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Full Length Article

Optimisation of ship-based CO_2 transport chains from Southern Europe to the North Sea

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ABSTRACT

Among the technologies for climate change mitigation, carbon capture and storage is considered as a technically and economically viable option to reduce CO_2 emissions from hard-to-abate industrial sectors. When it comes to CO_2 logistics, ship-based chains are emerging as an attractive alternative to other CO_2 transport modes (e.g., pipelines), as these could exhibit lower operational risk, higher infrastructural flexibility, and lower costs. This work provides insights into the cost of optimal ship-based CO_2 transport chains at a European level, by proposing a detailed economic model of CO_2 transport by ship, including all the echelons of the infrastructure (i.e., liquefaction, buffer storage, loading, ship, conditioning, and unloading). The final aim is to determine the minimum CO_2 transport cost from Southern Europe to North Sea sequestration. Different unloading scenarios (port-to-port, port-to-floating storage and injection, and port-to-direct offshore unloading) and carbon reduction targets are investigated. The minimum unitary transport cost is 26 €/t of CO_2 for transporting 103 Mt/y.

List of symbols

Acronyms	
CAPEX	Capital expenditure
CCS	Carbon capture and storage
DAC	Direct air capture
FSI	Floating storage and injection unit
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MILP	Mixed integer linear programming
OPEX	Operative expenditure
S1	Scenario 1 - port-to-port
S2	Scenario 2 - port-to-FSI
S3	Scenario 3 - port-to-direct injection
Mathematical symbols	
Sets	
i	Ship-based CO_2 transport stages
c	Countries with collection ports
n	Collection ports and sequestration hub
$ship$	Ship capacity discretisation
Parameters	
α [%]	Carbon reduction target
c_1^{S2} and c_1^{S3} [M€]	Unloading cost calculation
c_2^{S2} and c_2^{S3} [M€/ship]	Unloading cost calculation
c_3 [€/t]	Floating storage and injection cost calculation
CCF [%]	Capital charge factor

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C_{ship}^{FSI} [t/y]	Capacity of the floating storage and injection unit
C_{ship} [kt]	Ship capacity
c^{el} [€/MWh]	Electric energy cost
c^{w} [€/m^3]	Water unitary cost
c_{ship}^{fee} [€/y]	Ship harbour fee depending on capacity
c_{ship}^{fuel} [€/y]	Ship fuel cost depending on capacity
d [km]	Sailing distance
$e_{P_t}^{cond,el}$ [kWh/t]	Specific electric consumption of conditioning stage
$e_{P_{in},P_t}^{liq,el}$ [kWh/t]	Specific electric consumption of liquefaction stage
e_{P_{in},P_t}^{w} [m^3/t]	Specific water consumption of liquefaction stage
F^{unav} [-]	Unavailability factor
$K_{P_t}^{cond,S1}$ [€/t/y]	Specific investment cost for onshore conditioning
$K^{cond,S2,S3}$ [€/t]	Specific investment cost for offshore conditioning
K_{P_{in},P_t}^{liq} [€/t/y]	Unitary liquefaction investment cost
$K_{P_t,ship}^{ship}$ [€/ship]	Unitary investment cost of ship
$K_{P_t}^{stor,S1,S3}$ [€/t]	Unitary investment cost of buffer tanks
η^{op} [-]	Operation factor
η^{tank} [-]	Maximum percentage tank filling
$\eta^{weather}$ [-]	Weather factor
N_{ship}^{rtrip} [y^{-1}]	Number of trips per year
P_{in} [barg]	Pressure from the capture plant
P_t [barg]	Transport pressure
$\dot{Q}_n^{capt}$ [t/y]	Yearly amount available for capture in node n

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$\dot{Q}^{load}$ [t/h]	Ship loading flow rate
$\dot{Q}^{unload}$ [t/h]	Ship unloading flow rate
SF [-]	Buffer storage factor
$t^{app/dep}$ [h]	Approach/departure time
t^{load}_{ship} [h]	Ship loading time
$t^{moor/unmoor}$ [h]	Mooring/unmooring time
t^{rtrip}_{ship} [h]	Roundtrip time
t^{sail}_{ship} [h]	Sailing transit time
t^{unload}_{ship} [h]	Ship unloading time
v_{ship} [km/h]	Operational transit speed
Variables	
$CAPEX^i$	Capital expenditure of stage i
N_{ship}	Number of ships
$OPEX^i$	Operative expenditure of stage i
$\dot{Q}_{n,n'}$ [t/y]	Amount transported from node n to node n'
$\dot{Q}^{tr}_n$ [t/y]	Captured amount in node n
$\dot{Q}^{seq}_n$ [t/y]	Sequestered amount in node n
$\dot{Q}_{ship}$ [t/y]	Yearly transported amount
$\dot{Q}_{ship,n,n'}$ [t/y]	Yearly transported amount via $ship$ from n to n'
TC [€/y]	Total cost
TC^i [€/y]	Total cost of stage i

1. Introduction

Carbon capture and storage (CCS) is meant to separate the carbon dioxide (CO_2) from concentrated sources or from the air as for direct air capture (DAC). Upon being separated, the CO_2 is compressed, purified, transported, and permanently stored in underground geological basins (IPCC, 2005). Concentrated sources mainly account for the flue gases and process streams deriving from electricity and heat production, or from carbon intensive industrial sectors, such as cement, iron and steel, and refining industry (IEA, 2022; IPCC, 2005).

In Europe, there is large potential for CO_2 geological sequestration, particularly in onshore sedimentary basins scattered throughout the continent and in the offshore North Sea area (Holler and Viebahn, 2011; Viebahn et al., 2012). One way to reach these storage basins from European emission points would be the setting up of an onshore CO_2 transport infrastructure (i.e., via onshore pipelines), which may result less costly than offshore transport routes under specific logistic circumstances (Svensson et al., 2004). However, safety-related arguments (Cristiu et al., 2023; Gale and Davison, 2004; Vitali et al., 2022; 2021) support social opposition and resistance towards the installation and operation of CCS chains, and may result in opposition and projects cancellations due to 'Not In My Back Yard'-like phenomena. Differently, the offshore transport and sequestration of CO_2 could be an option to minimise the risk perception from the public towards CCS hence, to maximise the social acceptance of these projects (d'Amore et al., 2020). Aside these risk-related issues, the complexity of building such a large-scale onshore CO_2 transport and sequestration infrastructure across Europe may be an argument, too, in favour of exploiting the storage capacity located in the North Sea, and of reaching these basins by means of offshore transport routes. However, as the cost of an offshore infrastructure based on pipelines may be higher than its onshore alternative, the use of ship-based CO_2 transport could be key, especially during the early-stage development of CCS, due to its potentially competitive transport cost (Becattini et al., 2022; Hua et al., 2023; Weihs et al., 2014), its inherent flexibility (Neele et al., 2014), and lower operational risk (Kjarstad et al., 2016), compared to pipelines. Moreover, the use of ships could foster the development of CCS projects in those European regions that are geographically located far from the North Sea, such as the Mediterranean area. If on the one hand some geological basins have been identified for medium-term CO_2 sequestration projects (e.g., in the Adriatic Sea and Greece), their current early-stage degree of investigation makes the North Sea area a potential backup storage option also for Southern Europe CO_2 emissions (e.g., Northern Lights, 2022). Moreover, the Mediterranean CO_2 storage sites exhibit an estimated capacity (e.g.: less than 1 Gt in the Italian Northern Adriatic, Donda et al., 2011 about 1 Gt off the coasts of Greece, Koukouzas et al., 2021) which is relatively small if compared with the large-scale industrial CO_2 sources located in Southern Europe (over 100 Mt/y from steel, cement, and refining sectors; EEA, 2021), which may lead to the necessity of linking the Mediterranean CO_2 point sources to the North Sea area in a long term CCS perspective.

During the last decade, in the wake of an increased interest in CCS applications (Bui et al., 2018), different studies have been published on ship-based CO_2 transport, e.g. focussing on regulatory aspects (Tsimplis and Noussia, 2022; Weber, 2021), on technological parameters related to specific stages of the transport chain, such as transport pressure (Roussanaly et al., 2021), and on the high-level techno-economic analysis of full scale systems (see the review article by Al Baroudi et al., 2021). In fact, ship CO_2 transport is inherently constituted by multiple echelons, namely liquefaction, intermediate buffer storage, naval shipping, conditioning, and unloading, each comprising several design alternatives (IEAGHG, 2020). For instance, the CO_2 unloading stage could take place either onshore or offshore (Roussanaly et al., 2013; 2014). Hence, the necessity of addressing ship-based CO_2 transport networks from a systems perspective, to assess their best design (e.g., in terms of minimum transport cost). This is done in the literature through techno-economic and optimisation models, but these typically investigate only small-scale transport chains. For instance, several studies on ship CO_2 transport chains were proposed based on a local-to-regional geographic framework; e.g., Norway and North Sea area (Bjerketvedt et al., 2020; 2022; Neele et al., 2017), industrial clusters located in the United Kingdom (Calvillo et al., 2022), Swedish industries (Karlsson et al., 2023), and Brazilian coasts (Nogueira et al., 2022). Differently, a higher-level analysis was proposed by d'Amore et al. (2021a), where a CCS infrastructure with naval transport was optimised at a European scale, but ship transport was modelled on average unitary transport costs and simplified logistics. As such, that model did not detail the different transport stages within the naval infrastructure, nor the effect of choosing alternative options (e.g., the unloading strategy, the transport pressure) on the optimal design and costs. This work aims at filling this gap, by optimising a large-scale (i.e., European level) ship-based CO_2 chain, while providing a thorough assessment of the transport stages in terms of technological options, decarbonisation ambitions, and costs.

Based on a detailed economic model of ship CO_2 transport derived from IEAGHG (2020), this work proposes a multi-echelon mixed integer linear programming (MILP) optimisation, to minimise the cost of ship-based logistics at a European level. In particular, the objective is to transport via ships the CO_2 deriving from the most significant industrial emitters located in Southern Europe, to geological sequestration in the North Sea, to determine costs, chain design (e.g., strategic ports and hubs), and competitiveness of different logistic strategies (e.g., unloading options). The final aim is to provide insights into optimal ship-based CO_2 transport routes and their characteristics (e.g., optimal size and number of ships, best ship capacity for each transport route), for a given carbon reduction target. The significance of the case study lays on the fact that it is representative of the current situation in which CO_2 geological sequestration in Southern Europe is not exploited yet at scale (due to legal, policy, or technical reasons), or of a long-term perspective in which Mediterranean basins with limited capacity have been already fully exploited. Overall, this article presents a versatile modelling framework, that could help stakeholders and decision-makers in planning ship-based CO_2 transport infrastructures, also for different geographic contexts and scales.

2. Ship-based CO_2 transport chain

Ship transport of liquefied CO_2 has been deployed for years at small-scale level in the context of food and beverage industry (Hua et al., 2023). The design of CO_2 carriers and their operation (e.g., loading and unloading strategies) can largely benefit from the well-established knowledge of the liquefied petroleum gas (LPG) and liquefied natural gas (LNG) industries (Datta et al., 2020; Element Energy, 2018).

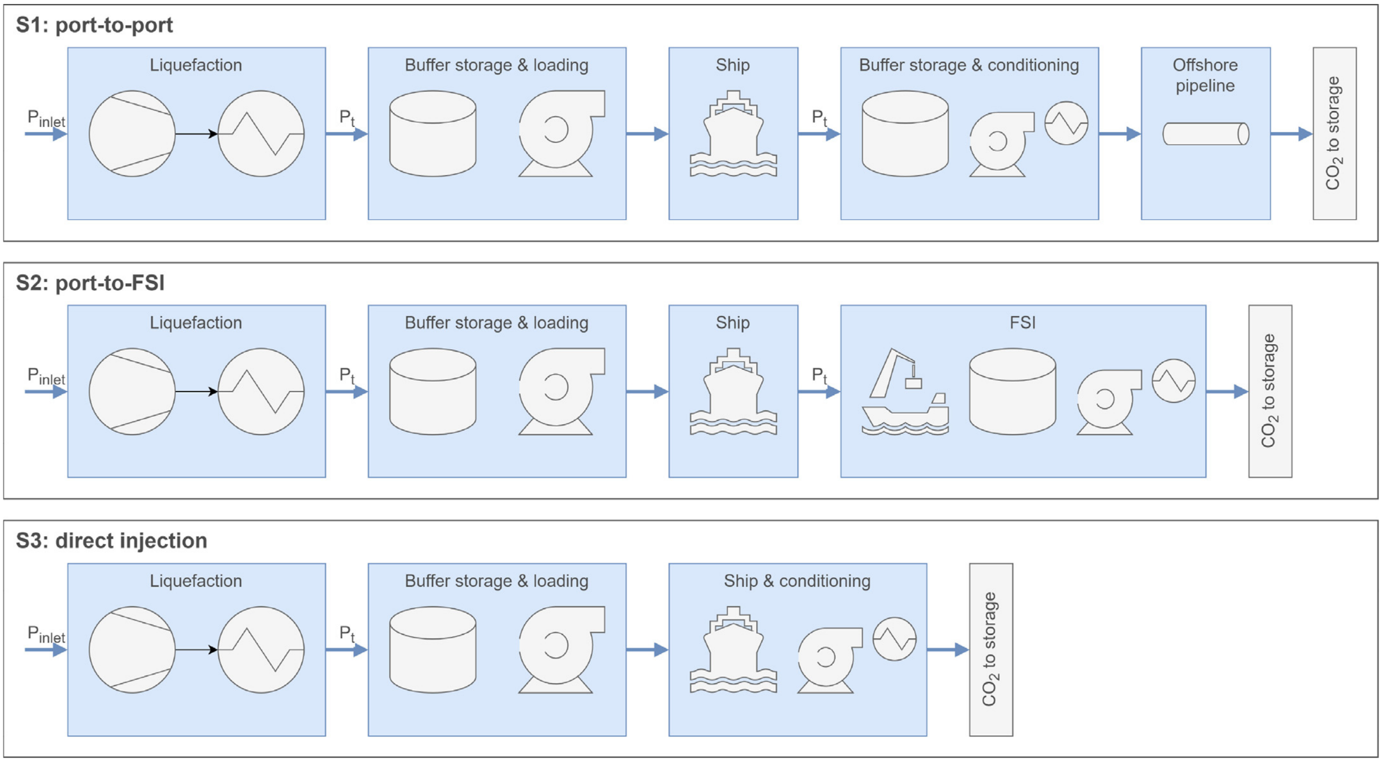


Fig. 1. Schematic representation of ship-based CO_2 transport chains and possible unloading scenarios: S1, port-to-port; S2, port-to-FSI; and S3, port-to-direct offshore injection.

Transporting CO_2 via ships comprises different sequential operations, or stages (Fig. 1). The first one is the liquefaction plant, in which the CO_2 (deriving from the capture plant) is liquefied to reduce its specific volume by compressing it at its transport pressure (P_t). Following liquefaction, the CO_2 is stored in buffer tanks (that keep it at transport pressure P_t). These buffer tanks are needed to ensure continuous operation (as ships are 'batch-like' processes), so as to provide an efficient and 'as steady as possible' shipping schedule; moreover, they can be exploited as intermediate storage hubs, i.e. as collectors of CO_2 deriving from multiple sources (Fraga et al., 2021). Then, the liquid CO_2 is loaded onto the ships, by means of loading equipments which are well known from LPG and LNG industrial practice. Ships have different configurations depending on their design capacity (Element Energy, 2018). The transport capacity (C_{ship}) depends also on the chosen transport pressure: transport capacities up to 10 kt can be achieved adopting medium P_t (e.g., 15 barg), but by using low P_t (e.g., 7 barg) it is possible to deploy ships with larger capacities Roussanaly et al. (2021). It has been demonstrated that current vessels could be designed to transport the CO_2 at low P_t for up to 50 kt of capacity, while more advanced configurations could be scaled up to 100 kt of capacity (IEAGHG, 2020). The CO_2 unloading from the ship can take place in three alternative options:

- Scenario 1 (S1). Transport occurs between two onshore ports (port-to-port). This is a rather intuitive scheme, in which the CO_2 is unloaded from the ship to an onshore facility, to be then stored in an unloading buffer tank to ensure continuous operation (conceptually similar to that present at the departure harbour). Finally, the CO_2 flow rate is sent via pipeline to offshore permanent sequestration (e.g., Northern Lights, 2022).
- Scenario 2 (S2). Transport from an onshore port to an offshore floating storage and injection platform (FSI) which is located on top of the sequestration site (port-to-FSI). Accordingly, S2 does not require an offshore pipeline to reach the storage basin. Differently from S1, in S2 the CO_2 is directly unloaded from the ship to the floating platform through additional unloading equipment that must be present onboard each ship. Intermediate storage tanks are located on the platform to ensure a continuous CO_2 injection into the well.
- Scenario 3 (S3). Transport from an onshore port to an offshore sequestration site, with direct injection from the ship into the sequestration basin (port-to-direct offshore injection). As in S2, as the CO_2 unloading from the ship takes place offshore, additional unloading equipment is needed onboard each ship. This option, unlike S1 and S2, does not consider the installation of an offshore buffer storage before CO_2 injection into the sequestration basin. Direct injection without an intermediate storage has lower capital investment than S1 and S2, but it has the downside of being characterised by a batch-wise unloading. As such, S3 may have higher risk in operation and it has not been proven for CO_2, yet (IEAGHG, 2020).

Finally, the CO_2 is conditioned at its injection pressure and temperature, by pumping the fluid to more than 100 bar and heating it. This step takes place in the unloading port in scenario S1, while it is carried out offshore in S2 and S3. In particular, when the FSI is present (i.e., S2), conditioning takes place on the platform, while in the case of direct injection (i.e., S3), each ship will be equipped for CO_2 conditioning (IEAGHG, 2020).

3. Modelling framework

3.1. Economic model

The aim of the economic model is to determine the investment cost (i.e., CAPEX) and operational expenditures (i.e., OPEX) of the ship-based CO_2 transport chain (Fig. 2). The economic model was validated on results from IEAGHG (2020) (see Supplementary Material). The key operational design input parameters are:

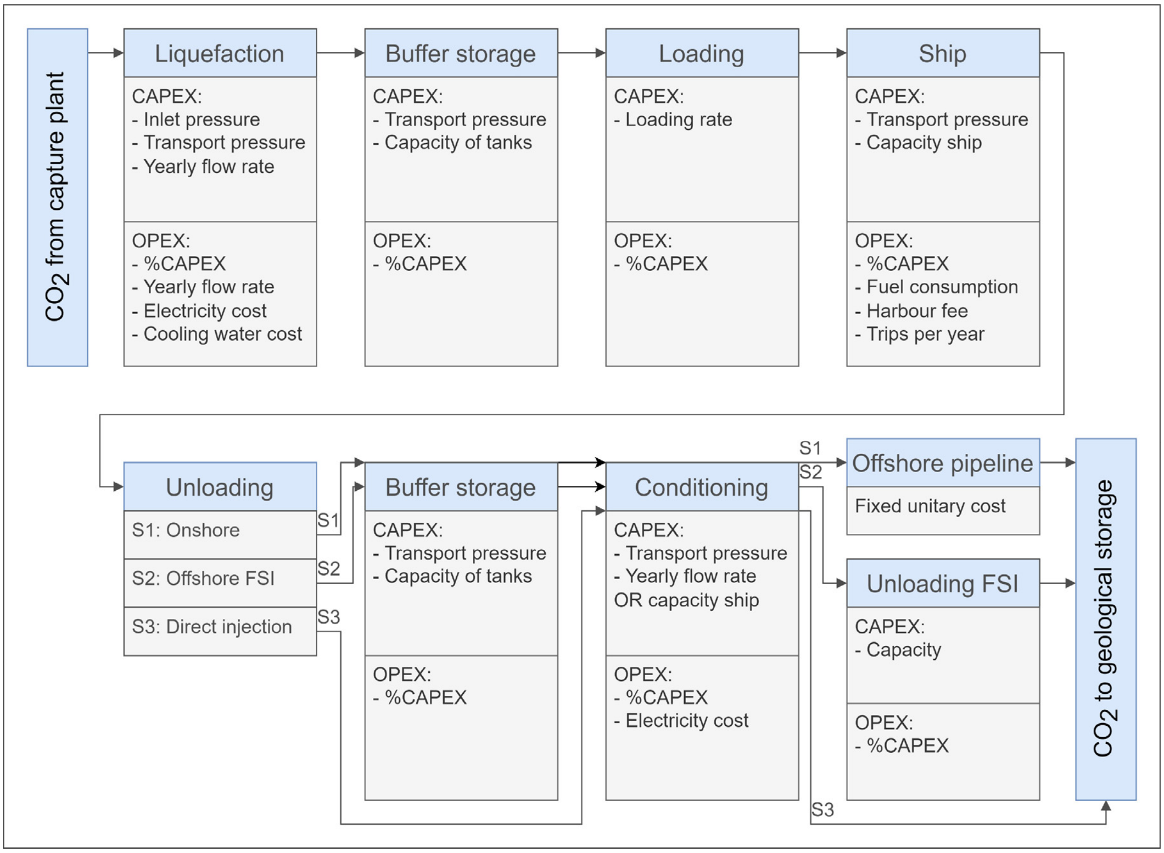


Fig. 2. Schematic representation of the economic model for costs calculation of a ship-based CO_2 transport chain.

- Inlet pressure P_{in}: it is here assumed that the CO_2 is received from the capture plant as a pressurised gas; hence, the CO_2 compression stage is associated to the capture plant and excluded from the model boundaries. A comparison with the economic results from unpressurised cases is reported in the Supplementary Material.
- Transport pressure P_t, which is the pressure of CO_2 after operations in the liquefaction plant and up to conditioning[1] This study assumes that the CO_2 is transported at low P_t (7 barg, $-50°$ C), as previous studies indicate that this choice may determine an economic advantage (IEAGHG, 2020; Pérez-Bódalo et al., 2023). Roussanaly et al. (2021) have demonstrated that low pressure shipping would enable an economic advantage compared to medium pressure (e.g., 15 barg) if considering the cost of the full chain. For large distances (greater than 1500 km), low pressure shipping would become even more cost competitive (over -50% of costs compared to 15 barg shipping). On this topic, see also Deng et al. (2019) and Aasen et al. (2017).
- Vessel capacity C_{ship} [t of CO_2], representing how many tonnes of CO_2 the vessel can transport. The vessel capacity C_{ship} ranges between 10 kt and 100 kt of CO_2. To decrease the computational burden and linearise the optimisation model, the vessels are discretised through a set $ship = \{1-6\}$ of capacities $C_{ship} = \{10, 20, 40, 60, 80, 100\}$ kt of CO_2.
- Number of ships N_{ship}.
- Sailing distance d [km], which is the naval distance between the departure and arrival nodes.
- Operational transit speed v_{ship} [km/h].

The economic model outputs are:

- Transported CO_2 amount $\dot{Q}_{ship}$ [t of CO_2/y].
- CAPEX^i, which represents the investment costs for each stage i.
- OPEX^i, which represents the operation and maintenance costs of stages i.

In particular, $\dot{Q}_{ship}$ derives from the number of ships (N_{ship}), from the capacity of ships (C_{ship}), and from the number of trips per year (N^{rtrip}_{ship} [y^{-1}]):

$$\dot{Q}_{ship} = C_{ship} \cdot N_{ship} \cdot N^{rtrip}_{ship} \cdot \eta^{tank} \tag{1}$$

where the coefficient η_{tank} (here assumed equal to 0.95) represents the percentage maximum filling capacity of the ship CO_2 tanks, based on technological limitations in their design and operation, while N^{rtrip}_{ship} is the maximum number of trips per year:

$$N^{rtrip}_{ship} = 8760/t^{rtrip}_{ship} \tag{2}$$

The term t^{rtrip}_{ship} [h] represents the time required for a single round-trip. The latter comprises the transit time (i.e., t^{sail}_{ship} [h]) of the ship for a given distance d [km] at speed v_{ship} [km/h], the loading time (i.e., t^{load}_{ship} [h]), and the unloading time (i.e., t^{unload}_{ship} [h]):

$$t^{rtrip}_{ship} = \frac{t^{sail}_{ship} + t^{load}_{ship} + t^{unload}_{ship}}{F^{unav}} \tag{3}$$

The parameter F^{unav} of Eq. (3) accounts for the impossibility of unloading the CO_2 offshore due to adverse weather conditions, and it is assumed equal to 1 in the onshore unloading case (i.e., S1), or equal to

[1] A key operational design parameter for CO_2 transport is density, that in general depends on pressure, temperature, and presence of impurities. However, as this study focusses on liquefied CO_2 transport, the effect of temperature on density is marginal, while we assume that the presence of impurities can be neglected downstream CO_2 purification.

0.92 in offshore unload case (i.e., S2 and S3) (IEAGHG, 2020). As for t^{sail}_{ship} of Eq. (3), it can be calculated by summing up the round-trip distance $2d$ divided by the operational transit speed (i.e., v_{ship}), to the time for mooring/unmooring (i.e., $t^{moor/unmoor}$ [h]) and approach/departure (i.e., $t^{app/dep}$ [h]).

$$t^{sail}_{ship} = \frac{2d/v_{ship} + t^{moor/unmoor} + t^{app/dep}}{\eta^{weather} \cdot \eta^{op}} \tag{4}$$

In particular, the time for mooring/unmooring is set equal to 0.25 h and that for approach/departure is assumed of 1 h. Eq. (4) includes two coefficients to account the uncertainty in weather and operation (i.e., $\eta^{weather}$ and η^{op}) which are assumed equal to 0.95 and 0.98, respectively (IEAGHG, 2020). Finally, loading and unloading times of Eq. (3) are evaluated according to the loaded (i.e., $\dot{Q}^{load}$ [t of CO_2/h]) and unloaded (i.e., $\dot{Q}^{unload}$ [t of CO_2/h]) flow rates:

$$t^{load}_{ship} = \frac{C_{ship}}{\dot{Q}^{load}} \tag{5}$$

$$t^{unload}_{ship} = \frac{C_{ship}}{\dot{Q}^{unload}} \tag{6}$$

Following the indications of IEAGHG (2020), $\dot{Q}^{load}$ of Eq. (5) is set equal to 600 t/h, while $\dot{Q}^{unload}$ of Eq. (6) is imposed equal to 600 t/h in case of onshore unloading (i.e., S1) and FSI (i.e., S2), or to 228 t/h in the direct injection case (i.e., S3), being this designed with two wells capable of a flow rate of 114 t/h (i.e., about 1 Mt/y), each.

LIQUEFACTION. As in Fig. 2, the first stage of a ship-based CO_2 transport chain is the CO_2 liquefaction plant, which is designed as a combined internal and external cooling loop (IEAGHG, 2020). The main components of the liquefaction plant are turbomachines and heat exchangers, so the cost associated to this stage derives from the amount of CO_2 (i.e., $\dot{Q}$ [t of CO_2/y]) and pressures P_{in} and P_t:

$$CAPEX^{liq}_{P_{in},P_t} = K^{liq}_{P_{in},P_t} \cdot \dot{Q} \tag{7}$$

$$OPEX^{liq,fix}_{P_{in},P_t} = 0.06 \cdot CAPEX^{liq} \tag{8}$$

$$OPEX^{liq,var}_{P_{in},P_t} = \dot{Q} \cdot (c^{el} \cdot e^{liq,el}_{P_{in},P_t} + c^{lab} + c^{w} \cdot e^{w}_{P_{in},P_t}) \tag{9}$$

where $K^{liq}_{P_{in},P_t}$ [€/t of CO_2/y] in Eq. (7) is a scalar representing the specific investment cost of liquefaction unit, depending on P_{in} and P_t, which results equal to 16.3 €/t of CO_2/y in the case of pressurised CO_2 and low pressure transport. The OPEX is divided into fixed $OPEX^{liq,fix}_{P_{in},P_t}$ of Eq. (8), assumed as 6% of $CAPEX^{liq}_{P_{in},P_t}$, and variable $OPEX^{liq,var}_{P_{in},P_t}$ of Eq. (9), which depends on the electricity consumption for liquefaction $e^{liq,el}_{P_{in},P_t}$ (equal to 39 kWh/t of CO_2) and its unitary cost c^{el} [€/kWh] (set equal to 80 €/MWh), on the labour cost c_{lab} (equal to 0.49 €/t of CO_2/y), and on the cooling water consumption $e^{w}_{P_{in},P_t}$ (resulting 3.65 m^3/t of CO_2) and its unitary cost c^{w} (set at 0.02 €/m^3). The above parameters were retrieved from IEAGHG (2020) and validated on relevant literature (Alabdulkarem et al., 2012; IEAGHG, 2004; Lee et al., 2015; Seo et al., 2016) (see details in Supplementary Material).

BUFFER STORAGE. Costs associated to onshore buffer storage capacity (i.e., $CAPEX^{stor,S1,S3}_{P_t,ship}$) or offshore storage in FSI case (i.e., $CAPEX^{stor,S2}$) depend on the ship capacity C_{ship} and on the FSI capacity C^{FSI}_{ship} [t of CO_2], respectively:

$$CAPEX^{stor,S1,S3}_{P_t,ship} = K^{stor,S1,S3}_{P_t} \cdot C_{ship} \cdot SF \tag{10}$$

$$CAPEX^{stor,S2}_{ship} = 1300 \cdot C^{FSI}_{ship} = 1300 \cdot C_{ship} \tag{11}$$

being $K^{stor,S1,S3}_{P_t}$ [€/t of CO_2] the specific investment cost for tanks (set equal to 1300 €/t of CO_2 for low transport pressure) and SF a storage factor defined as the ratio between the tanks and the ship capacities. This factor is 1 for onshore storage and 1.5 for offshore storage (IEAGHG, 2020). The capacity of the FSI C^{FSI}_{ship} is the minimum capacity required to ensure a continuous flow rate of CO_2, equal to C_{ship} (IEAGHG, 2020). As for variable costs (i.e., $OPEX^{stor}$), this study considers only fixed operative costs, which are set equal to 5% of the CAPEX for storage.

LOADING. Costs associated to ship loading stage (i.e., $CAPEX^{load}$) depend on the loading rate $\dot{Q}^{load}$ [t/h]:

$$CAPEX^{load} = 600 \cdot \dot{Q}^{load} \tag{12}$$

where the multiplicative factor is derived from IEAGHG (2020). As for variable costs of loading (i.e., $OPEX^{load}$), this study assumes only the fixed contribution evaluated as 5% of its CAPEX.

SHIP. As for ships, their investment cost depends on the transport pressure P_t, and is evaluated from the capacity C_{ship} and number N_{ship} of ships deployed:

$$CAPEX^{ship}_{P_t,ship} = K^{ship}_{P_t,ship} \cdot N_{ship} \tag{13}$$

where $K^{ship}_{P_t,ship}$ [€/ship] is a parameter depending on P_t and determined by interpolating data of investment costs of CO_2 ship carriers. In particular, the specific investment costs of ships are derived from Element Energy (2018), which provides cost curves as detailed in the Supplementary Material. Fixed OPEX (i.e., $OPEX^{ship,fix}_{P_t,ship}$) of ships is assumed equal to 5% of their CAPEX, while their variable OPEX (i.e., $OPEX^{ship,var}_{ship}$) derives from:

$$OPEX^{ship,var}_{ship} = N_{ship} \cdot (c^{fuel}_{ship} + c^{fee}_{ship}) \tag{14}$$

The terms c^{fuel}_{ship} [€/y] and c^{fee}_{ship} [€/y] represent the fuel and harbour fee costs, respectively, for a ship of a given capacity C_{ship} which is travelling for a distance d, and they are retrieved from Element Energy (2018) (see Supplementary Material). In agreement with Element Energy (2018), it is assumed to fuel the ship with marine diesel oil with unitary cost of 26.62 €/MWh (a test is reported in the results considering low-carbon alternatives).

CONDITIONING. The costs of the CO_2 conditioning stage are evaluated differently, depending on the choice of onshore (i.e., S1), or offshore unloading (i.e., S2 and S3). Accordingly, investment costs for onshore (i.e., $CAPEX^{cond,S1}_{P_t}$) or offshore (i.e, $CAPEX^{cond,S2,S3}_{ship}$) unloading are calculated as:

$$CAPEX^{cond,S1}_{P_t} = K^{cond,S1}_{P_t} \cdot \dot{Q}_{CO_2} \tag{15}$$

$$CAPEX^{cond,S2}_{ship} = K^{cond,S2,S3} \cdot C_{ship} \tag{16}$$

$$CAPEX^{cond,S3}_{ship} = K^{cond,S2,S3} \cdot C_{ship} \cdot N_{ship} \tag{17}$$

being $K^{cond,S1}_{P_t}$ [€/t of CO_2/y] and $K^{cond,S2,S3}$ [€/t of CO_2] the specific investment costs of CO_2 conditioning for onshore or offshore unloading, respectively. In particular, $K^{cond,S1}_{P_t}$ is equal to 4.21 €/t of CO_2/y for low transport pressure, while $K^{cond,S2,S3}$ is set equal to 800 €/t of CO_2 (IEAGHG, 2020). Note that in S3 every ship is equipped for conditioning thus, in Eq. (17) the cost is multiplied by N_{ship}. As for the variable costs of conditioning, fixed variable costs (i.e., $OPEX^{cond,fix}$) are assumed as 11% (for S1) or 5% (for S2 and S3) of investment costs, while variable costs (i.e., $OPEX^{cond,var}$) are determined as:

$$OPEX^{cond,var}_{P_t} = e^{cond,el}_{P_t} \cdot \dot{Q} \cdot c^{el} \tag{18}$$

with $e^{cond,el}_{P_t}$ [kWh/t of CO_2] representing the specific energy consumption of the process. In the case of onshore (i.e., S1) or FSI (i.e., S2) unloading and low transport pressure, $e^{cond,el}_{P_t}$ is equal to 2.53 kWh/t of CO_2, while for direct offshore unloading (i.e., S3), it is assumed of 2.3 kWh/t of CO_2 (IEAGHG, 2020).

UNLOADING. The investment cost for unloading depends on the unloading scenario (i.e., S2 or S3). In particular, it is given by:

$$CAPEX^{unload,S2}_{ship} = c^{S2}_1 + c^{S2}_2 \cdot N_{ship} + c_3 \cdot C^{FSI}_{ship} \tag{19}$$

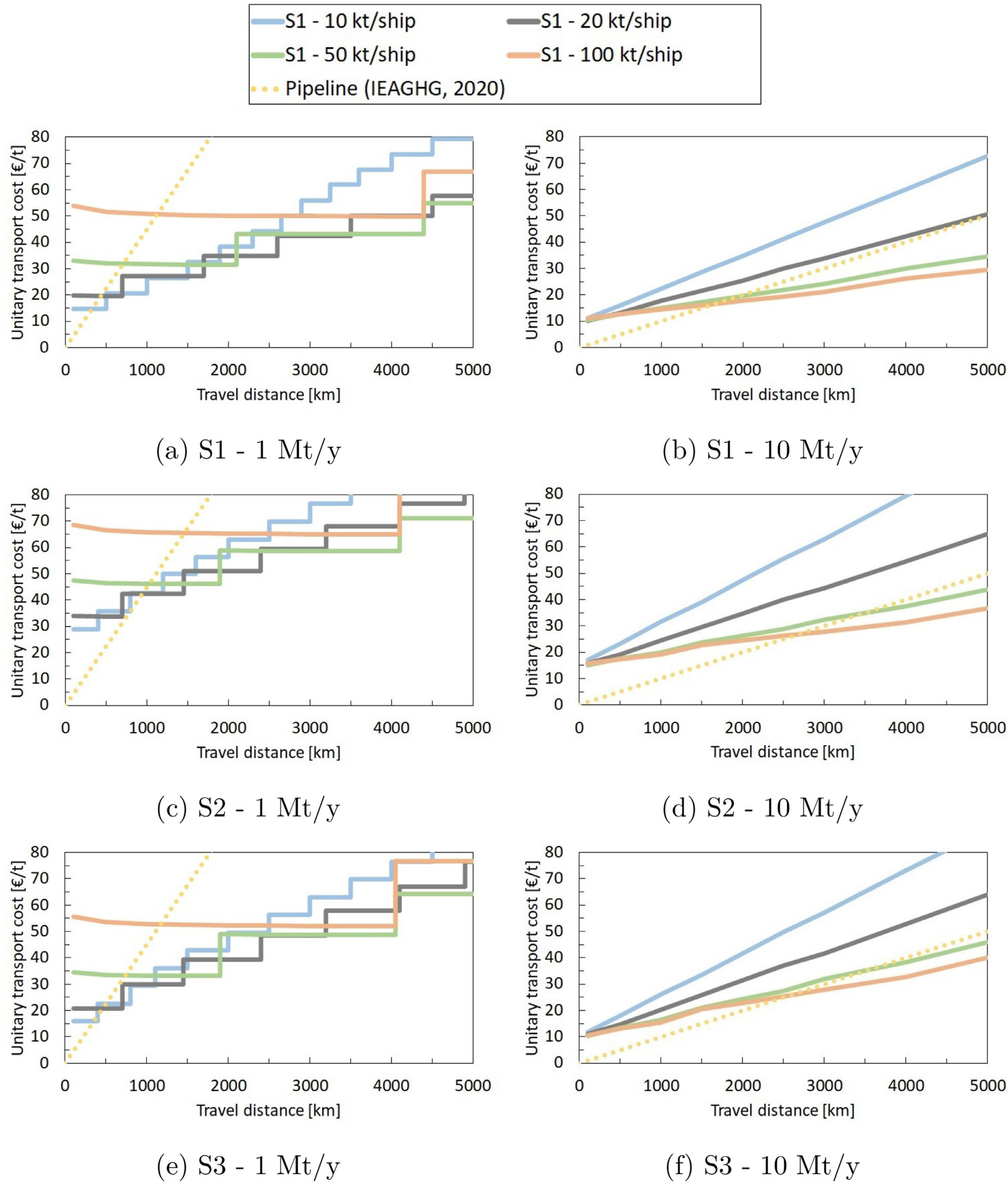


Fig. 3. Economic model results in terms of unitary transport cost [€/t of CO_2], depending on travel distance [km], total transported amount of CO_2 [Mt of CO_2/y], ship capacity [kt of CO_2/ship], and unloading scenario (S1, S2, and S3) (pipelines costs not included). The step-wise trend of the 1 Mt/y transport cases (left) reflects the progressive increase in the number of ships alongside longer distances. In the 10 Mt/y cases (right), the number of ships is significantly higher and the individual steps are much more frequent and numerous, so that the linear interpolation shown here is a good and graphically preferable representation of the trend. Dotted lines represent an estimate of equivalent (i.e., same annual flow rate) pipeline costs derived from IEAGHG (2020).

$$CAPEX_{ship}^{unload,S3} = c_1^{S3} + c_2^{S3} \cdot N_{ship} \quad (20)$$

where c_1 is a fixed contribution (equal to 95 M€ for S2, and to 16.5 M€ for S3), c_2 represents the cost of unloading equipment onboard each ship (equal to 11.8 M€/ship for S2, and to 2.8 M€/ship for S3), while c_3^{S2} is equal to 1800 €/t of CO_2 of capacity of the FSI unit (data retrieved from IEAGHG, 2020). Fixed operating costs are calculated as 5% of $CAPEX^{unload}$ both for S2 and S3.

The outcomes in terms of unitary transport cost of the above described economic model are reported in Fig. 3 for the different unloading scenarios, depending on the travel distance (between 100 and 5000 km), on the total transported amount of CO_2 (1 or 10 Mt of CO_2/y), and on the ship capacity (10, 20, 50, or 100 kt of CO_2/ship) (see model validation in the Supplementary Material).

3.2. Chain optimisation model

The optimisation model is based on a MILP architecture with the objective of minimising the total cost TC [€/y] of the ship-based CO_2 chain, comprising all the stages i; hence: liquefaction cost TC^{liq} [€/y], intermediate storage cost TC^{stor} [€/y], loading cost TC^{load} [€/y], ship cost TC^{ship} [€/y], conditioning cost TC^{cond} [€/y], and unloading cost TC^{unload} [€/y] (including the FSI cost in S2):

$$objective = min(TC) \quad (21)$$

$$TC = \sum_i TC^i \quad (22)$$

Each of the TC^i cost components of Eq. (23) is evaluated from the $CAPEX^i$, scaled over a capital charge factor CCF of 5% as in IEAGHG (2020) (see sensitivity analysis on capital charge factor), and $OPEX^i$ contributions of the chain stages i as described in the economic model:

$$TC^i = CCF \cdot CAPEX^i + OPEX^i \qquad \forall i \quad (23)$$

Costs of each stage i depend on the optimal logistics deriving from the mass balances among capture and sequestration nodes n of the ship-based CO_2 infrastructure. The yearly CO_2 amount (i.e., $\dot{Q}_n^{tr}$ [t of CO_2/y]) transported from each port n must be lower than the amount available (i.e., $\dot{Q}_n^{capt}$ [t of CO_2/y]) from nearby capture plants:

$$\dot{Q}_n^{tr} \le \dot{Q}_n^{capt} \qquad \forall n \quad (24)$$

Accordingly, the mass balance is imposed between n and n':

$$\dot{Q}_n^{tr} + \sum_{n'} \dot{Q}_{n',n} = \sum_{n'} \dot{Q}_{n,n'} + \dot{Q}_n^{seq} \qquad \forall n \quad (25)$$

where $\dot{Q}_{n,n'}$ [t of CO_2/y] is the yearly amount of CO_2 transported from n to n' and $\dot{Q}_n^{seq}$ [t of CO_2/y] that geologically sequestered in the North Sea. The total amount transported $\dot{Q}_{n,n'}$ is linked with the ship-specific routes $\dot{Q}_{ship,n,n'}$ [t of CO_2/y] of ships of type $ship$ from n to n', through:

$$\dot{Q}_{n,n'} = \sum_{ship} \dot{Q}_{ship,n,n'} \qquad \forall n, n' \quad (26)$$

The ship-specific routes $\dot{Q}_{ship,n,n'}$ are determined analogously to Eq. (1) thus, according to the optimal number of ships $N_{ship,n,n'}$ of type $ship$ travelling from n to n', to the capacity of these ships C_{ship}, to the maximum number of round-trips per year on that transportation arc $N_{ship,n,n'}^{rtrip}$, and to the maximum filling parameter η^{tank}:

$$\dot{Q}_{ship,n,n'} \le N_{ship,n,n'} \cdot C_{ship} \cdot N_{ship,n,n'}^{rtrip} \cdot \eta^{tank} \qquad \forall ship, n, n' \quad (27)$$

$$\dot{Q}_{ship,n,n'} \ge 0.8 \cdot N_{ship,n,n'} \cdot C_{ship} \cdot N_{ship,n,n'}^{rtrip} \cdot \eta^{tank} \qquad \forall ship, n, n' \quad (28)$$

where Eq. (28) allows some flexibility in the maximum filling of the ship.

4. Case studies

The economic model of ship-based CO_2 transport is tested by addressing the chain optimisation of a European infrastructure, according to the following assumptions:

- CO_2 capture is operated at large-scale industries (i.e., with an yearly emission of at least 1 Mt of CO_2/y for steel mills and refineries, and of at least 0.5 Mt of CO_2/y for cement plants) located in Southern Europe or, generally, in the vicinity of Mediterranean ports (d'Amore et al., 2021a). Overall, the model takes into account 5 steel plants producing 26.5 Mt of CO_2/y, 25 refineries generating 43.8 Mt of CO_2/y, and 42 cement plants emitting 33.1 Mt of CO_2/y (Fig. 4). These numbers correspond to 17%, 33%, and 23% of the European respective sectorial emissions. The levels of CO_2 emissions are retrieved from the European database provided by EEA (2021), and are assumed constant during a year time frame. Each emission point is associated to its nearest port; thus, the model does not include the capture stage associated to emission points, nor the transport of CO_2 from each emission point to its corresponding port.
- The CO_2 captured from industrial emitters is collected at existing strategic ports located in proximity to the plants (Fig. 4). As the case of onshore CO_2 unloading from the ship (i.e., S1) requires the presence of a sequestration hub prior to geological storage, the port of Stavanger is chosen for this purpose given its proximity to the North Sea storage area. The geographic location of ports is taken from World Port Sources (2022), while naval distances are evaluated from Sea-Distances (2022).
- In the case of onshore unloading (i.e., S1), an offshore pipeline infrastructure of 250 km of length is considered to connect the port of Stavanger to offshore geological sequestration. The unitary cost of this pipeline is derived from d'Amore et al. (2021b) and set equal to 0.0145 €/t of CO_2/km. This cost is summed up on top of expenditures alongside other stages i of Eq. (23).

The choice of the minimum CO_2 reduction target determines the optimisation case study: 'Global' and 'National' (Fig. 5). When considering the 'Global' reduction target, it is meant to reduce at least a portion α of the total CO_2 available from the capture plants:

$$\sum_n \dot{Q}_n^{tr} \ge \alpha \cdot \sum_n \dot{Q}_n^{capt} \quad (29)$$

The second reduction target is set on a 'National' scale (country-wise reduction target), meaning that the objective is to minimise the TC by imposing a lower bound on the CO_2 to be captured in each investigated country c:

$$\sum_{n \in c} \dot{Q}_n^{tr} \ge \alpha \cdot \sum_{n \in c} \dot{Q}_n^{capt} \qquad \forall c \quad (30)$$

5. Results

5.1. Baseline outcomes

The ship-based CO_2 transport chain MILP optimisation was carried out on a 3.0 GHz laptop with GAMS software, by using CPLEX solver. The optimisations always reached an optimality gap lower than 2%. Table 1 shows CAPEX^i and OPEX^i costs breakdown for the stages i of the investigated scenarios, for a carbon reduction target α of 50% (higher values are discussed subsequently). As for investment costs, liquefaction and the ships represent a significant share of CAPEX (about 10% and 40%, respectively), independently from the analysed scenario. Scenarios based on onshore unloading (i.e., S1) highlight the noticeable cost of offshore pipelines, which ranges between a minimum of 35% (national reduction target) up to a maximum of 39% (global reduction target) of CAPEX. Differently, the direct injection option (i.e., S3) exhibits a substantially higher conditioning cost with respect to that of alternatives, being it equal to 29% of CAPEX. In S2, the cost of unloading and FSI is

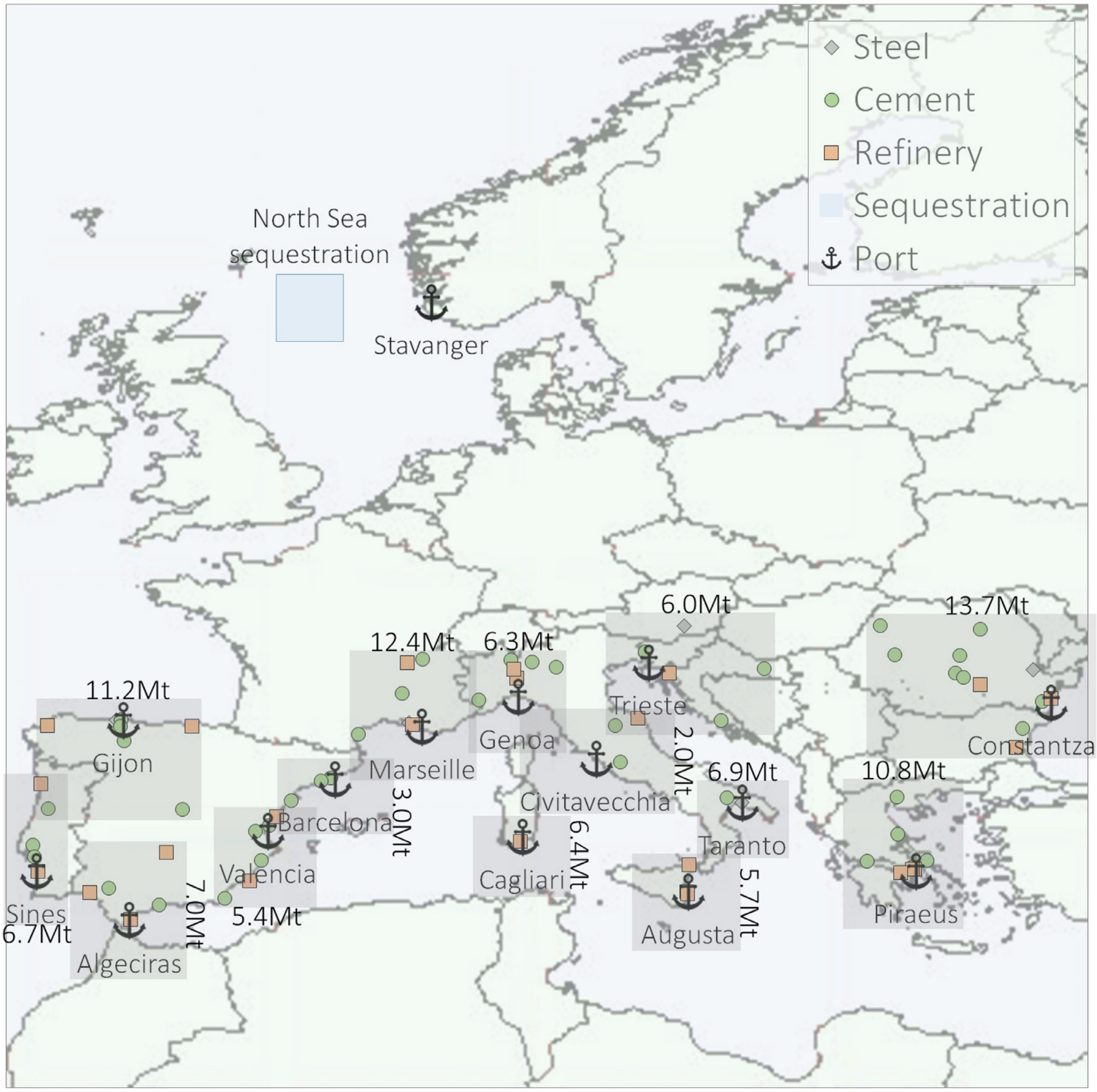


Fig. 4. CO_2 emissions [Mt/y], collection ports, and North Sea sequestration.

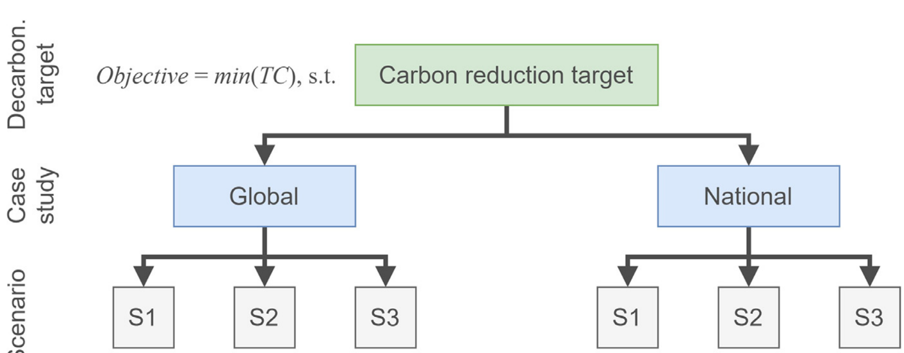


Fig. 5. Case studies (Global and National) and CO_2 unloading scenarios analysed: S1, port-to-port; S2, port-to-FSI; S3, direct offshore injection.

almost comparable to the investment for ships (about 30% of CAPEX). The total investment results between 7.5 and 9.4 B€ for the global case study, and between 9.0 and 10.6 B€ for the national case study. Operative expenditures are dominated by the yearly costs of ships (between 304 M€/y and 374 M€/y, i.e. between 40% and 44% of OPEX), followed by liquefaction (about 245 M€/y, i.e. between 27% and 33% of OPEX). The other stages i represent about 30% of the overall chain OPEX. Of the three CO_2 unloading scenarios, as in IEAGHG (2020), the most cost-effective one is S3, involving direct injection to the offshore well. This result is justified by the fact that S3 is the only scenario in which there

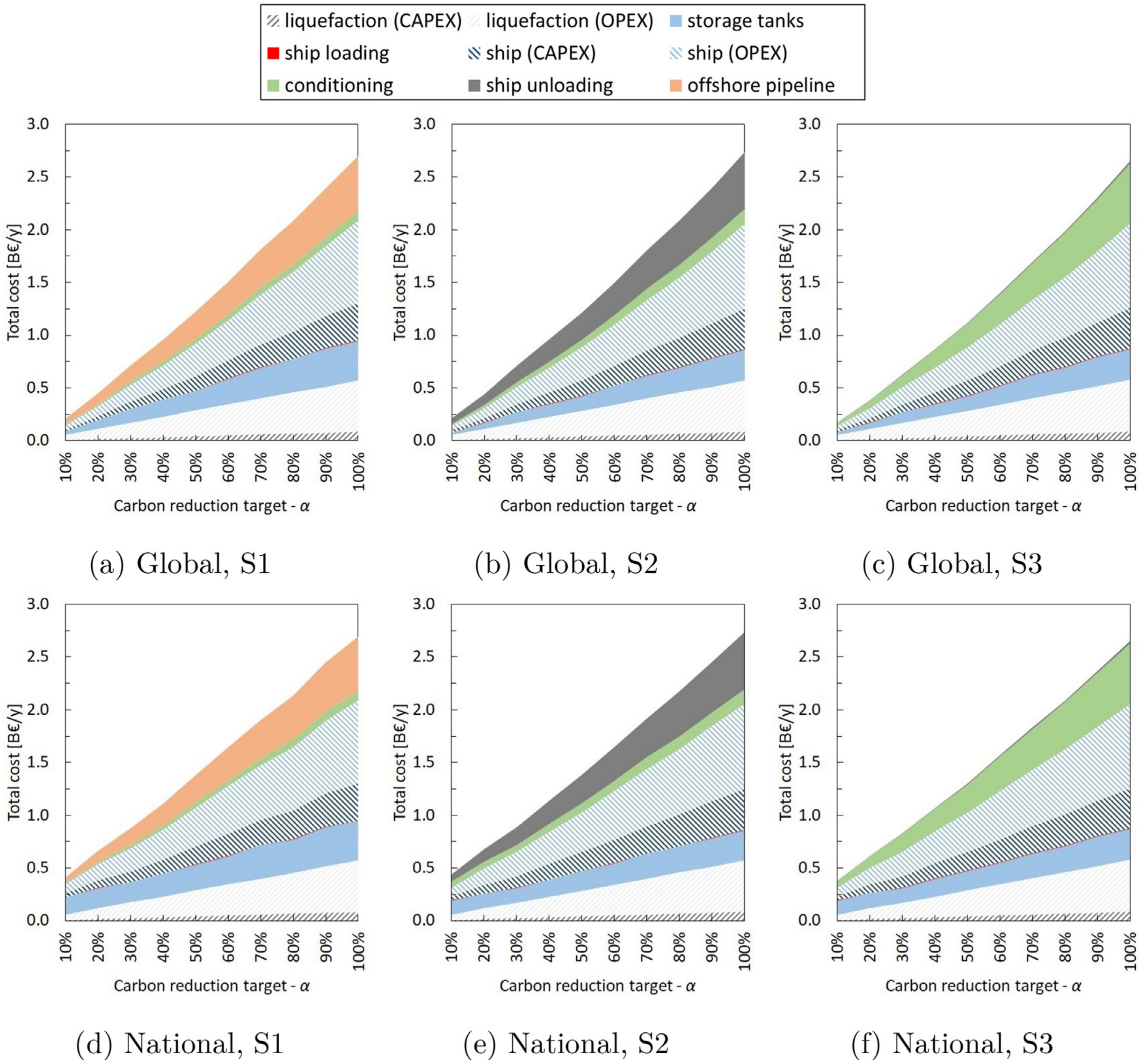


Fig. 6. Total cost [B€/y] for global and national carbon reduction target, depending on unloading case study (i.e., S1, S2, and S3).

Table 1
Resulting $CAPEX^i$ [M€] and $OPEX^i$ [M€/y] breakdowns of stages i for global and national carbon reduction target α of 50%, depending on unloading case study (i.e., S1, S2, and S3).

			$CAPEX^i$ [M€]							
Case study	Scen.	α	*liq*	*stor*	*load*	*ship*	*cond*	*unload*	*pipe*	Tot.
Global	S1	50%	854.5	1846.0	25.6	2747.2	220.7	0.0	3699.1	9393.0
Global	S2	50%	847.9	1384.5	25.6	2964.3	568.0	2610.6	0.0	8400.8
Global	S3	50%	847.9	1384.5	25.6	2964.3	2168.0	92.1	0.0	7482.4
National	S1	50%	863.8	2418.0	33.5	3356.2	223.1	0.0	3699.1	10593.6
National	S2	50%	851.1	1852.5	34.2	3574.8	760.0	2689.8	0.0	9762.5
National	S3	50%	866.1	1813.5	33.5	3554.5	2584.0	108.3	0.0	8959.9
			$OPEX^i$ [M€/y]							
Case study	Scen.	α	*liq*	*stor*	*load*	*ship*	*cond*	*unload*	*pipe*	Tot.
Global	S1	50%	244.3	92.3	1.5	304.3	34.9	0.0	74.0	751.3
Global	S2	50%	242.4	69.2	1.5	313.3	38.9	130.5	0.0	795.9
Global	S3	50%	242.4	69.2	1.5	313.3	118.0	4.6	0.0	749.1
National	S1	50%	247.0	120.9	2.0	369.0	35.3	0.0	74.0	848.1
National	S2	50%	243.4	92.6	2.1	373.6	48.6	134.5	0.0	894.7
National	S3	50%	247.7	90.7	2.0	372.2	139.0	5.4	0.0	856.9

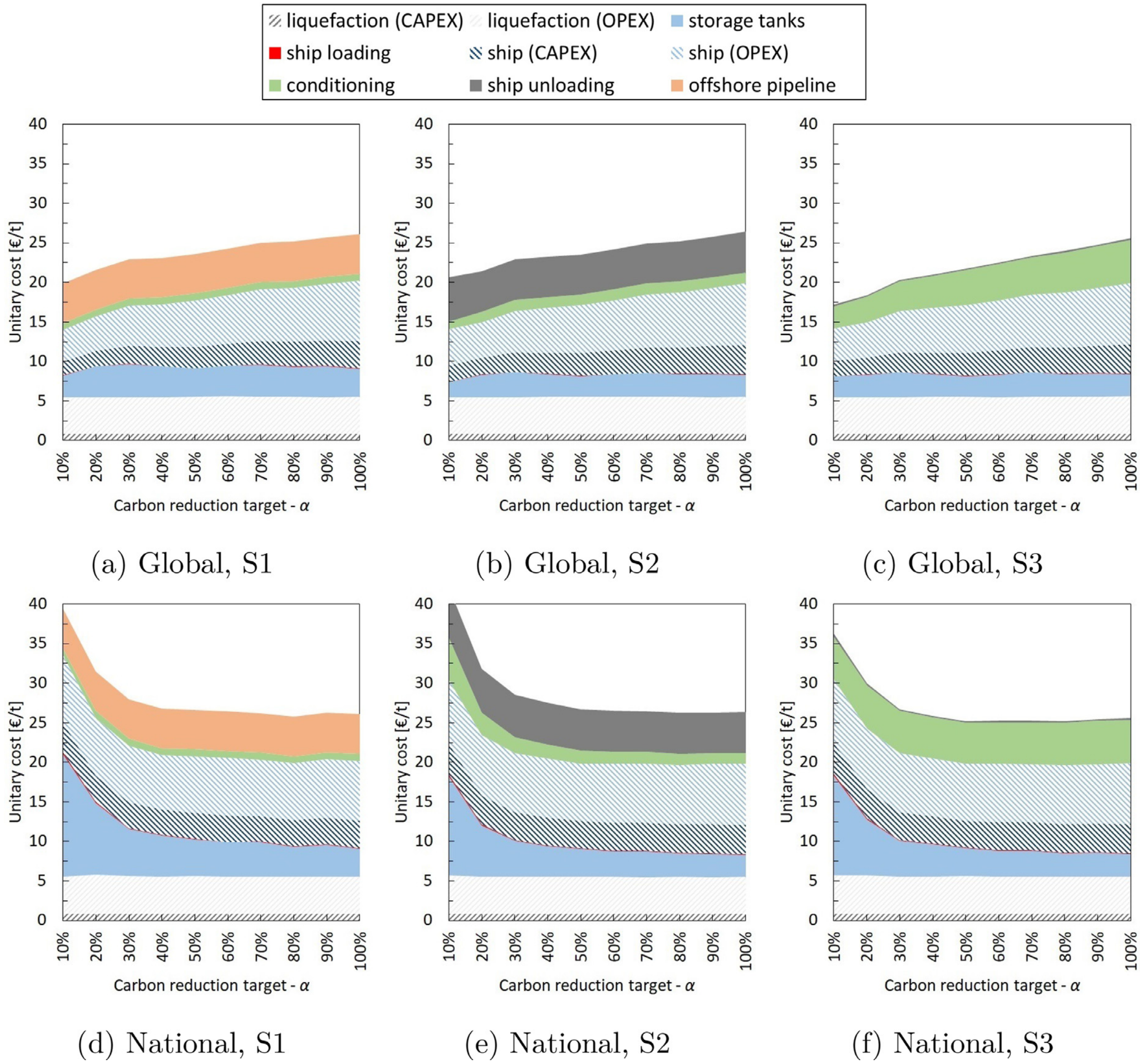
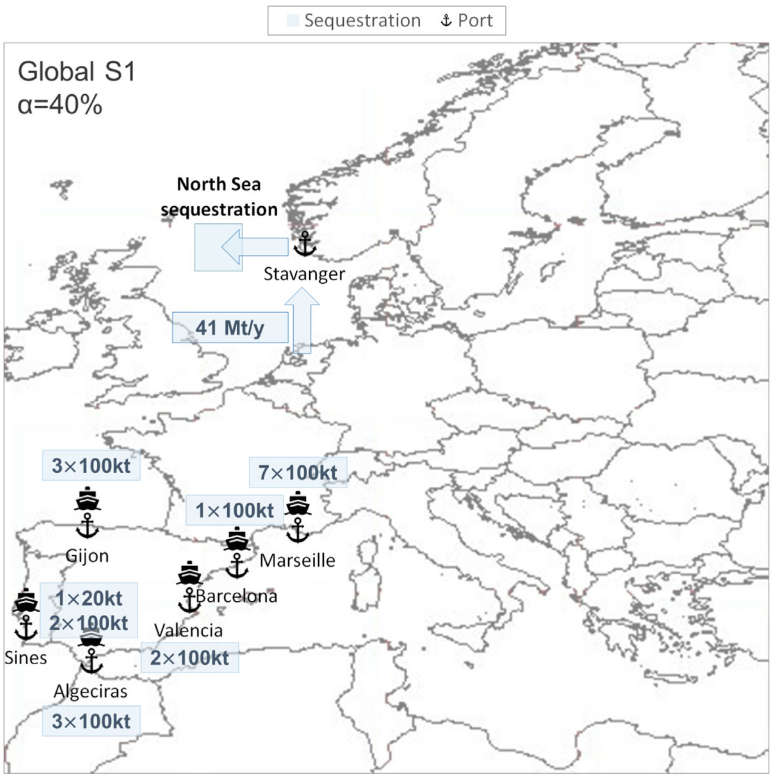


Fig. 7. Unitary cost [€/t of CO_2] for global and national carbon reduction target, depending on unloading case study (i.e., S1, S2, and S3).

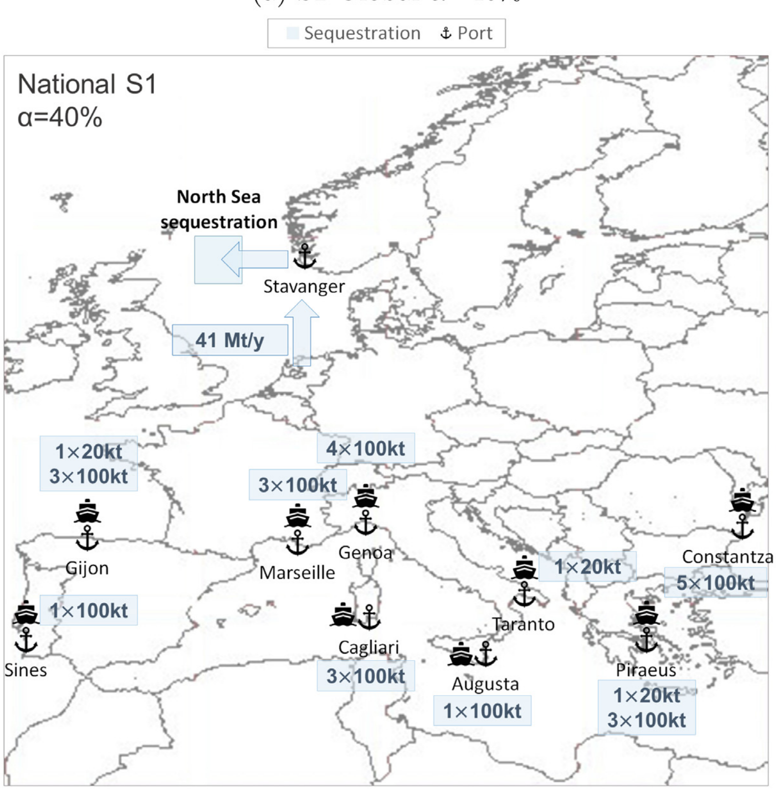
is no contribution in investment cost of the offshore pipeline infrastructure (which is needed in S1), nor of the FSI platform (which is installed in S2). As a consequence, the direct injection scenario has lower total and unitary costs, being just liquefaction and vessel costs the remaining cost drivers. However, S1 and S2 have the advantage of ensuring continuous injection of CO_2 to the well thanks to the buffer storage present onshore before the pipeline (S1) and on the FSI unit (S2). In contrast, direct injection (i.e., S3) involves discontinuous injection, which can be unfavourable in certain cases.

Among the analysed scenarios, those characterised by a global carbon reduction target α exhibit lower CAPEX and OPEX with respect to the national option (Table 1). This outcome reflects also in the resulting total costs (Fig. 6) and unitary costs (Fig. 7). Moreover, the cases based on a global reduction target are characterised by the lowest cost of ships, as these configurations are inherently designed to exploit the most cost-effective transport routes, whereas the national case study is logistically bounded and it represents a sub-optimal solution. In fact, in the global case study the optimal solutions tend to avoid as much as possible (i.e., for low values of α) the use of ports that are far from Stavanger, to minimise ship transport costs. As a result, optimal chains under a global reduction target tend in first instance to deploy few and large ships from Spain and Portugal for modest value of α, to then expand the CO_2 sourcing to other Mediterranean ports in France and Italy, and, finally, to Greece and the Black Sea. An increase of α leads to an increase in unitary cost due to the combination of additional onshore infrastructure present at more harbours, and progressively increased distances and sailing times being handled by more ships (Fig. 7a–c).

The optimal transport chains based on a national reduction target involve in general a more complex and long-distance CO_2 sourcing, even for moderate values of α (see the example for unloading S1 and α=40% in Fig. 8). In fact, the national case is designed to comply with a carbon reduction target that is set on a country-wise scale. As a result, the unitary costs decrease until about α of 50% and the remain roughly constant (Fig. 7 d–f). This trend is motivated by the fact that the number of ports selected hence, the average travel distance, increases slightly with α. Accordingly, unitary costs do not increase with α, but rather decrease due to scale effects of ship capacity on investment costs. This is testified by the variation of the number of ships deployed alongside an increase in carbon reduction target (Fig. 9). National case studies require more and larger vessels than their corresponding global ones for low carbon reduction targets α, as they need to transport the same amount of CO_2 of



(a) S1 Global α=40%



(b) S1 National α=40%

Fig. 8. Optimal ship-based CO_2 transport chain for unloading option S1 and α=40%, for: (a) global target, and (b) national target.

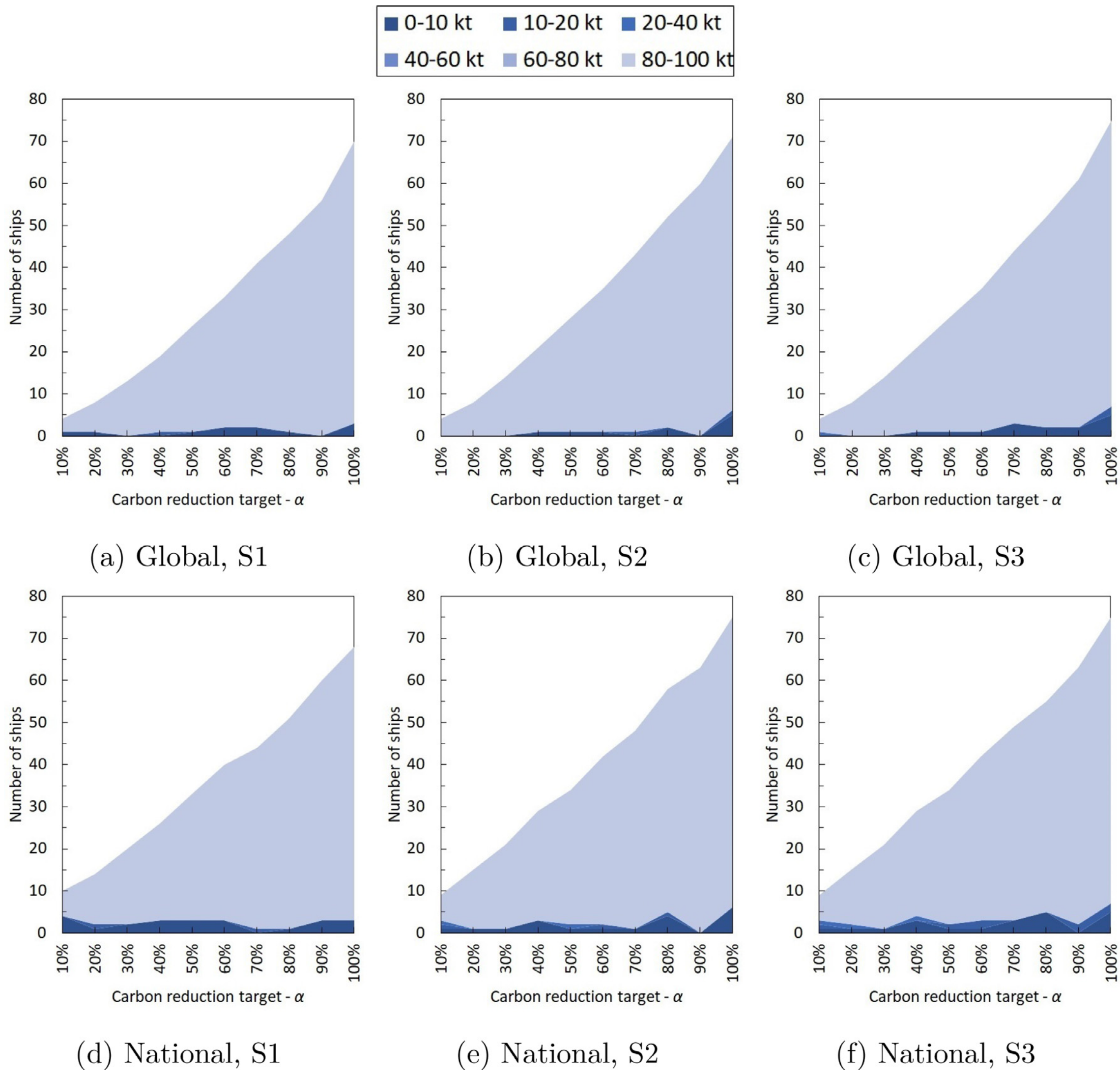
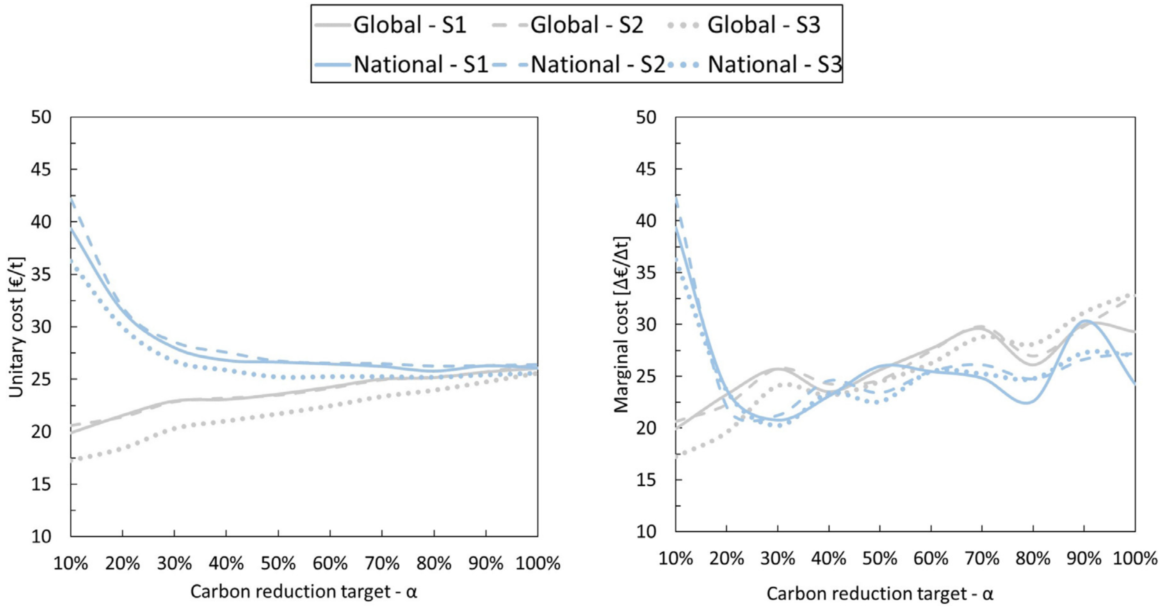


Fig. 9. Number of ships per class of transport capacity for global and national carbon reduction target, depending on unloading case study (i.e., S1, S2, and S3).

the corresponding global cases but for longer distances; this gap in the deployed number of ships between the two case studies closes for very high levels of α, as also global case studies require to source the CO_2 from ports that are progressively farther from the North Sea. All scenarios converge towards a similar value of total cost (about 2.7 B€/y) and unitary transport cost (about 26 €/t of CO_2) for a carbon reduction target α of 100%, which corresponds to a yearly transported amount of more than 103 Mt of CO_2/y (Fig. 10a). As a result, ship-based CO_2 transport through large-scale vessels (e.g., over 50 kt) would result cost competitive with pipelines for long-distance routes, e.g. to connect Greece with the North Sea (Table 2). Differently, considering in our modelling framework smaller-size vessels would determine the opposite outcome. In fact, it was verified, through a test run on the size of ships, that if the maximum capacity of ships was decreased from the baseline 100 kt to 50 kt, the minimum unitary transport cost would increase from roughly 26 to 28 €/t of CO_2 (i.e., +10%), mainly due to the higher investment for ships (on average, +38% in $CAPEX^{ship}$), while even smaller 10 kt vessels would produce a raise in unitary transport cost of about +94%, i.e. about 50 €/t of CO_2 (on average among S1, S2, and S3). As for marginal costs (Fig. 10b), under a national reduction target they decrease substantially for increases of small values of α, while in general they raise from about 20–25 €/t (α of 20%) to 25–30 €/t (α of 100%) for fully developed infrastructures (subject to strong economies of scale), with fluctuations related to the variations in the number of ships.

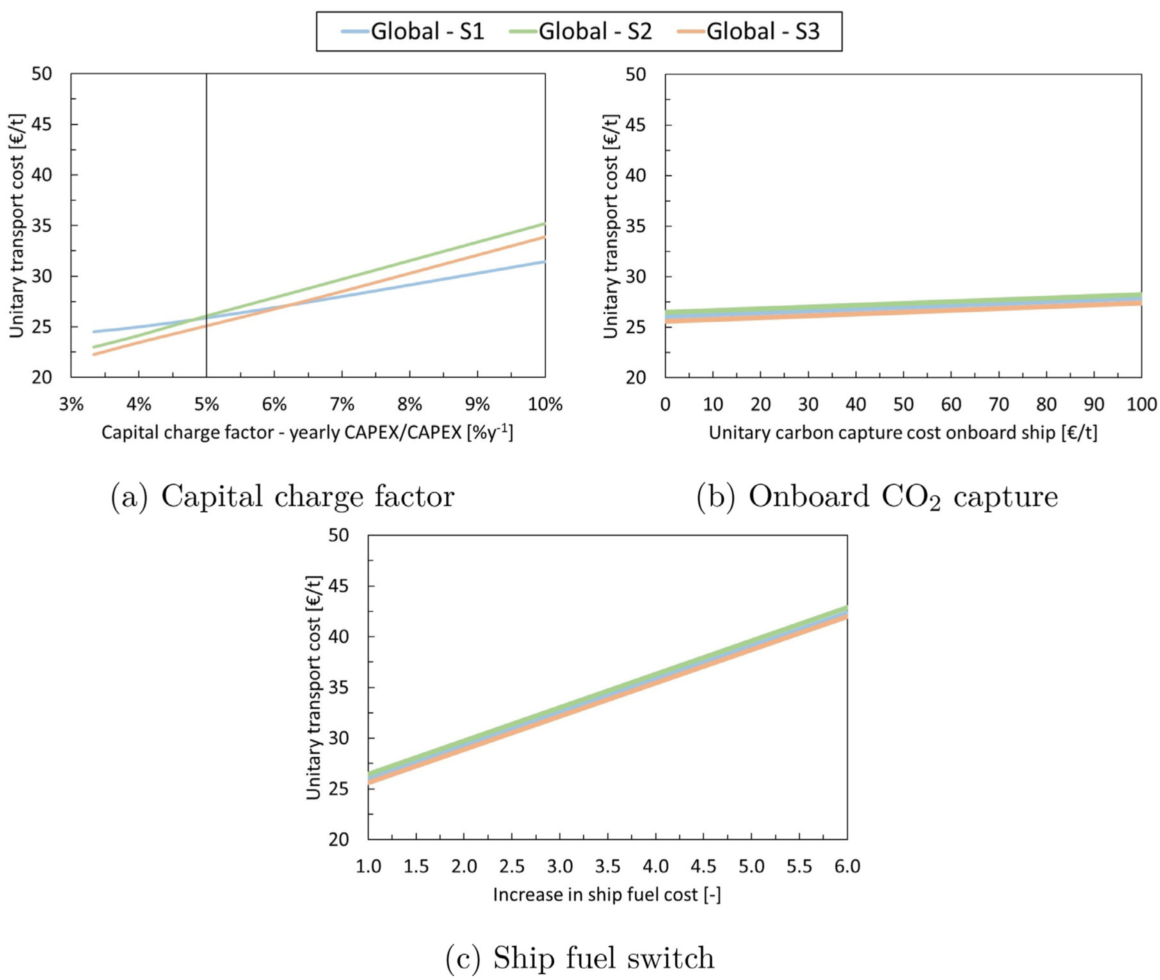
Table 2
Illustrative comparison between ship- and pipeline-based CO_2 long-distance CO_2 transport leg between Greece (port of Piraeus) and North Sea, in terms of unitary transport cost [€/t of CO_2] and number of ships. The total transported amount is 10.8 Mt/y of CO_2. As for the pipeline cost, this is based on the model proposed by d'Amore et al. (2021a).

Mode	Ship size [kt]	Vessels [ships]	Unitary cost [€/t]
Ship	10	81	55.4
Ship	20	41	36.0
Ship	50	17	31.1
Ship	100	9	28.1
Pipeline	–	–	27.1



(a) (b)

Fig. 10. Unitary transport cost [€/t of CO_2] and marginal cost [Δ€/Δt of CO_2], for the analysed scenarios and case studies.



(a) Capital charge factor

(b) Onboard CO_2 capture

(c) Ship fuel switch

Fig. 11. Sensitivity analyses on unitary transport cost [€/t of CO_2] for global case studies with carbon reduction target α of 100%: (a) test on capital charge factor [$\%y^{-1}$]; (b) test on onboard CO_2 capture, subject to variations in the unitary carbon capture cost [€/t of CO_2 captured]; and (c) test on ship fuel switch, subject to relative variations in the specific fuel cost (1=baseline value of 26.62 €/MWh).

5.2. Sensitivity analysis on capital charge factor

This section provides the results from the global optimisation case for unloading options S1, S2, and S3 and for the full decarbonisation case (i.e., carbon reduction target set at 100% of the emissions included in the modelling framework), under variations in the capital charge factor CCR between $3\%y^{-1}$ and $10\%y^{-1}$ (being $5\%y^{-1}$ the nominal value used in the previous results) (Fig. 11a).

It emerges that an increase in the capital charge factor from the baseline value of $5\%y^{-1}$ to a higher $10\%y^{-1}$ determines a raise in unitary transport costs from 25.9 to 31.5 €/t of CO_2 (S1), from 26.1 to 35.2 €/t of CO_2 (S2), and from 25.1 to 33.9 €/t of CO_2 (S3). Scenario S1 shows the lowest increase in unitary transport costs (+21.5%), with respect to S2 (+35.0%) and S3 (+35.0%). In fact, S1 is based on an onshore unloading infrastructure, which leads to lower CAPEX contribution in the overall chain cost when compared with S2 (which involves the use of the offshore injection platform) and with S3 (which involves conditioning and injection equipment installed onboard the ships).

5.3. Ship-related CO_2 emissions and effect of fuel cost

The CO_2 emissions from fuel combustion in the engines of the ships and from the generation of the electricity required for liquefaction are not significant (less than 2%) with respect to the amount of transported CO_2, even though this proportion may increase for very small-scale vessels due to the higher number of trips required (up to 8% for 1 kt ships) (Element Energy, 2018). Here, we test the economic outcome of choosing to capture this CO_2 (assumed as 2% of the transported amount) and to store it onboard the ship, by adding an additional CO_2 capture cost on top of the other expenditures of the transport chain (Einbu et al., 2022). In particular, we assume a capture efficiency of 90% and a unitary capture cost up to 50–100 €/t of CO_2 captured (compatibly with Awoyomi et al., 2020). Results from the global case studies under a carbon reduction target α of 100% are reported in Fig. 11b, and exhibit an increase in unitary transport cost of +3.5% (for 50 €/t of CO_2 captured) and +6.9% (for 100 €/t of CO_2 captured), which results from the additional expenses for onboard carbon capture, being these equal to 93 M€/y (for 50 €/t of CO_2 captured) and 186 M€/y (for 100 €/t of CO_2 captured).

Otherwise, ship-related CO_2 emissions could be avoided through a fuel switch to a low-carbon alternative, e.g. ammonia (Dolan et al., 2021), liquefied natural gas Deng et al. (2021), or other options such as biofuels and hydrogen (Xing et al., 2020), or electro-Fuels (e-Fuels) like e-Methanol (d'Amore et al., 2023). As this would increase the specific cost of the fuel by a factor 2–6 (Stolz et al., 2022), we tested the global case studies (with a carbon reduction target α equal to 100%) for higher values of this parameter (Fig. 11 c). It emerges that a doubled value of the specific cost of fuel would produce an increase in unitary transport cost to about 29 €/t of CO_2 (i.e., +11% with respect to the baseline case with a fuel cost of 26.62 €/MWh), while a 6 times more expensive fuel would lead to 42 €/t of CO_2 (i.e., +63%).

6. Conclusions

This study introduced an economic optimisation framework for designing liquefied CO_2 transport chains via naval vessels, in the context of decarbonising Southern European hard-to-abate industrial sectors. In particular, we included CO_2 emissions from 72 industrial plants (for a total of 103 Mt of CO_2 emissions per year), 14 CO_2 collection ports (located mainly in the Mediterranean area), 1 CO_2-to-storage hub in Norway (exploited in case of onshore ship unloading), and offshore storage basins located in the North Sea. The study was conducted on different unloading strategies: based on port-to-port shipping to Norway and subsequent offshore pipeline transport to permanent offshore sequestration (i.e., S1), on port-to-floating storage and injection unit (i.e., S2), or on direct offshore CO_2 injection (i.e., S3). It was found that:

- Though liquefaction and ship represented in all scenarios about 10% and over 40%, respectively, of the total chain investment, it was shown how the investment cost for ships is highly sensitive to the choice of the size of the vessel. Depending on the scenario, other significant investment costs were identified as: offshore pipelines (up to 39% of total investment, S1), floating platform for offshore injection (comparable investment to ships, S2), and CO_2 conditioning prior to offshore direct injection (S3). As expected, the variable costs were dominated by the operation of the ships and of the liquefaction plants.
- The unitary ship transport cost for the full-scale chain (i.e., handling 103 Mt/y of CO_2) was found equal to 26.1 €/t (S1), 26.4 €/t (S2), and 25.6 €/t (S3). Even though S3 appeared as the most cost-effective scenario, these differences in costs are relatively small, if acknowledging the uncertainty in model parameters. Plus, S3 could be a disadvantageous design due to its discontinuous operation given by the lack of buffer storage tanks prior to injection.
- As annualised capital costs represent a significant share of total annual costs, the capital charge factor (which depends on the lifetime of the infrastructure and on the discount rate) plays an in important role in the overall economic assessment. For instance, it was verified that for the full scale infrastructure an increase in capital charge factor from $5\%y^{-1}$ to $10\%y^{-1}$ would produce an increase in unitary transport costs between +21.5% (S1) and +35.0% (S2 and S3).
- Those case studies optimised on a global basis (in which the chain exploits the ports located as near as possible to the North Sea storage) were characterised by an increasing marginal cost with progressively larger carbon reduction targets, while the cases optimised on a national level (in which a carbon shipping target is set on a country-wise scale) showed a sudden decrease in marginal cost with modest (lower than 20%) carbon reduction targets, to then becoming more stable as soon as they reached sufficient size to benefit scale effects.
- For large amounts of CO_2 to be transported (e.g., Mt/y) it is crucial to adopt ships with high transport capacity to exploit the economies of scale and obtain competitive transport costs. For instance, to transport 10 Mt/y of CO_2 from Greece to the North Sea, the adoption of large-scale vessels with capacity higher than 50 kt compared to 10 kt of CO_2, allows to reduce the unit transport cost from 55 €/t to about 30 €/t, which is a competitive cost compared to pipeline transport.
- Though CO_2 emissions produced by the engines of the ships were found in limited amount with respect to the transported CO_2 (about 2%), the decarbonisation of these would lead to an increase in transport costs of +7% for the case of onboard CO_2 capture and storage at 100 €/t of CO_2, or between +10% and +60% in the case of fuel switch to a low-carbon alternative, with unitary cost 2–6 times higher than the reference cost.

Overall, this study hints at the potential competitiveness with pipelines of ship-based CO_2 transport through large vessels, to link the Mediterranean area to the North sea, which may be representative of a long-term perspective in which lower capacity CO_2 storage sites in Southern Europe may become insufficient to store large quantities of CO_2 from industrial emitters. Nevertheless, the high cost of CO_2 transport from the Mediterranean area to the North Sea for low amounts of captured CO_2 highlights the importance of exploiting the local Mediterranean CO_2 storage capacity in the initial phases of the value chain deployment, to achieve competitive costs of CO_2 avoidance.

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.

CRediT authorship contribution statement

Federico d'Amore: Conceptualization, Methodology, Supervision, Writing – original draft, Data curation, Formal analysis, Investigation, Writing – review & editing. **Luca Natalucci:** Data curation, Formal analysis, Investigation. **Matteo C. Romano:** Conceptualization, Methodology, Supervision, Writing – review & editing.

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Supplementary material

A Supplementary Material is attached to this article and comprises: additional information on the economic model, the economic model validation with data from the literature, the comparison of the economic results for liquefaction of unpressurised CO_2, the calculation of distance breakdown cost between ship- and pipeline-based CO_2 transport, and a test on variations in the unitary cost of electricity. Supplementary material associated with this article can be found, in the online version, at 10.1016/j.ccst.2023.100172

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