenhouse gas emissions occurring along the chain. The Life-Cycle Analysis of the chain has been conducted following the methodology described in Burger et al. (2024).

KVA Hagenholz is located in a densely built-up area, with limited space for additional logistic operations (see Fig. 10). Additionally, there is no private railway station despite the railway line running behind the plant. While the space is sufficient to build a capture plant on-site, it is possible neither to condition the CO_2 on-site, nor to load it onto container-based or dedicated trucks or trains. Therefore, the proposed plan involves constructing a pipeline to a location where enough space is available to handle the logistics and the filling stations. One possibility is directing the pipeline to the wastewater treatment plant (*de: Abwasserreinigungsanlage (ARA)*) Glatt and further to ARA Werdhölzli through an existing tunnel (Züst and ERZ, 2021). This solution has been considered to be the most promising for this study. As the pipeline planning and construction would be executed in parallel to the planning and construction of the capture plant, these projects would share the same time horizon.

A network of feasible transport connections linking KVA Hagenholz with the permanent storage site is established by selecting appropriate connections and exchange sites. Each of these locations is represented by a node. Possible direct connections between two nodes are represented by an edge, see Fig. C.2 in the *Supplementary Material*. This network can be translated into a simple directed graph, in which the weight of each edge is characterised by the cost of the transport option available for this connection. Applying the Yen's algorithm onto this graph (Yen, 1971), one obtains the *K* most economical paths for each pair of source and sink nodes.

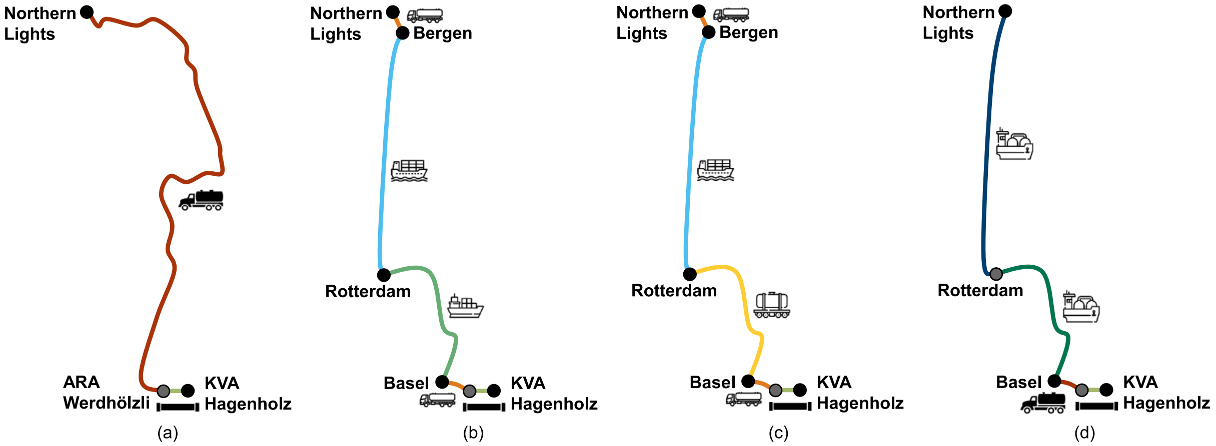

Fig. 11. Schematic description of the CCTS chains from KVA Hagenholz to the Northern Lights storage site: (a) Simplest chain, (b) Cost-effective pioneering (i.e., from emitters with a high willingness to act) supply chain, (c) Alternative pioneering chain, (d) Cost-effective dedicated supply chain. The nodes represent transport exchange sites, the grey ones having the specificity that the transport specifications of the CO_2 change.

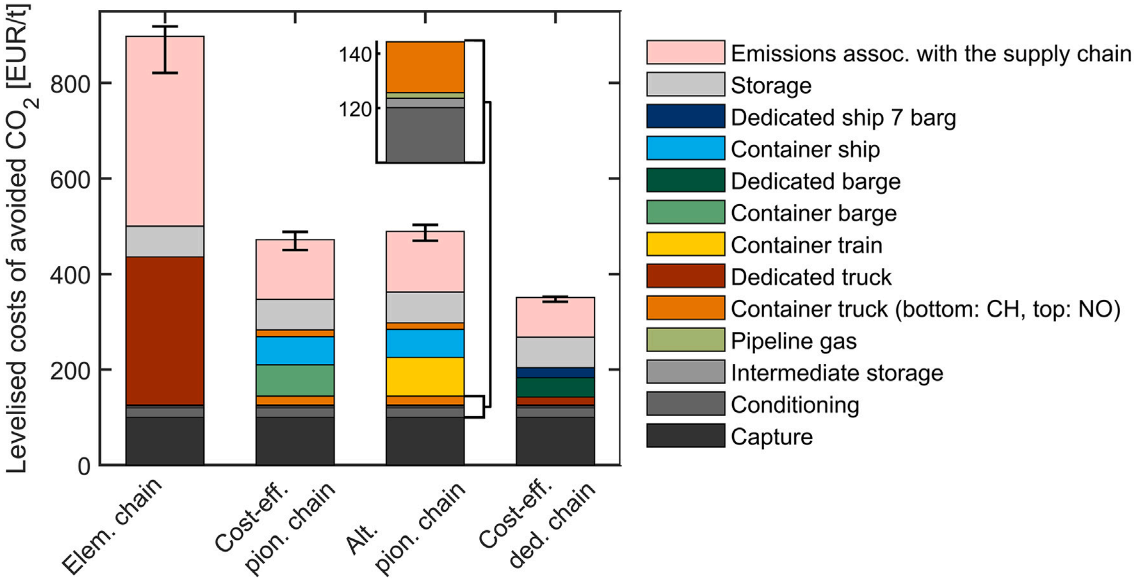

Fig. 12. Levelised costs of avoided CO_2 and cost breakdown of the CCTS chains from KVA Hagenholz to the Northern Lights storage site. *Left to right:* (a) Elementary chain, (b) Cost-effective pioneering supply chain, (c) Alternative pioneering chain, (d) Cost-effective dedicated supply chain. While the main bar represents the average scenario, the lower bound of the error bar shows the optimistic scenario, and the upper bound of the error bar the conservative scenario. All coloured bars from the capture and up to the storage represent the levelised costs of stored CO_2, while the pink bar on top represents the theoretical costs due to the emissions associated with each supply chain. For the sake of simplicity, the labour costs considered for truck transport correspond to the European average.

From the list of most economical paths computed as mentioned above, four transport scenarios have been selected and are described in the following paragraphs. They are schematically illustrated in Fig. 11. Fig. 12 shows the levelised costs of avoided carbon dioxide for the four corresponding chains, together with the costs breakdown.

The simplest chain (a) consists of a direct connection via dedicated truck between ARA Werdhölzli and the onshore facility of the Northern Lights storage site. Despite the high CO_2 transport emissions, these are lower than the amount of CO_2 transported and stored, making this chain still viable. Furthermore, numerous advantages exist over the other options: the complexity of the supply chain is low with only one transport exchange and one conditioning stage. The frequency of transport by truck is very high, and trucks can be operated in a flexible manner, which is advantageous in terms of chain resilience.

The second chain (b) shown in Fig. 11 is cost-effective in the near term. The supply chain consists of container-based transport, first by truck from ARA Werdhölzli to Basel, where the isotainers are transferred to a barge that conveys them to Rotterdam. There, they are transshipped and carried by sea to Bergen. The last miles are covered by truck. Dedicated road and railway transport are not included, because both would require intermediate storage tanks at transport exchange sites, and the latter solution is not possible because KVA Hagenholz does not have a private station. Both solutions would thus require greenfield infrastructure, which we exclude for near-term implementation. Therefore, the solution considered here relies on isotainers. The complexity of this supply chain is very high with four transport exchanges. Train and barge connections are commonly operated several times per week, but only once per week for most conventional cargo ship connections. This limits the frequency of the chain. In addition to the high duration variability due to the barge and ship transport, this increases the risk for delays and missed connections. The duration of the roundtrip for an isotainer is sixteen days on average, so that more than 1500 isotainers are needed to implement the chain. Nonetheless, the transport emissions are relatively small compared to chain (a).

The third chain (c) in Fig. 11 is an alternative pioneering chain. Its sole difference with respect to option (b) is the loading of the isotainers on a train instead of a barge between Basel and Rotterdam. In this regard, the complexity and frequency of chains (b) and (c) are similar. Nonetheless, train transport is faster and less subject to fluctuations than barge transport, such that the duration of the roundtrip for an isotainer is 10 days, and approximately a thousand isotainers are required. This chain can also be implemented in a near time horizon.

The fourth supply chain (d) displayed in Fig. 11 is a cost-effective dedicated supply chain. Its structure is similar to the cost-effective pioneering supply chain except that container-based transport options are replaced by dedicated transport options. The dedicated ship can also directly deliver the CO_2 to the storage terminal. The CO_2 transport emissions are decreased by one third compared to the near-term alternative. The frequency of the supply chain is determined by the size of the dedicated vessels. The complexity of the chain is high, with three transport exchanges and up to three reconditioning steps. For both cost-effective chains, the design is consistent with previous findings (Becattini et al., 2022).

Fig. 12 illustrates the levelised costs of avoided CO_2 for the four chains presented above. The levelised costs of stored CO_2 are obtained by summing up the costs of each stage of the chain, i.e., capture, conditioning, intermediate storage, transport, and storage. In this case study, the capture, conditioning, and storage costs are assumed to be the same for all cases. Further, the levelised costs of avoided CO_2 are obtained by dividing the levelised costs of stored CO_2 by the CO_2 avoidance efficiency of the supply chain, which has been computed after the methodology of Burger et al. (2024). In this way, the theoretical cost of the emissions associated with the supply chain is the difference between the levelised costs of avoided CO_2 and the levelised costs of stored CO_2.

Fig. 12 shows that the simplest chain (a) exhibits the highest levelised costs of avoided carbon, because dedicated road transport has relatively high unitary cost and emissions factor. The pioneering chains (b) and (c) exhibit similar levelised costs of avoided carbon, the sole difference being the container-based train transport (c), which has a higher unitary cost of transport than container-based barge transport (b). As a large part of the railway transport is in Germany, the specific emissions are also relatively high. For the cost-effective dedicated supply chain (d), the transport costs are approximately halved, because the selected transport options are more efficient in terms of costs and environmental performance.

6. Conclusions

This study investigates the design of the transportation part of carbon dioxide capture, transport, and storage (CCTS) supply chains aiming at decarbonising industries where avoiding completely to generate CO_2 is not foreseeable, i.e., the so called hard-to-abate sectors. Four main goals drove this investigation. First, we have identified viable options to transport CO_2, which are implementable in the near and medium term, so as to allow early movers to deploy CCTS in the near future, when long-term solutions such as pipelines and ships are not yet available. Second, we have developed a methodology for the techno-economic analysis of such chains, based mainly on data from the industry. Third, we have defined a multi-criteria framework, and we have applied it to carry out a general, comparative assessment of the feasible transport options above. And finally, we have demonstrated its application to a specific case study, for which we have designed feasible and potentially promising CO_2 transportation pathways.

We have shown that the unitary costs of point-to-point CO_2 transport over a given connection depend both on the distance covered and on the amount transported in the case of dedicated barges and ships as well as of pipelines, while they depend only on the distance covered for container-based transport options and dedicated trucks and trains. In practice, the best transport solution will be selected among those available for a specific location at a certain point in time in the future. We have observed that the long-term solutions are more cost-effective than the near-term solutions, but they require a larger greenfield infrastructure.

To complement the results above, for each transport option we have conducted a sensitivity analysis to quantify the impact of uncertainties on costs, and a multi-criteria comparative assessment to highlight the trade-offs associated. Container-based transport is the option of choice for the early deployment of CCTS supply chains, as it is a flexible and versatile solution, based on existing infrastructure, though it is modular and does not allow for economies of scale. For deployment at a later stage, dedicated transport options will be more cost-effective, as they are more efficient in terms of costs, economies of scale, and global warming impact. Ultimately, pipelines will be the preferred solution, as they perform particularly well in terms of costs, economies of scale, global warming impact, and reliability.

The application to a case study has shown that several pathways are possible for the implementation of CCTS supply chains from inland Europe to a storage site in the North Sea. It shows that coordination among the emitter, the transport provider, and the storage operator is obviously key to ensure the timely deployment and the smooth operation of the supply chains, thus highlighting how important considerations about infrastructure and logistics are.

The importance of this work lies in its portability and adaptability, in other words, in the possibility of using it for supply chains connecting emitters and storage sites of any length. The parameter values of the cost equations can be updated as they change in time and among geographical locations. Thus, transport costs can be computed for specific scenarios, and combined with information about capture, conditioning, and storage costs to obtain estimates for specific source-to-sink connections, beyond those considered in this work.

Moreover, the techno-economic analysis of transport can be combined with Life Cycle Analysis and resilience analysis to yield a multi-objective optimisation problem for CO_2 supply chains (Gabrielli et al., 2022; Becattini et al., 2022). Such optimisation problem can be solved both statically, i.e., for a set of demands and constraints that apply at a specific point in time, and dynamically, i.e., for varying demands and constraints, to simulate the roll-out of a CO_2 network infrastructure between now and 2050, in order to reach the scale needed to decrease the greenhouse gas emissions to net-zero by 2050.

CRediT authorship contribution statement

Pauline Oeuvray: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Johannes Burger:** Writing – review & editing, Resources, Data curation. **Simon Roussanaly:** Writing – review & editing, Validation, Resources, Funding acquisition. **Marco Mazzotti:** Writing – review & editing, Visualization, Supervision, Methodology, Funding acquisition. **Viola Becattini:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Data availability

All publicly available data can be found in the Supplementary Material.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.140781.

References

ACCSESS, 2021. Hafslund Oslo Celsio. https://www.projectaccsess.eu/partners/hafslund-oslo-celsio/.

ACCSESS, 2023. Project concept. https://www.projectaccsess.eu/concept/.

AirLiquide, 2022. Air liquide et Sogestran s'associent pour développer des solutions de transport maritime pour la gestion du carbone. https://www.airliquide.com/fr/groupe/communiques-presse-actualites/05-04-2022/air-liquide-et-sogestran-sassocient-pour-developper-des-solutions-de-transport-maritime-pour-la.

Alhajaj, A., Shah, N., 2020. Multiscale design and analysis of CO_2 networks. Int. J. Greenh. Gas Control 94, 102925. http://dx.doi.org/10.1016/J.IJGGC.2019.102925.

Anderson, C., Schirmer, J., Abjorensen, N., 2012. Exploring CCS community acceptance and public participation from a human and social capital perspective. Mitig. Adapt. Strateg. Glob. Change 17 (6), 687–706. http://dx.doi.org/10.1007/s11027-011-9312-z.

Becattini, V., Gabrielli, P., Antonini, C., Campos, J., Acquilino, A., Sansavini, G., Mazzotti, M., 2022. Carbon dioxide capture, transport and storage supply chains: Optimal economic and environmental performance of infrastructure rollout. Int. J. Greenh. Gas Control 117, 103635. http://dx.doi.org/10.1016/j.ijggc.2022.103635.

Bjerketvedt, V.S., Tomasgaard, A., Roussanaly, S., 2020. Optimal design and cost of ship-based CO_2 transport under uncertainties and fluctuations. Int. J. Greenh. Gas Control 103, 103190. http://dx.doi.org/10.1016/J.IJGGC.2020.103190.

Bjerketvedt, V.S., Tomasgard, A., Roussanaly, S., 2022. Deploying a shipping infrastructure to enable carbon capture and storage from Norwegian industries. J. Clean. Prod. 333, 129586. http://dx.doi.org/10.1016/J.JCLEPRO.2021.129586.

Borlaug, B., Muratori, M., Gilleran, M., Woody, D., Muston, W., Canada, T., Ingram, A., Gresham, H., McQueen, C., 2021. Heavy-duty truck electrification and the impacts of depot charging on electricity distribution systems. Nat. Energy 6 (6), 673–682. http://dx.doi.org/10.1038/s41560-021-00855-0.

Brevik CCS, 2022. Brevik CCS – world's first CO_2 capture facility at a cement plant. https://www.brevikccs.com/en. Accessed: 13.11.2022.

Brownsort, P., 2015. Ship transport of CO_2 for enhanced oil recovery – literature survey. https://era.ed.ac.uk/bitstream/handle/1842/15703/SCCS-CO2-EOR-JIP-WP15-Shipping.pdf?sequence=1&isAllowed=y.

Burger, J., Nöhl, J., Seiler, J., Gabrielli, P., Oeuvray, P., Becattini, V., Reyes-Lúa, A., Riboldi, L., Sansavini, G., Bardow, A., 2024. Environmental impacts of pioneering carbon capture transport and storage supply chains: Status and the way forward. Int. J. Greenh. Gas Control 132, 104039. http://dx.doi.org/10.1016/j.ijggc.2023.104039.

Çabukoglu, E., Georges, G., Küng, L., Pareschi, G., Boulouchos, K., 2019. Fuel cell electric vehicles: An option to decarbonize heavy-duty transport? Results from a swiss case-study. Transp. Res. D 70, 35–48. http://dx.doi.org/10.1016/j.trd.2019.03.004, URL https://www.sciencedirect.com/science/article/pii/S1361920918306953.

d'Amore, F., Romano, M.C., Bezzo, F., 2021. Carbon capture and storage from energy and industrial emission sources: A Europe-wide supply chain optimisation. J. Clean. Prod. 290, 125202. http://dx.doi.org/10.1016/J.JCLEPRO.2020.125202.

d'Amore, F., Romano, M.C., Bezzo, F., 2021. Optimal design of European supply chains for carbon capture and storage from industrial emission sources including pipe and ship transport. Int. J. Greenh. Gas Control 109, 103372. http://dx.doi.org/10.1016/j.ijggc.2021.103372.

Dan-Unity CO_2, 2021. DAN - UNITY CO_2 is able to order world's first vessels capable of large-scale CO_2 transportation. https://dan-unity.dk/dan-unity-co2-is-able-to-order-worlds-first-vessels-capable-of-large-scale-co2-transportation/.

Dan-Unity CO_2, 2022. Dan-unity and Victrol to ship the CO_2 from inland Europe's largest industry emitters to safe storage. https://dan-unity.dk/dan-unity-and-victrol-to-ship-the-co2-from-inland-europes-largest-industry-emitters-to-safe-storage/.

Demir, E., Huang, Y., Scholts, S., Van Woensel, T., 2015. A selected review on the negative externalities of the freight transportation: Modeling and pricing. Transp. Res. E 77, 95–114. http://dx.doi.org/10.1016/j.tre.2015.02.020.

DemoUpCARMA, 2022. DemoUpCARMA & DemoUpStorage - the projects in brief. http://demoupcarma.ethz.ch/en/home/.

Deng, H., Roussanaly, S., Skaugen, G., 2019. Techno-economic analyses of CO_2 liquefaction: Impact of product pressure and impurities. Int. J. Refrig. 103, 301–315. http://dx.doi.org/10.1016/j.ijrefrig.2019.04.011.

Der Bundesrat, 2022. CO_2-Abscheidung und Speicherung (CCS) und Negativemissionstechnologien (NET). https://www.newsd.admin.ch/newsd/message/attachments/71551.pdf.

DETEC, 2022. Vereinbarung VBSA-UVEK zur Reduktion der fossilen CO_2-Emissionen aus der Abfallverbrennung und Umsetzung von Technologien zur Abscheidung, Speicherung und Nutzung von CO_2 in Schweizer Kehrichtverwertungsanlagen. URL https://www.bafu.admin.ch/bafu/en/home/topics/climate/info-specialists/reduction-measures/sector-agreements/agreement-waste-treatment.html.

DNV, 2022. DNV supports innovations in CO_2 carrier design. https://www.dnv.com/expert-story/maritime-impact/DNV-supports-innovations-in-CO2-carrier-design.html?utm_campaign=Gas_411_KNCC_LCO2_AIP&utm_medium=email&utm_source=Eloqua.

Dütschke, E., Wohlfarth, K., Höller, S., Viebahn, P., Schumann, D., Pietzner, K., 2016. Differences in the public perception of CCS in Germany depending on CO_2 source, transport option and storage location. Int. J. Greenh. Gas Control 53, 149–159. http://dx.doi.org/10.1016/j.ijggc.2016.07.043.

Elahi, N., Shah, N., Korre, A., Durucan, S., 2014. Multi-period least cost optimisation model of an integrated carbon dioxide capture transportation and storage infrastructure in the UK. Energy Procedia 63, 2655–2662. http://dx.doi.org/10.1016/j.egypro.2014.11.288.

Eliasson, Å., Fahrman, E., Biermann, M., Normann, F., Harvey, S., 2022. Efficient heat integration of industrial CO_2 capture and district heating supply. Int. J. Greenh. Gas Control 118, 103689. http://dx.doi.org/10.1016/j.ijggc.2022.103689, URL https://www.sciencedirect.com/science/article/pii/S1750583622001074.

Endrava, 2022. A tool for mapping CO_2 emissions in Europe. https://www.capturemap.no/. Accessed: 03.05.2022.

Entsog, 2021. Transport & Speicherung von Wasserstoff – Zahlen & Fakten. https://www.gasconnect.at/fileadmin/Broschueren-Folder/entsog_gie/entsog_gie_he_QA_hydrogen_transport_and_storage_DE_210630.pdf.

equinor, 2019. Northern Lights Project Concept Report. Technical Report RE-PM673-00001, equinor.

Equinor, 2023. Onshore facilities - Hammerfest LNG. https://www.equinor.com/energy/onshore-facilities. Accessed: 20.12.2023.

European Union Agency for the Cooperation of Energy Regulators (ACER), 2021. Transporting pure hydrogen by repurposing existing gas infrastructure: Overview of existing studies and reflections on the conditions for repurposing. https://www.acer.europa.eu/Publications/Transporting%20Pure%20Hydrogen%20by%20Repurposing%20Existing%20Gas%20Infrastructure_Overview%20of%20studies.pdf.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., Van Dorland, R., 2007. Changes in atmospheric constituents and in radiative forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-chapter2-1.pdf.

Gabrielli, P., Campos, J., Becattini, V., Mazzotti, M., Sansavini, G., 2022. Optimization and assessment of carbon capture, transport and storage supply chains for industrial sectors: The cost of resilience. Int. J. Greenh. Gas Control 121, 103797. http://dx.doi.org/10.1016/j.ijggc.2022.103797.

Gale, J., Davison, J., 2004. Transmission of CO_2—safety and economic considerations. Energy 29 (9), 1319–1328. http://dx.doi.org/10.1016/j.energy.2004.03.090, URL https://www.sciencedirect.com/science/article/pii/S0360544204001744.

Global CCS Institute, 2015. Fact sheet - transporting CO_2. https://www.globalccsinstitute.com/archive/hub/publications/191083/fact-sheet-transporting-co2.pdf.

Haugen, H.A., Eldrup, N.H., Fatnes, A.M., Leren, E., 2017. Commercial capture and transport of CO_2 from production of ammonia. Energy Procedia 114, 6133–6140. http://dx.doi.org/10.1016/j.egypro.2017.03.1750.

Heiskanen, E., Hodson, M., Mourik, R., Raven, R., Feenstra, C., Alcantud Torrent, A., Brohmann, B., Daniels, A., Di Fiore, M., Farkas, B., et al., 2008. Factors influencing the societal acceptance of new energy technologies: Meta-analysis of recent European projects.

Herdzik, J., 2021. Decarbonization of marine fuels—The future of shipping. Energies 14 (14), http://dx.doi.org/10.3390/en14144311, URL https://www.mdpi.com/1996-1073/14/14/4311.

Horvath, A., 2006. Environmental assessment of freight transportation in the US. Int. J. Life Cycle Assess. 11, 229–239. http://dx.doi.org/10.1065/lca2006.02.244.

International Tank Container Organisation (ITCO), 2011. Tank containers: A sustainable solution for bulk liquid transport. https://international-tank-container.org/storage/uploads/ITCOSustainabilityFinal.pdf.

Internationale Kommission zum Schutz des Rheins (IKSR), 2015. Klimawandelanpassungsstrategie für die IFGE Rhein. https://www.iksr.org/fileadmin/user_upload/DKDM/Dokumente/Fachberichte/DE/rp_De_0219.pdf.

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, http://dx.doi.org/10.1017/9781009157896.

IPCC, 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III To the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, http://dx.doi.org/10.1017/9781009157926.

Kalyanarengan Ravi, N., Van Sint Annaland, M., Fransoo, J.C., Grievink, J., Zondervan, E., 2017. Development and implementation of supply chain optimization framework for CO_2 capture and storage in the Netherlands. Comput. Chem. Eng. 102, 40–51. http://dx.doi.org/10.1016/j.compchemeng.2016.08.011.

Kelderman, B., Friedhoff, B., Guesnet, T., Holtmann, B., Kaiser, R., Markus, E., Robert, R., Dasburg, N., Liere, R., Quispel, M., Maierbrugger, G., Schweighofer, J., 2016. PROMINENT - D1.1 List of Operational Profiles and Fleet Families - Identification of the Fleet, Typical Fleet Families & Operational Profiles on European Inland Waterway. Technical Report, European Commission, https://www.prominent-iwt.eu/wp-content/uploads/2015/06/2015_09_23_PROMINENT_D1.1-List-of-operational-profiles-and-fleet-families-V2.pdf.

Klopčič, N., Stöhr, T., Grimmer, I., Sartory, M., Trattner, A., 2022. Refurbishment of natural gas pipelines towards 100% hydrogen—A thermodynamic-based analysis. Energies 15 (24), 9370. http://dx.doi.org/10.3390/en15249370.

Knoope, M.M., Guijt, W., Ramírez, A., Faaij, A.P., 2014. Improved cost models for optimizing CO_2 pipeline configuration for point-to-point pipelines and simple networks. Int. J. Greenh. Gas Control 22, 25–46. http://dx.doi.org/10.1016/j.ijggc.2013.12.016.

Knoope, M.M., Ramírez, A., Faaij, A.P., 2013. A state-of-the-art review of techno-economic models predicting the costs of CO_2 pipeline transport. Int. J. Greenh. Gas Control 16, 241–270. http://dx.doi.org/10.1016/j.ijggc.2013.01.005.

Koornneef, J., Spruijt, M., Molag, M., Ramírez, A., Turkenburg, W., Faaij, A., 2010. Quantitative risk assessment of CO_2 transport by pipelines—A review of uncertainties and their impacts. J. Hazard. Mater. 177 (1), 12–27. http://dx.doi.org/10.1016/j.jhazmat.2009.11.068, URL https://www.sciencedirect.com/science/article/pii/S0304389409018664.

Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. Proc. Natl. Acad. Sci. 108 (9), 3465–3472. http://dx.doi.org/10.1073/pnas.1100480108.

Leonzio, G., Foscolo, P.U., Zondervan, E., 2019. An outlook towards 2030: Optimization and design of a CCUS supply chain in Germany. Comput. Chem. Eng. 125, 499–513. http://dx.doi.org/10.1016/j.compchemeng.2019.04.001.

Luo, X., Wang, M., Oko, E., Okezue, C., 2014. Simulation-based techno-economic evaluation for optimal design of CO_2 transport pipeline network. Appl. Energy 132, 610–620. http://dx.doi.org/10.1016/j.apenergy.2014.07.063, URL https://www.sciencedirect.com/science/article/pii/S0306261914007466.

Man Energy Solutions, 2022. ME-GI engines to power liquid-CO_2 carriers in groundbreaking carbon-transport-and-storage project. https://www.man-es.com/company/press-releases/press-details/2022/03/09/me-gi-engines-to-power-liquid-co2-carriers-in-groundbreaking-carbon-transport-and-storage-project.

McCoy, S.T., Rubin, E.S., 2008. An engineering-economic model of pipeline transport of CO_2 with application to carbon capture and storage. Int. J. Greenh. Gas Control 2 (2), 219–229. http://dx.doi.org/10.1016/S1750-5836(07)00119-3, URL https://www.sciencedirect.com/science/article/pii/S1750583607001193.

Meeberg, 2023. About ISO tanks. https://www.meeberg.com/en/iso-tanks/iso-tanks-about/. Accessed: 13.01.2023.

Mitsubishi, 2022. Mitsubishi shipbuilding concludes agreement on construction of world's first demonstration test ship for liquefied CO_2 transportation. https://www.mhi.com/news/220202.html.

Morbee, J., Serpa, J., Tzimas, E., 2012. Optimised deployment of a European CO_2 transport network. Int. J. Greenh. Gas Control 7, 48–61. http://dx.doi.org/10.1016/j.ijggc.2011.11.011.

National Energy Technology Laboratory (NETL), 2013. Technology learning curve (FOAK to NOAK). https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=b40ad5366a7491bde1bfbb9f5f4d0c4c60e56060.

National Energy Technology Laboratory (NETL), 2022. FECM/NETL CO_2 transport cost model. https://www.netl.doe.gov/energy-analysis/details?id=e4eac672-e1b8-478d-be09-bcf5ca29d9fb. Last Update: March 2022 (Version 3).

Nie, Z., Korre, A., Elahi, N., Durucan, S., 2017. Real options analysis of CO_2 transport and storage in the UK continental shelf under geological and market uncertainties and the viability of subsidies for market development. Energy Procedia 114, 6612–6622. http://dx.doi.org/10.1016/j.egypro.2017.03.1815.

Nilson, E., Astor, B., Bergmann, L., Fischer, H., Fleischer, C., Haunert, G., Helms, M., Hillebrand, G., Höpp, S., Kikillus, A., Labadz, M., Mannfeld, M., Razafimaharo, C., Patzwahl, R., Rasquin, C., Rauthe, M., Riedel, A., Schröder, M., Schulz, D., Seiffert, R., Stachel, H., Wachler, B., Winkel, N., 2020. Beiträge zu einer verkehrsträgerübergreifenden Klimawirkungsanalyse: Wasserstraßenspezifische Wirkungszusammenhänge – Schlussbericht des Schwerpunktthemas Schiffbarkeit und Wasserbeschaffenheit (SP-106) im Themenfeld 1 des BMVI-Expertennetzwerks. https://www.bmdv-expertennetzwerk.bund.de/DE/Publikationen/TFSPTBerichte/SPT106.html.

NorthWoodsHiawatha, 2007. CC BY. https://commons.wikimedia.org/wiki/File:TILX290344.JPG.

OpenStreetMap, 2023. OpenStreetMap. https://www.openstreetmap.org/.

Otgonbayar, T., Mazzotti, M., 2024. Modeling and assessing the integration of CO_2 capture in waste-to-energy plants delivering district heating. Energy 290, 130087. http://dx.doi.org/10.1016/j.energy.2023.130087.

Pörtner, H.-O., Roberts, D., Adams, H., Adelekan, I., Adler, C., Adrian, R., Aldunce, P., Ali, E., Begum, R.A., Friedl, B.B., Kerr, R.B., Biesbroek, R., Birkmann, J., Bowen, K., Caretta, M., Carnicer, J., Castellanos, E., Cheong, T., Chow, W., G. Cissé, G.C., Ibrahim, Z.Z., 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability. In: Technical Summary, Cambridge University Press, Cambridge, UK and New York, USA, pp. 37–118. http://dx.doi.org/10.1017/9781009325844.

Prata, J., Arsenio, E., 2017. Assessing intermodal freight transport scenarios bringing the perspective of key stakeholders. Transp. Res. Procedia 25, 900–915. http://dx.doi.org/10.1016/j.trpro.2017.05.465.

Roussanaly, S., Brunsvold, A.L., Hognes, E.S., 2014. Benchmarking of CO_2 transport technologies: Part II – offshore pipeline and shipping to an offshore site. Int. J. Greenh. Gas Control 28, 283–299. http://dx.doi.org/10.1016/J.IJGGC.2014.06.019.

Roussanaly, S., Deng, H., Skaugen, G., Gundersen, T., 2021. At what pressure shall CO_2 be transported by ship? An in-depth cost comparison of 7 and 15 barg shipping. Energies 14 (18), 5635. http://dx.doi.org/10.3390/en14185635.

Roussanaly, S., Jakobsen, J.P., Hognes, E.H., Brunsvold, A.L., 2013. Benchmarking of CO_2 transport technologies: Part I—Onshore pipeline and shipping between two onshore areas. Int. J. Greenh. Gas Control 19, 584–594. http://dx.doi.org/10.1016/J.IJGGC.2013.05.031.

Roussanaly, S., Skaugen, G., Aasen, A., Jakobsen, J., Vesely, L., 2017. Techno-economic evaluation of CO_2 transport from a lignite-fired IGCC plant in the Czech Republic. Int. J. Greenh. Gas Control 65, 235–250. http://dx.doi.org/10.1016/j.ijggc.2017.08.022, URL https://www.sciencedirect.com/science/article/pii/S1750583617300373.

Russell, K., Smialek, J., 2022. Interest rates rise around the world, as war and high inflation grind on. N.Y. Times URL https://www.nytimes.com/interactive/2022/06/16/business/economy/global-interest-rate-increases.html?searchResultPosition=1.

Span, R., Wagner, W., 1996. A new equation of state for carbon dioxide covering the fluid region from the triple-point temperature to 1100 K at pressures up to 800 MPa. J. Phys. Chem. Ref. Data 25, 1509–1596. http://dx.doi.org/10.1063/1.555991.

SRF, 2022. Rheinschifffahrt muss sich auf häufige Niedrigpegel einstellen. SRF, URL https://www.srf.ch/news/schweiz/klimawandel-rheinschifffahrt-muss-sich-auf-haeufige-niedrigpegel-einstellen.

Stadt Zürich - Tiefbau- und Entsorgungsdepartement, 2014. Thermische Verwertung von Abfall — Kehrichtheizkraftwerk Hagenholz. https://www.stadt-zuerich.ch/content/dam/stzh/ted/Deutsch/erz/khkw/ZW_Thermische_Verwertung_Hagenholz_1708.pdf.

Stolaroff, J.K., Pang, S.H., Li, W., Kirkendall, W.G., Goldstein, H.M., Aines, R.D., Baker, S.E., 2021. Transport cost for carbon removal projects with biomass and CO_2 storage. Front. Energy Res. 165. http://dx.doi.org/10.3389/fenrg.2021.639943.

SWZ Maritime, 2022. Approval in principle for MOL's large liquefied CO_2 carrier design. https://swzmaritime.nl/news/2022/08/25/approval-in-principle-for-mols-large-liquefied-co2-carrier-design/.

TCC1, 2010. CC BY-SA 3.0. https://commons.wikimedia.org/wiki/File:CIMC_tank_container_T11.jpg.

TGE, 2022. Contract for two CO_2 carriers. https://www.tge-marine.com/contract-for-two-co2-carriers/.

van der Spek, M., Ramirez, A., Faaij, A., 2017. Challenges and uncertainties of ex ante techno-economic analysis of low TRL CO_2 capture technology: Lessons from a case study of an NGCC with exhaust gas recycle and electric swing adsorption. Appl. Energy 208, 920–934. http://dx.doi.org/10.1016/j.apenergy.2017.09.058, URL https://www.sciencedirect.com/science/article/pii/S0306261917313405.

van der Spek, M., Roussanaly, S., Rubin, E.S., 2019. Best practices and recent advances in CCS cost engineering and economic analysis. Int. J. Greenh. Gas Control 83, 91–104. http://dx.doi.org/10.1016/j.ijggc.2019.02.006.

van Rossum, R., Jens, J., La Guardia, G., Weng, A., Kühnen, L., Overgaag, M., 2022. European hydrogen backbone. https://ehb.eu/files/downloads/ehb-report-220428-17h00-interactive-1.pdf.

Wallquist, L., Seigo, S.L., Visschers, V.H., Siegrist, M., 2012. Public acceptance of CCS system elements: A conjoint measurement. Int. J. Greenh. Gas Control 6, 77–83. http://dx.doi.org/10.1016/j.ijggc.2011.11.008.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. http://dx.doi.org/10.1007/s11367-016-1087-8.

Wüstenhagen, R., Wolsink, M., Bürer, M.J., 2007. Social acceptance of renewable energy innovation: An introduction to the concept. Energy Policy 35 (5), 2683–2691. http://dx.doi.org/10.1016/j.enpol.2006.12.001.

Yara, 2015. New liquid CO_2 ship for Yara. https://www.yara.com/news-and-media/news/archive/2015/new-liquid-co2-ship-for-yara/.

Yen, J.Y., 1971. Finding the k shortest loopless paths in a network. Manage. Sci. 17 (11), 712–716. http://dx.doi.org/10.1287/mnsc.17.11.712.

Zanobetti, F., Martynov, S., Cozzani, V., Mahgerefteh, H., 2023. Multi-objective economic and environmental assessment for the preliminary design of CO_2 transport pipelines. J. Clean. Prod. 411, 137330. http://dx.doi.org/10.1016/j.jclepro.2023.137330, URL https://www.sciencedirect.com/science/article/pii/S0959652623014889.

Zhang, Z., Wang, G., Massarotto, P., Rudolph, V., 2006. Optimization of pipeline transport for CO_2 sequestration. Energy Convers. Manag. 47 (6), 702–715. http://dx.doi.org/10.1016/j.enconman.2005.06.001.

Zhang, D., Wang, Z., Sun, J., Zhang, L., Li, Z., 2012. Economic evaluation of CO_2 pipeline transport in China. Energy Convers. Manag. 55, 127–135. http://dx.doi.org/10.1016/j.enconman.2011.10.022.

Zhang, S., Zhuang, Y., Liu, L., Zhang, L., Du, J., 2020. Optimization-based approach for CO_2 utilization in carbon capture, utilization and storage supply chain. Comput. Chem. Eng. 139, 106885. http://dx.doi.org/10.1016/j.compchemeng.2020.106885.

Züst, P., ERZ, 2021. CO_2 transport logistics at KVA Hagenholz. private communication. 20.08.2021.