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CO_2 transport for fast-track CCS: Balancing economics and environmental impacts in industrial clusters

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ABSTRACT

Carbon Capture and Sequestration is a key technology for decarbonizing energy-intensive industries and power generation. To accelerate its deployment, affordable and efficient carbon dioxide (CO_2) transport solutions are needed. In this paper a tiered multi-objective optimization method is developed to predict a hierarchy of CO_2 transport strategies, balancing the financial costs and environmental impacts. The method is applied to optimize the strategies for collecting CO_2 from five energy-intensive industries in the North Sea Port industrial cluster. The results show that a low pressure (35 bar) CO_2 collection pipeline network and a point-to-point CO_2 transport by barges (the 'hub and spoke' design) are the two most optimal (tier 1) competitive strategies. Lower-tier solutions involving using higher pressure (110 bar) pipelines and 'milk round' shipping of CO_2, come at greater costs and larger environmental impacts. The costs and environmental impacts are largely attributed to the electricity consumed in CO_2 compression and liquefaction. The use of a low-carbon electricity mix is shown to reduce the environmental impacts by ca 80 % across all the scenarios studied. The study concludes that paying for unabated emissions during two years of construction of the CO_2 pipelines nearly doubles the cost of the project, making CO_2 shipping the more cost-effective solution.

1. Introduction

A majority of the world's nations have signed the 2015 Paris Agreement to limit global warming to 1.5 °C, necessitating unprecedented changes in scale and rate of reduction of the anthropogenic greenhouse gas emissions (UNFCCC, 2015). It is widely recognized that timely and efficient mitigation of climate change requires implementing a whole set of decarbonization measures. These include Carbon Capture and Sequestration (CCS), improving energy and process efficiency, using feedstock circularity, CO_2 utilization, and electrification and switching to renewable energy sources (wind, solar, geo-thermal, etc.) (IEA 2020; European Commission 2019; Smart Delta Resources 2020). Also, Carbon Dioxide Removal (CDR) from the atmosphere complements the above set of technologies, aiming to reach net-zero CO_2 emissions and limit global warming to 1.5 °C above the pre-industrial level. Among the decarbonization measures, CCS is a crucial set of technologies being developed to mitigate CO_2 emissions from energy-intensive industries and power generation. CCS complements the transition to renewable energy sources, green hydrogen, and bio-energy, as recognized by the IPCC and IRENA (IRENA 2021; IPCC, 2022) and aligned with the UN Sustainable Development Goals (Mikunda et al., 2021) and the EU's 2050 net-zero targets (European Commission 2019).

While there is a clear need for CCS, particularly in industrial clusters such as the North Sea Port (NSP) cluster, which emits over 21 Mt of CO_2 annually (North Sea Port 2022; CUST, 2019), its deployment is currently hampered by several factors, including high costs and a lack of investment in the necessary CO_2 transport infrastructure (Ejeh et al., 2022). To

Abbreviations: AMG, ArcelorMittal Ghent; CAPEX, Capital Expenditure; CCS, Carbon Capture and Sequestration; CO_2 eq., With reference to emissions of greenhouse gases that have the same global warming potential as the equivalent amount of CO_2; DALY, Disability-adjusted life year; EE, Engie Electrabel; ETS, Emission Trading System; GHG, Greenhouse Gas; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; LPG, Liquefied Petroleum Gas; NSP, North Sea Port; OPEX, Operational Expenditure; SI, Supplementary Information; TEA, Techno-Economic Assessment; TMOO, Tiered Multi-Objective Optimization; ZR, Zeeland Refinery.

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Nomenclature

C^{ship}	Conditioning and transport lifetime cost for shipping €/t_{CO2}
$C^{tonnage}$	Tonnage cost for shipping €/t_{CO2}
$C^{mileage}$	Mileage cost for shipping €/(t_{CO2} km)
C_{pipe}	Conditioning and transport lifetime cost for pipeline €/t_{CO2}
$COST$	Total levelized costs €/t $_{CO2}$
$CAPEX$	Capital expenditure €/t $_{CO2}$
$CAPEX_{PV}$	Present value total capital costs €
CRF_{oper}	Capital recovery factor over the project lifetime –
E_{comp}	Energy requirement for CO_2 compression kWh/t_{CO2}
E_{cool}	Energy requirement for cooling kWh/t_{CO2}
ETS	The ETS annual penalty €/t_{CO2}
ETS_{PV}	Present value ETS costs €
ETS_t	Annual ETS price €/t_{CO2}
f^{load}	Multiplier for loading and unloading time –
f^{safety}	Safety factor for interim storage –
i	Index for route or emitter –
J	Synthetic objective function (eq (7)) –
$J_{j,k}$	Normalized objective j for the transport case k –
k_{max}	Total number of infrastructure cases –
n_{max}	Number of weight discretization points –
l_i	Length of the i^{th} route km
LC	Levelized costs €/t_{CO2}
$O_{1,k}$	Cost of the transport case k €/t_{CO2}
$O_{2,k}$	Global warming impact of the transport case k $kg_{CO2\text{-}eq}$/t_{CO2}
$O_{3,k}$	Human health impact of the transport case k DALY/t_{CO2}
$O_{4,k}$	Ecosystems impact of the transport case k y/t_{CO2}
$OPEX_{var}$	Variable operating expenditure €/y
$OPEX_{fix}$	Fixed operating expenditure €/y
$OPEX_{PV}$	Present value total operating costs €
$OPEX_t$	Annual operating costs €/y
p	Number of Pareto-optimal solutions –
P	Set of Pareto-optimal solutions –
q_i	CO_2 flowrate from emitter i / Annual throughput of the pipeline t/y
q	CO_2 amounts transported by the network t/y
Q	Set of cases under optimization –
r	Discount rate –
rk	Rank (tier) of Pareto-optimal solution –
$S^{H\&S}$, S^{MR}	Interim storage capacity for the hub and spoke (H&S) and milk round (MR) strategies t_{CO2}
t_i^{cycle}	Roundtrip sailing time of the i^{th} route h
t	Time y
t_{constr}	Construction duration y
t_{oper}	Project lifetime y
v^{ship}	Ship speed km/h
w_i	Weighting factor for objective i –

overcome these barriers, particularly financial risks for first-of-a-kind projects, governmental intervention is needed to provide the required regulatory, policy, and societal supporting framework to provide revenue stability for CCS (C4U, 2024; Durusut and Mattos, 2018; Swennenhuis et al., 2024). In the EU, the state regulatory mechanisms include the Emissions Trading System (ETS) (EC, 2023) and the Carbon Border Adjustment Mechanism (CBAM) (EC, 2023). Importantly, the expected stricter regulations and higher future ETS price on CO_2 emissions create urgency for finding optimal CO_2 transport solutions based on pipelines and also interoperable and modular/mobile modes of transport (Lockwood and Bertels, 2022; Oeuvray et al., 2022).

In the context of CCS, where CO_2 is not a valuable commodity, minimizing the costs of CO_2 transport and storage infrastructure is essential for the economic viability of CCS projects. High-pressure pipelines are commonly considered to be the most economic option for transporting large quantities of dense-phase CO_2 (Doctor et al., 2005), while low-pressure pipelines may be justified for transporting gaseous CO_2 over short distances (Roussanaly et al., 2013). For transporting small amounts of CO_2 and short-duration projects, mobile modes of CO_2 transport, such as trucks, barges and ships, can be more cost-effective than pipelines (Becattini et al., 2022; Geske et al., 2015), while offering greater flexibility (Al Baroudi et al., 2021; Aspelund et al., 2006; IEAGHG, 2020). In industrial clusters with multiple emitters aiming for the same storage location, using shared CO_2 transport and storage infrastructure has been shown to significantly reduce the transportation costs and economic risks for the cluster (Brownsort et al., 2016; Chandel et al., 2010). Additionally, shipping CO_2 from emitters in a CCS cluster to a collection hub for subsequent offshore pipeline transportation can be more economical than shipping CO_2 directly to the offshore storage location from individual emitters (IEAGHG, 2020).

However, while mobile CO_2 transport solutions can accelerate the rollout of CCS (Becattini et al., 2024; Oeuvray et al., 2022), the deployment of ready-to-use fossil-fuel-operated transport modes comes with a significant environmental burden due to associated CO_2 emissions (Burger et al., 2022). In particular, recent studies, primarily focused on long-distance CO_2 transport, showed that trucks, railway and ship transport can have much higher life-cycle operational impacts than the pipelines (e.g., (Burger et al., 2022; Burger et al., 2024; Dong et al., 2025; Nöhl et al., 2025)). Partially this can be attributed to the fact that for large-volume long-distance CO_2 transport via pipelines, the environmental impacts of the construction and conditioning are relatively low (e.g., (Dong et al., 2025)). In contrast, for mobile modes of transport, the source of energy, e.g., in the form of fossil fuel, or electricity consumed for operation and conditioning, can have large environmental impact. As a result, short-distance, low-volume CO_2 transport solutions are more case-specific and require more detailed and careful approaches to analyze their costs and environmental impacts. Furthermore, decision making on CO_2 transport infrastructure is influenced by additional factors, such as public acceptance, environmental impacts and construction time (Oeuvray et al., 2024). Given these challenges, particularly the need to balance cost, environmental impacts, and other non-economic factors, this study seeks to develop a multi-objective optimization method that addresses these complexities head-on. By systematically evaluating CO_2 transport solutions, we aim to offer a comprehensive approach that integrates both economic and environmental considerations, ensuring that CCS projects, especially within industrial clusters like the NSP, are not only viable but also sustainable.

In the past, methods and tools have been developed for the techno-economic optimization of CO_2 transport infrastructure, primarily focusing on pipelines and ships, and for the multi-criteria optimization of CO_2 transport chains and pipeline networks at large scale (e.g., (D'Amore et al., 2018; Fraga et al., 2023; Lee et al., 2017; Middleton and Yaw, 2018)). To evaluate environmental impacts of CCS and CO_2 transport technologies, various approaches are used. A simple way of accounting for CO_2 emissions in the CCS chain design optimization is to calculate costs using the CO_2 avoided concept (Fimbres Weihs and Wiley, 2012; Oeuvray et al., 2022) and set constraints according to the emission reduction targets specified for a given period (Becattini et al., 2022; Leonzio et al., 2019; Wang et al., 2020). However, recent studies have shown that aggregating GHG life cycle emissions in the annualized cost of CO_2 pipeline transport (calculated either as the cost of CO_2 avoided or incorporating the penalties for additional CO_2 emissions) may underestimate the CO_2 emissions factor compared to a multi-objective approach, which offers better flexibility in balancing the environmental and economic objectives (Zanobetti et al., 2023). Separating costs and environmental impacts can also be beneficial when the environmental impacts, predicted using Life Cycle Assessment (LCA) method (see, e.g., (Bisinella et al., 2022; de Kleijne et al., 2022; Volkart et al., 2013)), vary depending on the energy source (e.g., fossil-fuel-based or renewable electricity) or project duration (Burger et al., 2022).

Multi-objective optimization is particularly useful for balancing costs, environmental impacts and other factors, including the speed of deployment of CO_2 transport infrastructure. This is especially important for transport modes like pipelines and ships/barges, relevant to industrial CCS clusters in the coastal regions of the North Sea (Aramis, 2023; Equinor, 2019; Fluxys, 2023), where these factors may not correlate, necessitating case-by-case assessment. When planning CO_2 transport infrastructure for clusters and regions, single- and multi-objective optimization methods are often combined to determine solutions that satisfy several specified criteria simultaneously (D'Amore et al., 2018; Fraga et al., 2023; Lee et al., 2017; Middleton and Yaw, 2018). Although most current CO_2 transport design optimization models employ a single cost-based objective, the influence of other criteria on the optimal solution is comparatively less explored.

It should also be noted that while multi-objective decision analysis provides a useful framework, this solution may become invalidated in some practical situations where additional criteria or constraints are imposed on the system design *a posteriori*, e.g., due to permitting issues at later stage of the project. In such cases, finding a range of optimal and sub-optimal solutions enables more flexible design that can accommodate new circumstances, offering better security for the CCS infrastructure project. It is noteworthy that in recent years methods have been developed to aid the selection of the optimal non-dominant solutions from a Pareto front (e.g., TOPSIS, LINMAP, FUKA, VIKOR, PROMETHEE, ELCTRE, *etc*.), with Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Grey Relational Analysis (GRA), and Simple Additive Weighting (SAW) being most simple and robust for practical implementation (Vassoney, 2021; Wang and Rangaiah, 2017). Furthermore, techniques for ranking the sub-optimal solutions that enable constructing Pareto fronts of various fitness levels, have been developed with application to various engineering problems (e.g., (Abonyi et al., 2023) and (Behzadian, 2012; Yao, 2023; Zanobetti, 2025)), although none were directly applied to optimization problems in the field of CCS.

In this context, the present study aims to (a) develop a multi-objective optimization method for systematically evaluating the costs and environmental impacts of CO_2 transport solutions for CCS clusters implementing the well-established methods of Techno-Economic Assessment (TEA) and LCA, and (b) apply this method to compare the performance of realistic CO_2 transport strategies, including shared pipeline infrastructure and barges, proposed for aggregating CO_2 in the NSP cluster before transporting it to geological storage locations. Section 2 describes the methodology of the study, including:

- Design strategies for CO_2 transport in the NSP cluster,
- The feasible CO_2 transport options for a realistic cluster CCS scenario,
- TEA model for sizing and costing of CO_2 transport systems,
- LCA methods for evaluating the CO_2 transport system's environmental impacts,
- Tiered Multi-Objective Optimization (TMOO) model developed for determining optimal CO_2 transport solutions for the cluster.

Section 3 reports the network costs and environmental impacts of CO_2 transport in the NSP via the different modes. It also describes the results of the TMOO and the scenario analyses of the impacts of the construction delay and electricity mix on the costs and environmental impacts.

Section 4 presents the discussion of the results and the methods applied, while the conclusions for the study are stated in Section 5.

2. Methodology

2.1. Aims and scope

In the present work, TEA and LCA were applied to assess the financial costs and environmental impacts of intra-cluster CO_2 transport in the NSP industrial cluster. To align the TEA and LCA, a single functional unit was defined: conditioning, storing, and transporting 1 tonne of CO_2 from the capture points to an offtake point within the NSP. All flows in the TEA and LCA were related to the functional unit. Fig. 1 shows the NSP region, located between Ghent in Belgium and the Western Scheldt estuary in the Netherlands, along with locations of five major industrial CO_2 emitters considered in the present study. The CCS transport solutions were proposed to handle all of the planned CO_2 emissions from the five industries in 2030 (CE Delft 2018; Smart Delta Resources 2020), as shown in Table 1. Decarbonization plans for industrial CO_2 emitters and the power sector rely on several measures, including CCS/CCU, electrification, switching to renewable energy, using green and blue hydrogen, implementing technology innovation and improving feedstock circularity. In line with the European Union ambition to decarbonize the industrial, transport and energy sectors by 55 % in 2030 as compared to 1990 levels and achieving carbon neutrality by 2050 (EC, 2019; The Council of the EU and the European Council 2025), the consortium of industries in the NSP region has set plans to reduce the CO_2 emissions by ca 52 % by 2030, with 27 % coming from implementing CCS, ca 2 % via electrification, 9 % by implementing hydrogen and CCU, and 14 % using other measures (SDR 2020). In the NSP region, ca 90 % of CO_2 emissions come from major industrial plants that include ArcelorMittal steel plant, Engie Electrabel (EE) Knippegroen power station, Dow Benelux plastics and basic chemicals plant, Yara Sluiskil mineral fertilizer and ammonia plant, and Zeeland Refinery plant. Table 1 shows the historical data on the CO_2 emissions from the five industries in the years 2019 and 2024 (EEA Data Hub 2022), and estimated amounts of CO_2 to be captured for CCS by the industries in 2030. These projections are made assuming ca 30 % of captured CO_2 is destined for storage (in line with the 27 % target set in (SDR 2020)), except for ZR, which targets about 0.8 Mt/year (CE Delft 2018) and the EE plant, which operates on AMG off-gases and can be decarbonized through CO_2 capture at AMG to produce H_2-rich fuel (Fernandez et al., 2025). The total amounts of CO_2 emissions targeted for CCS from the industries sum to ca 4.9 Mt_{CO2}/year, which fall within the range of recent projections made for the region (3.7 Mt_{CO2}/year (CE Delft 2018) and ca 6 Mt_{CO2}/year (SDR 2020)).

Two CO_2 transportation modes, namely pipelines and barges, were considered realistic and modelled for the NSP cluster. Truck and railway transport were not included, as they were shown to be only relevant for transporting CO_2 amounts of an order of magnitude smaller than those in the NSP cluster (Becattini et al., 2022). Similarly, the use of pipelines to transport low pressure flue gas rather than captured CO_2 is only appropriate for small flows (Gunawan et al., 2024). Four strategies implementing the two chosen modes of transport were considered for further optimization, as shown in Fig. 2. Pipeline transportation included low- and high-pressure cases. For barges, 'hub and spoke' and 'milk round' strategies were studied, where the topology and infrastructure required for each strategy are schematized in Fig. 2 with Table 2 stating the CO_2 transport conditions for each strategy. In the hub and spoke strategy, each emitter has an associated barge that carries CO_2 to the offtake point. In the milk round strategy there is a single ship that collects CO_2 from each emitter in a circuit. While optimal CO_2 shipping conditions for CCS is the ongoing subject of research, these typically fall

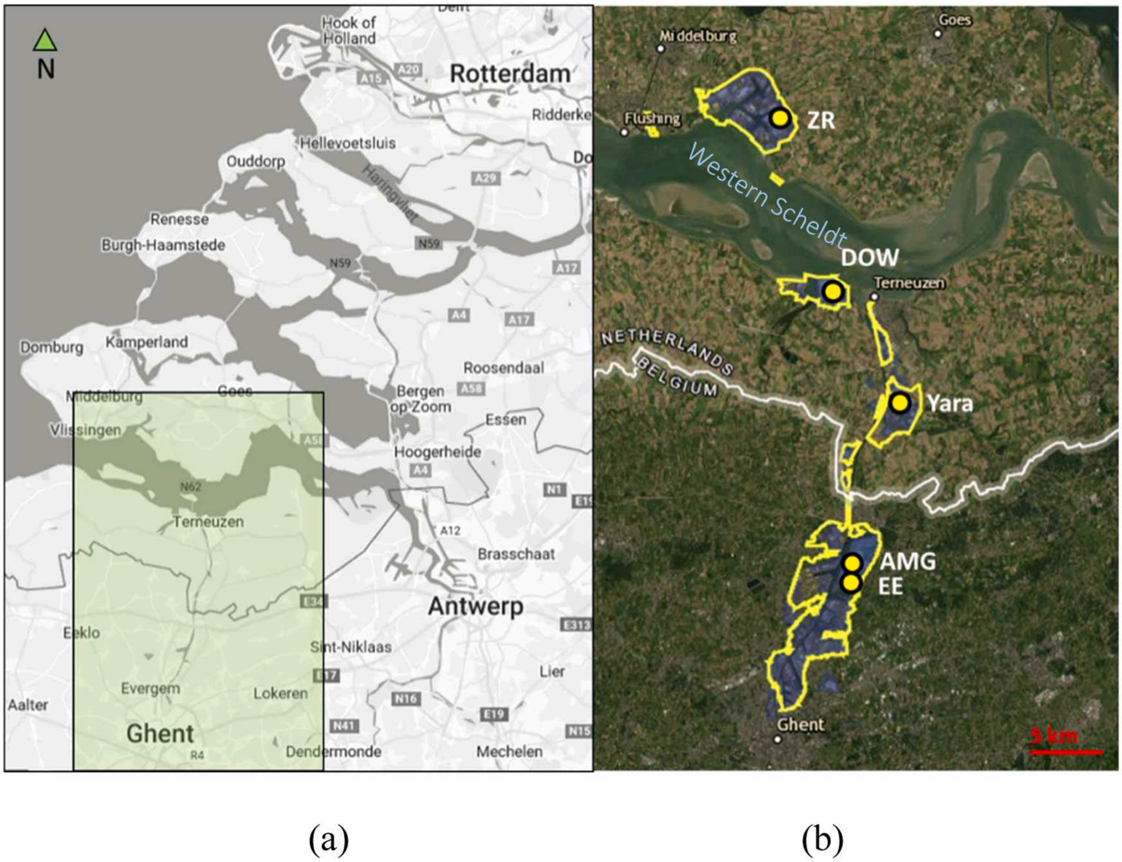

Fig. 1. Maps of the NSP region at the border between Belgium and Netherlands (a) and a zoom-in on the region (b), showing locations (dots) of the five CO_2 emitters considered in the present study. Figure b) from https://northseaport.maps.arcgis.com/home/index.html.

Table 1
CO_2 emissions reported in 2019 and 2024 (EEA Data Hub 2022) and the estimated annual amounts of CO_2 targeted for CCS in 2030 for the five industries in the NSP cluster.

Emitter	CO_2 emissions (Mt/y)		CO_2 captured for CCS 2030 targets (Mt/y)
	Year 2019	Year 2024	
Zeeland Refinery (ZR)	1.59	1.53	0.8
DOW	4.04	3.31	1.4
Yara	3.45	3.08	0.9
ArcelorMittal Ghent (AMG)	4.33	4.58	1.2
Engie Electrabel (EE)	5.08	4.60	0.6

within the range from ‘low pressure’ (–48 °C and 7 bar) to ‘high pressure’ (10 °C and 44 bar) (Element Energy, 2018). In the present study, given significant experience with commercial transport of food grade CO_2 at ‘mid pressure’ 20 bar and –30 °C, the latter conditions were chosen for shipping scenarios and the onward transport of CO_2. More details on the CO_2 processing steps corresponding to the different transport strategies are provided in the Supplementary Information (SI) (Figures S1 and S2). Two offtake points were also considered for both modes of transport, at Yara and at AMG. Finally, for the milk round scenarios, north and south directions were considered for each offtake point. This yielded a total of 10 cases, as shown in Table 2.

Gate-to-gate system boundaries are defined, starting after the carbon capture system and ending with CO_2 ready for long-distance transport outside the NSP. CO_2 capture, terminal storage, and onward transport outside the NSP were not included as they occur independently of the comparisons studied here. For all the strategies, it was assumed that at each source the captured CO_2 is available at 5 bar and 40 °C and has high purity. This is justified for CO_2 streams from hydrogen production via methane reforming at Yara, DOW and ZR. At AMG and EE gas-fired power station, suitable CO_2 capture and purification technologies (e.g., solvent-based post-combustion capture or CASOH and DISPLACE sorbent technologies (C4U, 2020)) can be used to meet the CO_2 purity specifications required by the transport and storage operators (Equinor, 2019; Aramis, 2023; Fluxys, 2022). The liquid CO_2 conditions for transport and hub storage were chosen based on the literature recommendations and specifications for planned projects (IEAGHG, 2020; Equinor, 2019; Element Energy, 2018). At the delivery end of the intra-cluster transport network, the CO_2 is assumed to be liquefied for terminal storage for onward transport, allowing a consistent final state at 20 bar and – 30 °C (see SI, Figures S1 and S2). The elements of infrastructure required for each of the strategies are shown in Fig. 2.

2.2. CO_2 transport network operational capacity

In the case of pipeline transport, the pipeline sizes were optimized in order to minimize the lifetime costs, defined as the sum of pipeline CAPEX and the OPEX (Ejeh et al., 2023). In the present study, the Mixed Integer Non-Linear Programming (MINLP) model was used to solve for the standard pipeline internal/external diameter pairs that minimize CAPEX subject to constraints on mechanical integrity, flow velocity and pressure drop. The maximum pressure drop on each pipeline arc was constrained to 2.5 % to avoid the need to specify boost compression. In order to account for the OPEX in the cost budget, the MINLP model was run for a set pressure drop (established in a preliminary study) to determine the optimum pipe size corresponding to minimum total costs.

CO_2 ship transport was optimized by a scenario approach, with the

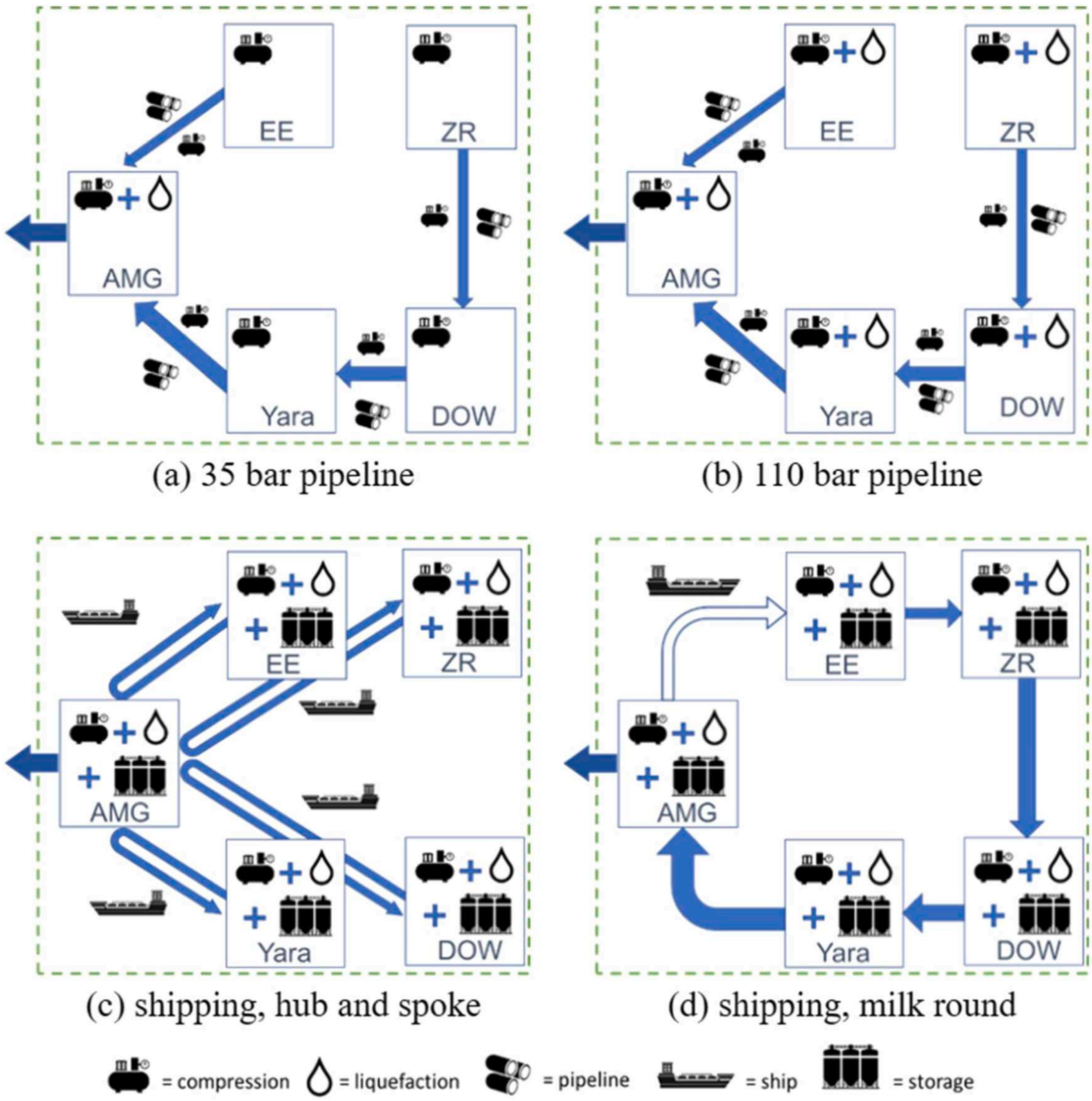

Fig. 2. The four intra-cluster CO_2 transport strategies: (a) 35 bar pipeline, (b) 110 bar pipeline, (c) shipping, hub and spoke, and (d) shipping, milk round (south), implementing the infrastructure elements, including compression, liquefaction, pipelines, ships, and interim storage. The arrows indicate the direction of CO_2 flow on transport routes. The green dashed lines indicate the system boundaries. AMG is shown as the offtake point here, but Yara was also considered as the alternative offtake point in the analysis. In the hub and spoke strategy one barge is deployed on each arc, and in the milk round scenario one barge is deployed to cover all arcs.

Table 2
Conditions and design specifications for CO_2 transport cases studied. For onward transport, the CO_2 was conditioned at – 30 °C and 20 bar for all cases.

Case number	Mode of CO_2 transport	Transport strategy	Offtake point	Direction of flow	T (°C)	P (bar)	Interim storage
1	Pipeline	Low pressure	Yara	-	30	35	No
2	Pipeline	High pressure	Yara	-	30	110	No
3	Pipeline	Low pressure	AMG	-	30	35	No
4	Pipeline	High pressure	AMG	-	30	110	No
5	Ship	Hub and spoke	Yara	-	–30	20	Yes
6	Ship	Hub and spoke	AMG	-	–30	20	Yes
7	Ship	Milk round	Yara	North	–30	20	Yes
8	Ship	Milk round	Yara	South	–30	20	Yes
9	Ship	Milk round	AMG	North	–30	20	Yes
10	Ship	Milk round	AMG	South	–30	20	Yes

aim of minimizing the combination of tonnage and per kilometer shipping costs and interim storage costs. The roundtrip sailing time (h) for the shipping run on the i^{th} route was defined by:

$$t_i^{cycle} = \frac{l_i f^{load}}{v^{ship}} \tag{1}$$

where l_i is the length of the i^{th} route in km (noting that this is a round trip distance in the hub and spoke strategy, but a one-way distance in the milk round – see Fig. 2), v^{ship} is the ship speed (20 km/h) and f^{load} is the multiplier for loading and unloading (1.4, from (Element Energy, 2018)). Shipping distances were obtained using the Python package

Searoute (Halili, 2023).

The interim storage capacity was calculated for the hub and spoke strategy (t_{CO2}) as:

$$S^{H\&S} = f^{safety}\sum_i q_i t_i^{cycle} \quad (2)$$

where q_i is the CO_2 flow rate from the i^{th} emitter (t_{CO2}/y) and f^{safety} is a safety factor (1.2 from (Element Energy, 2018)).

For the milk round strategy the interim storage capacity was defined as:

$$S^{MR} = f^{safety}\sum_i t_i^{cycle}\sum_i q_i \quad (3)$$

Given that the emission sources in the cluster are distributed along a single route, the milk round is modelled as a simple loop. CO_2 collection is arranged for either the northward or southward travel path to minimize the freight burden (t_{CO2}km). In both transport scenarios, the offtake location was varied. Collected CO_2 is stored as a liquid at this location for onward transport, and the variation allowed assessment of economic and environmental impacts.

2.3. Cost of CO_2 transport

Levelized annual costs of intra-cluster CO_2 conditioning and transport (€/t_{CO2}) are defined as the ratio of the total present value costs, including the environmental liability costs resulting from CO_2 emissions incurred during construction years, to the present value of the total amount of CO_2 transported during operational years of the project:

$$LC = \frac{CAPEX_{PV} + OPEX_{PV} + ETS_{PV}}{\sum_{t=t_{constr}+1}^{t_{constr}+t_{oper}} \frac{q}{(1+r)^t}} \quad (4)$$

where $CAPEX_{PV}$ and $OPEX_{PV} = \sum_{t=t_{constr}+1}^{t_{constr}+t_{oper}} \frac{OPEX_t}{(1+r)^t}$ are the present value capital investment and operational costs, $ETS_{PV} = \sum_{t=1}^{t_{constr}} \frac{ETS_t \cdot q}{(1+r)^t}$ is the present value of the ETS annual costs in (€/t_{CO2}), and q is the annual amount of CO_2 transported (t_{CO2}/y). Assuming constant annual costs, and after some rearrangements (see the details in SI), the final expression for LC is:

$$LC = \left(CAPEX_{PV} + ETS_t \cdot q \cdot \frac{1-(1+r)^{-t_{constr}}}{r}\right) \times$$

$$\times \frac{CRF_{oper} \cdot (1+r)^{t_{constr}}}{q} + \frac{OPEX_t}{q} \quad (5)$$

where and $CRF = \frac{r}{[1-(1+r)^{-t_{oper}}]}$ is the capital recovery factor. The lifetime of the pipeline and storage infrastructure t_{oper} was set at 25 years, a period falling in the middle of the range used previously for both shipping (Element Energy, 2018) and pipeline studies (Skaugen et al., 2016; McCoy and Rubin, 2008; Knoope et al., 2015). This is also consistent with the 25 year lifetime of compressors and pumps (Knoope et al., 2014).

CAPEX and OPEX were obtained for each component of the transport system, including pipeline and ship transport, compression, liquefaction and interim storage, as detailed in Table 3. In particular, for the pipeline transport, CAPEX was annualized using a capital recovery factor calculated for 25 years payback period at $r = 8$ % interest rate (Skaugen et al., 2016). The compressor CAPEX model accounts for economies of scale, hence costs are calculated for each compressor specified on the network (see Fig. 2). For liquefaction, the specific CAPEX term (€/t_{CO2}/y) in Table 3 was multiplied by q for unit consistency.

One difference between equation (5) and its original version in (Skaugen et al., 2016) is that in the cited article, CO_2 emissions associated with the electricity consumed in conditioning were subtracted from the q term, i.e. the costs were calculated per 1 tonne of CO_2 avoided. This is not done here as this CO_2 associated cost is dealt with as a separate objective, so including it here would constitute double counting.

The economics of CO_2 shipping have been less studied than those of pipeline transport. Recently, a shipping cost model was constructed where CAPEX and OPEX are combined into a tonnage cost (€/t_{CO2}) and a mileage cost (€/t_{CO2}km) (D'Amore et al., 2021) derived from (Element Energy, 2018). In that report, a 20 years project lifetime and discount rate of 8 % were assumed, which are consistent with the values used for pipeline transport in the present study.

The conditioning and transport lifetime cost for shipping included the costs of compression, liquefaction, intra-cluster storage and transport ships.

The cost of ship(s) in particular was calculated as:

$$C^{ship} = C^{tonnage} + \frac{\sum_i l_i\, q_i}{\sum_i q_i} C^{mileage} \quad (6)$$

Here, the tonnage cost $C^{tonnage}$ (€/t_{CO2}) and mileage cost $C^{mileage}$ (€/t_{CO2}km) are taken from (D'Amore et al., 2021). The tonnage cost is scale-dependent (based on thresholds in terms of t_{CO2}/y carried on the route), hence calculated per route for the hub and spoke strategy. The cost of interim storage comprises CAPEX (the product of S from equations (2) or (3) and the specific CAPEX in Table 3) and fixed OPEX.

The liquefaction model is limited by a lack of consideration of scale. For this reason, a possible benefit of the 35 bar pipeline strategy, where a single liquefaction plant is required as opposed to one per emitter, is not

Table 3

Cost parameters used in the TEA and their sources. Figures have been converted from original currency to 2023 €. * Scale: 250–1500 kt_{CO2}/y per route, ** Scale: 1500–2500 kt_{CO2}/y per route, *** Scale: 2500–30,000 kt_{CO2}/y per route, n/a – not applicable, † Mean of CAPEX estimates for 70 bar inlet, 14–40 bar outlet pressures, ‡ Mean values.

Cost element	Item	Pipeline	Shipping	Reference
CAPEX	Pipeline	€, Empirical non-linear model based on length and outer diameter.	-	(Ejeh et al., 2023)
	Land	Included in above	-	-
	Compression	€, Empirical scaling model		(Knoope et al., 2014)
	Pumping	€, Empirical scaling model	-	
	Liquefaction	14.1 €/(t_{CO2}/y)		(Element Energy, 2018) †
	Storage	-	1140 €/t_{CO2}	(Element Energy, 2018)
OPEX (fixed)	Pipeline	3 % of CAPEX/y	n/a	(Wildenborg, 2005)
	Compression / pumping	4 % of CAPEX/y		(Knoope et al., 2014)
	Liquefaction	7.5 % of CAPEX/y		(Element Energy, 2018) ‡
	Storage	n/a	5 % of CAPEX/y	(Element Energy, 2018)
OPEX (variable)	Compression	Electricity cost in 5 stage compression		(Ejeh et al., 2023)
	Cooling	Electricity cost in 2 step Carnot cycle (see SI)		(Martynov et al., 2016)
Per unit shipping costs	Tonnage cost	n/a	18.5 €/t_{CO2}* 17.0 €/t_{CO2}** 11.3 €/t_{CO2}***	(D'Amore et al., 2021)
	Mileage cost	n/a	0.0087 €/t_{CO2}.km	

captured. Furthermore, for the 110 bar strategy, although the majority of the liquefaction work is carried out at the emission point, additional plant would be required at the offtake point where the CO_2 collected from the pipeline must be cooled so that it remains liquid at the lower shipping pressure of 20 bar. The compression CAPEX model does include a scaling term, hence the additional cost in the 35 bar pipeline strategy of having an additional compression train at the offtake point (35 bar pipeline outlet to 60 bar liquefaction plant inlet) is captured.

To calculate the variable OPEX associated with CO_2 conditioning, the specific energy requirements were first calculated for compression cycles based on a common pathway employing sub-critical liquefaction at 60 bar (Wadas, 2010), in order to be consistent with the liquefaction CAPEX model (Element Energy, 2018). The process steps for each transport strategy vary slightly and are shown on the pressure-enthalpy diagrams in the SI. The energy demand for compression was calculated after (Knoope et al., 2014), and that required for cooling (including inter-stage cooling during compression) was calculated based on a Carnot cycle after (Martynov et al., 2016). The energy requirements for conditioning the CO_2 between capture plant outlet and the cluster storage hub were assumed to be met using electricity imported from the grid at €125/MWh (the average electricity price for large installations in EU in 2023 (EC Eurostat, 2024)). In addition to the variable OPEX associated with CO_2 conditioning, fixed OPEX expressed as a percentage of CAPEX was applied to most of the infrastructure, as shown in Table 3. All costs were converted from the original currency in the cited sources to 2023 euros (€).

2.4. LCA of CO_2 transport

The LCA was conducted in four steps, as defined in ISO 14,044 (ISO, 2022). First, in the goal and scope step, the functional unit, relevant processes and system boundaries (see Section 2.1) and the LCA aims were defined. Then, for all the flows going in (e.g., energy and materials) and out (e.g., emissions and waste) of the system boundaries, across the life cycle of the processes modeled, the relevant data were collected in the Life Cycle Inventory (LCI) step. The LCI data was then converted to environmental impacts and organized into impact categories in the Life Cycle Impact Assessment (LCIA) step. Finally, the results were interpreted (see Section 3). Some details are provided here for the LCI and LCIA steps.

LCI data for the foreground system, i.e. the data which specifically describes the system examined (for instance in this study the electricity consumption for CO_2 compression) was collected from the TEA step and are summarized in Table 4. Given the transport cases studied (see Table 2), the foreground LCI data were collected for CO_2 conditioning, shipping, pipeline transport, and interim storage. The system boundaries are shown in Fig. 3. It was assumed that the electricity used is a European average mix. The pipelines were assumed made of chromium steel fabricated from sheet to pipe. The tanks for interim storage were assumed to be fabricated from carbon steel, and processing was not included. The weight of a tank was estimated to be ca. two-thirds of its capacity based on manufacturer data (UIG 2009). For all infrastructure, a lifetime of 25 years was assumed, consistent with TEA model in Section 2.3.

Shipping was modeled as a diesel tanker barge including the operation of refrigeration also running on diesel fuel. Two classes of tanker barges were modeled: a low capacity (350 t on average) for the hub and spoke shipping strategy, and a high capacity (1150 t on average) for the milk round strategy. The size and fuel consumption of the two classes of tanker barges were based on data from (Friedrich and Bickel, 2001). The Ecoinvent v. 3.8 database (Wernet et al., 2016) was used for the background system, i.e. all the processes upstream and downstream of the foreground system.

Life cycle environmental impacts were calculated based on the LCI data using the ReCiPe 2016 LCIA methodology (Huijbregts et al., 2017). The hierarchist ReCiPe perspective was chosen, which represents a "middle-of-the-road" grouping of assumptions and value choices related to the time horizon considered and the inclusion of known impact pathways (Huijbregts et al., 2016). Out of the impact categories available in ReCiPe, impacts on global warming were selected due to their relevance for a carbon capture system. Impacts on ecosystems and human health were also investigated to avoid burden shifting as, together with global warming, they reflect the three main current environmental threats faced by humanity, referred to as the "triple planetary crisis" (Hellweg et al., 2023; UNFCCC 2024). A complete collection of results is available in the SI (Table S1).

2.5. Tiered multi-objective optimization (TMOO) model

To determine the optimal strategy for intra-cluster CO_2 transport in the NSP region among the number of feasible design cases (see Table 2), a multi-objective optimization method was applied by using the Pareto efficiency criterion that achieves a best compromise between the different objectives (Ehrgott, 2005). The discrete Pareto optimal solutions were constructed using the weighted sum method (Ehrgott, 2005), where the cost and the integral environmental impacts of the CO_2 transport case k from Table 2 (each case representing the discrete independent variable for the problem) were combined in a single objective function:

$$J(\boldsymbol{w},k) = \sum_{i=1}^{4} w_i J_{i,k} \tag{7}$$

In this equation, $J_{i,k}$ are the normalized objective functions associated with the cost ($i = 1$), and three environmental impact categories [the impacts on global warming ($i = 2$), human health ($i = 3$), and ecosystems ($i = 4$)], evaluated for the infrastructure design case k, and $\boldsymbol{w} = (w_1, w_2, w_3, w_4)$ is the vector of weighting factors applied to the objectives $J_{i,k}$ satisfying the constraint $\sum_{i=1}^{4} w_i = 1$.

The normalized objectives $J_{i,k}$ in equation (7) were defined as:

$$J_{i,k} = \frac{O_{i,k} - \min_j O_{i,j}}{\max_j O_{i,j} - \min_j O_{i,j}} \tag{8}$$

where $O_{j,k}$ are the combined costs ($i = 1$) calculated as described in Section 2.2, and the environmental impacts ($i = 2,3,4$), obtained from the LCA, as described in Section 2.3, evaluated for the design case k.

For the synthetic objective function $J(\boldsymbol{w},k)$, the minimization problem was formulated as:

$$\min_k J(\boldsymbol{w},k) \tag{9}$$

This discrete minimization problem was solved for various combinations of weighting factors w_i, sampled in the range between 0 and 1, with the increment of 0.1. This resulted in a set of optimal solutions for the CO_2 transport infrastructure corresponding to a Pareto front, where the balance is achieved between the costs and the environmental impacts.

The Pareto optimal solutions were obtained first for the full set of CO_2 transport cases using Algorithm 1 (these are referred to as 'tier 1' optimal solutions). To obtain other optimal solution tiers (sub-optimal to tier 1) the optimization was repeated on the reduced set of cases, excluding the previously identified optimal solutions, following the steps in Algorithm 2, until the number of cases was exhausted.

3. Results

In this section, the first part (Section 3.1) describes the results of TEA and LCA of CO_2 transport solutions in the cluster. It also presents the results of multi-objective optimization using the TMOO of the CO_2 transport cases for the base-line scenario, which assumes overnight construction in 2023 and using the current EU-average electricity mix.

Table 4
Life cycle inventory per 1 t_{CO2} for the CO_2 transport cases from Table 2.

Case num-ber	Case name	Specific power		Materials		
		Compres-sion (kWh/t_{CO2})	Lique-faction (kWh/t_{CO2})	Shipping ($t{\cdot}km/ t_{CO2}$)	Pipeline (kg_{steel}/ t_{CO2})	Storage (kg_{steel}/ t_{CO2})
1	Pipeline, 35 bar, Yara	34	25	0	0.072	0
2	Pipeline, 35 bar, AMG	34	25	0	0.14	0
3	Pipeline, 110 bar, Yara	35	29	0	0.091	0
4	Pipeline, 110 bar, AMG	35	29	0	0.18	0
5	Ship, hub and spoke, Yara	33	25	11	0	0.006
6	Ship, hub and spoke, AMG	33	25	13	0	0.007
7	Ship, milk round, Yara, North	33	25	34	0	0.042
8	Ship, milk round, Yara, South	33	25	30	0	0.038
9	Ship, milk round, AMG, North	33	25	36	0	0.040
10	Ship, milk round, AMG, South	33	25	22	0	0.034

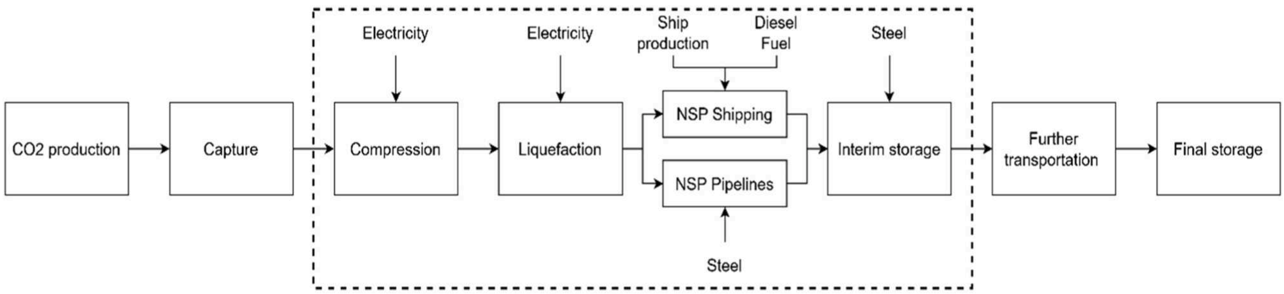

Fig. 3. Life cycle of CO_2 capture and storage. The system boundaries of the LCA conducted in this study are shown with the dashed lines. The foreground system is indicated by boxes within the system boundaries (e.g., 'compression'), while the background system is the inputs to the foreground processes in plain text (e.g., 'electricity' production for 'compression').

Algorithm 1
Pseudocode for calculating the Pareto front using the weighted sum method.

```
Inputs: The number of optimization variables, i_max = 4
    The number of independent variables (the infrastructure cases), j_max
    A set of independent variables (the infrastructure cases), Q = {1, … j_max}
    Number of points on the interval [0, 1] for the weight factors discretization, n_max
  Outputs: Number of Pareto optimal solutions, p
    The set of Pareto optimal solutions, P = {P_1, … P_p}, (P_n ∈ ℕ)
p ← 0 // Initializing the counter of Pareto optimal solutions
P ← {0} // Empty the set of Pareto optimal solutions upon initilalization
// Loop over the weight factors w_1, w_2, w_3 and w_4
for n_1 = 1 to n_max
  w_1 ← (n_1 – 1) / n_max
  for n_2 = 1 to n_max
    w_2 ← (n_2 – 1) / n_max
    for n_3 = 1 to n_max
      w_3 ← (n_3 – 1) / n_max
      w_4 ← min [1, 1 – (w_1 + w_2 + w_3)]
        J_min ← inf // Set the objective function to a large number upon initialization
        ← 0: // Initialization a counter for the Pareto solutions
     // Loop over the independent variables (infrastructure cases)
        for j from Q
       // Calculate the synthetic objective function
          J ← w_1 * J_n1 + w_2 * J_n2 + w_3 * J_n3 + w_4 * J_n4
       // Check if the new minimum is found
          if J < J_min then
            J_min ← J // Update the minimum value
            ← j // The minimum solution index
          end if
       // Add the new solution to the Pareto set
          p ← p + 1
          P ← P ∪ {m}
       // Remove the solution from the search set
          Q ← Q ∩ {m}
          endif
        end for
      end for
    end for
  end for
```

Algorithm 2
Pseudocode for calculating tiered Pareto optimal solutions.

Inputs: The number of optimization variables, $i_{max} = 4$
The number of independent variables (the infrastructure cases), j_{max}
The total set of independent variables (the infrastructure cases), $Q_0 = \{1, \dots j_{max}\}$
Number of points on the interval [0, 1] for the weight factors discretization, n_{max}
Outputs: The number of tiers (ranks) of the Pareto optimal solutions, rk_{max}
The ranked sets of the Pareto optimal solutions, P_{rk} ($rk = 1, \dots rk_{max}$)
1. $rk \leftarrow 0$ // Initialization
2. $Q \leftarrow Q_0$ // A set of cases for optimization
3. $j \leftarrow j_{max}$ // Number of elements (infrastructure cases) in the set Q
4. **repeat**
5. $rk \leftarrow rk + 1$ // update the tier index (rank)
// Determine the Pareto front solutions or rank "*rk*"
6. P, $p \leftarrow$ Algorithm 1 (Q, *j*)
7. $P_{rk} \leftarrow P$// The Pareto front of rank "*rk*"
8. $Q \leftarrow Q \cap P_r$ // Reduce the search set
9. $j \leftarrow j - p$ // The size of the set Q
10. **until** $j \leq 1$
11. $rk_{max} = rk$

The second part (Section 3.2) is focused on scenario studies of (a) the impacts of a delay in construction of the pipeline infrastructure and (b) the environmental benefits of switching to a future, low-carbon electricity mix for the cluster CO_2 transport infrastructure.

3.1. Costs and environmental impacts of intra-cluster CO_2 transport

Fig. 4 shows the results of calculation of the total cost (CAPEX + OPEX) of CO_2 transport in the NSP cluster per functional unit (1 t_{CO2} transported) for eight cases from Table 2. The two shipping milk round strategies involving uneconomical transport of CO_2 over long distance on the last leg of the milk round (cases 8 and 9 in Table 2) were discarded. The cost categories are shown for the main processing steps. A more detailed breakdown of CAPEX and OPEX may be found in the SI (see Figure S4).

The results in Fig. 4 show, firstly, that CO_2 pipeline transport strategies have a lower financial cost than shipping. The 35 bar pipeline strategy has a slightly lower cost than the 110 bar one, with its higher pipeline cost being outweighed by the savings in conditioning costs. Overall, the pipeline costs are dominated by energy consumption related OPEX due to conditioning. These conditioning costs are also very similar for the shipping strategies. Of the shipping strategies, the milk round is the most economical. This is because servicing the entire cluster using a single ship benefits from economies of scale (D'Amore et al., 2021). In this strategy a tonne of CO_2 travels a greater average distance. However, the mileage cost (€/t_{CO2}.km) makes a minor contribution to the total cost (0.14–0.23 €/t_{CO2} vs. 8.4 €/t_{CO2} for the tonnage cost).

The intermediate storage requirement for the milk round shipping is ca. 7.16 kt_{CO2} which is considerably larger than ca. 1.14 kt_{CO2} for the hub and spoke strategy. This is due to the longer shipping cycle for the milk round. However, the cost of storage is very low compared to the other cost components in the shipping strategies, so the impact on overall cost is negligible.

Fig. 5 shows the results of calculation of the life cycle environmental impacts of the NSP intra-cluster CO_2 transport on global warming, human health, and ecosystems, per functional unit (1 tonne of CO_2 transported). The results were obtained for the same eight cases as in

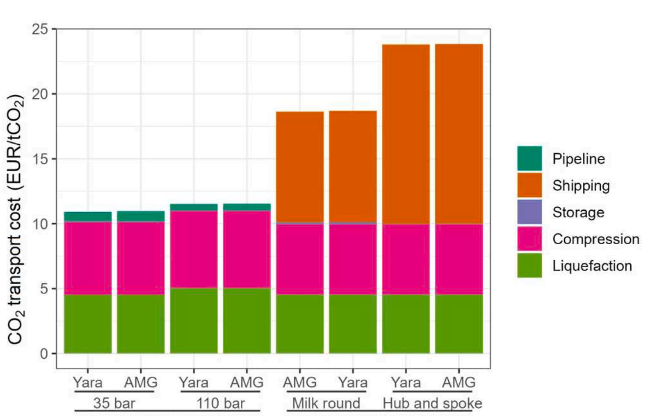

Fig. 4. Total cost (CAPEX + OPEX) of CO_2 transport in the NSP cluster per functional unit (1 tonne of CO_2 transported) for eight cases from Table 2. The cost breakdown is shown for different process stages. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

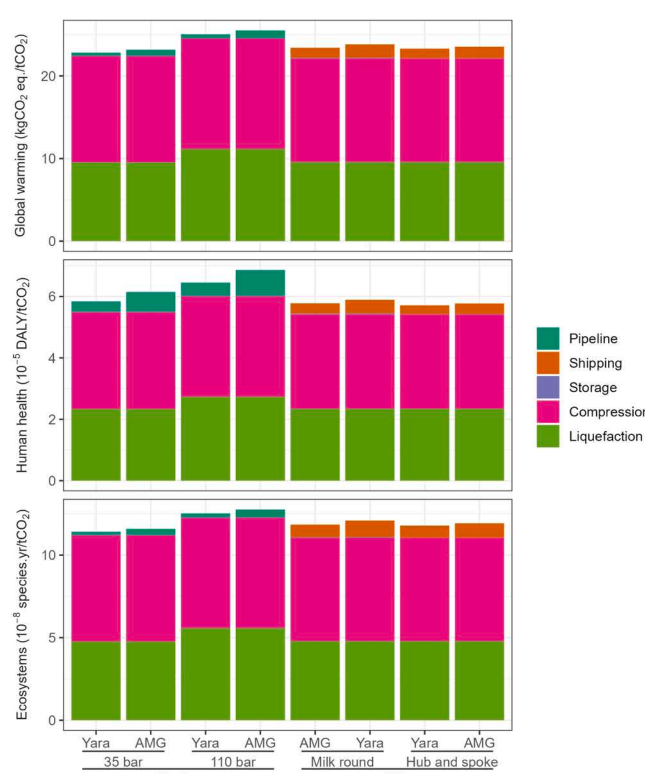

Fig. 5. The life cycle environmental impacts of CO_2 transport in the NSP cluster per functional unit (1 tonne of CO_2 transported) on the global warming, human health, and ecosystems. The cost breakdown is shown for different process stages. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

Fig. 4.

The results in Fig. 4 show relatively small differences between the environmental impacts for each mode of transportation on the global warming, human health, or ecosystems of the eight cases selected. Across all cases and impact categories, environmental impacts differ at most by 12 %, except for human health results which vary by up to 20 %. The environmental impacts are driven by the electricity consumption of the CO_2 conditioning, similar to the TEA results. The contribution of compression and liquefaction ranges between 52–54 % and 40–42 % for the three impact categories considered, on average across the eight selected cases. Unlike financial costs, the impact of shipping is relatively low, contributing at most to 8 % of the impact on ecosystems for the shipping milk round strategy (Yara south). Finally, the pipeline infrastructure has a notable impact on human health, especially for the AMG offtake point due to a thicker pipe, where it contributes to 11 % and 12 % of the impact on human health at 35 bar and 110 bar, respectively.

Fig. 6 shows the plots of environmental impacts against CO_2 transport costs for the ten cases from Table 2, with the tiered Pareto fronts predicted using the TMOO model of Section 2.5. These results illustrate the balance between costs and environmental impacts, while the rest of the TMOO results (i.e. environmental impacts categories against one another) are available in the SI (see Figure S4). In the plots, all the results (costs and the environmental impacts) are expressed per functional unit (1 t_{CO2} transported). As shown in Fig. 6, the first tier Pareto front represents the most optimal set of CO_2 transport solutions. It includes the low-pressure pipeline with the offtake at Yara (case 1 in Table 2) and the hub-and-spoke shipping option with the offtake from Yara (case 5 in Table 2). The former (case 1) shows the lowest score across all criteria considered, except for human health where the latter (case 5) shows a lower impact by 2 %. However, this 2 % reduction in human health impact comes at the price of a 54 % increase in the transport infrastructure costs. Therefore, the low-pressure pipeline with Yara offtake can be considered as the optimal CO_2 intra-cluster transport strategy for the NSP. The milk round strategy achieves a considerable cost saving (20 %) compared to the hub and spoke strategy, at the expense of minor increases (~1 %) to global warming and ecosystems impacts.

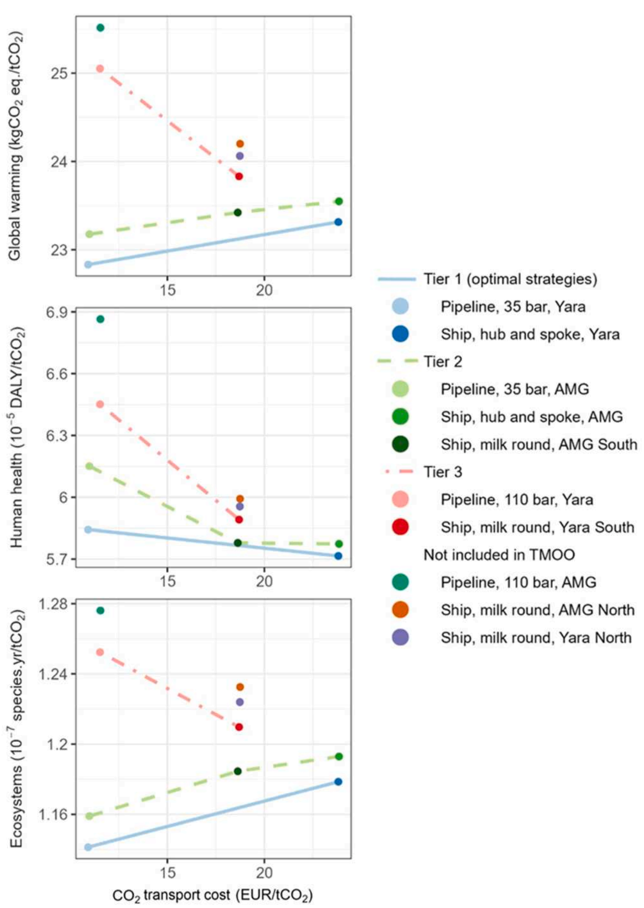

Fig. 6. Plots of environmental impacts versus costs for CO_2 transport solutions from Table 2, including tiers of Pareto optimal solutions obtained using TMOO method (see Section 2.5). Tier 1 solutions are both optimal, depending on the weight given to environmental impacts against costs. If Tier 1 solutions are excluded, then Tier 2 becomes optimal, which can be interpreted as a “Plan B”. Tier 3 follows the same logic. The final three solutions were not included in the TMOO. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

3.2. Scenario analyses

3.2.1. Effect of pipeline construction delay

In this scenario study, the potential delay in construction of the pipeline infrastructure was investigated. An advantage of shipping as an intra-cluster transport method is the more rapid implementation, due to reduced burden around land acquisition and planning permission. During the delay in building pipeline infrastructure, CO_2 emitted into atmosphere by the cluster industries would continue damaging the environment, leading to financial penalties, as emitters must currently pay the ETS price. The impact of this cost was estimated as 50 €/t_{CO2}, the average of 20 €/t_{CO2} (year 2019) and 80 €/t_{CO2} (year 2023) (Ember, 2024). The cost of the emissions in the period of delay is treated as CAPEX and annualized as described in Section 2.3. The environmental impact of this delay was also modelled as direct emissions of CO_2 to the air. To align the impact of the delay to the functional unit of 1 t_{CO2} transported, the direct emissions were divided by the total amount of CO_2 transported during the project lifetime.

Given that in practice, the CO_2 pipeline network can be developed in parallel with the CO_2 capture system, where construction can take as long as 3 years, the latter is taken as a maximum delay period in our study. It was also assumed that total CO_2 emissions from the cluster industries remain constant with time, and the lifetime of the CO_2 transport infrastructure project is 25 years.

The impact of pipeline construction delay time was investigated for the low-pressure pipeline with offtake at Yara (case 1 in Table 2), which corresponds to the most optimal transport solution in the case of zero delay time (Section 3.1). Fig. 7 shows contributions from the different elements of the pipeline infrastructure on the levelized CO_2 costs calculated using equation (5) and the environmental impacts. These are shown in comparison with the results for the most economical shipping option, case 10 from Table 2 (milk round strategy with the offtake at AMG, see Fig. 4). As can be seen in Fig. 7, the delay in the CO_2 capture system due to construction of the pipeline infrastructure results in an increase (at a rate of ca 50 kg_{CO2}/t_{CO2} per year) in global warming impacts, making shipping the preferred mode of CO_2 transport. The same trend was observed also for impacts on human health and ecosystems (see Figure S5 in SI). For financial costs, the tipping point where shipping becomes less costly than pipeline transport is between 1.5 and 2 years of delay.

3.2.2. Future electricity mix

In order to assess the impact of future changes in electricity supply mix on the CO_2 transport infrastructure costs and environmental impacts (particularly the CO_2 conditioning steps), we complemented our modelling of the base case scenario, based on the current electricity mix (Section 3.1), by simulations for a 2030 scenario of low-carbon electricity mix. The latter was developed based on the NSP regional energy strategy plans for 2030 (Smart Delta Resources 2020), assuming an electricity mix comprised of 40 % offshore wind and 60 % solar power. Only the electricity input of the foreground system was changed for this scenario analysis, based on Ecoinvent entries (Wernet et al., 2016).

Fig. 8 shows the results of global warming impacts of eight CO_2

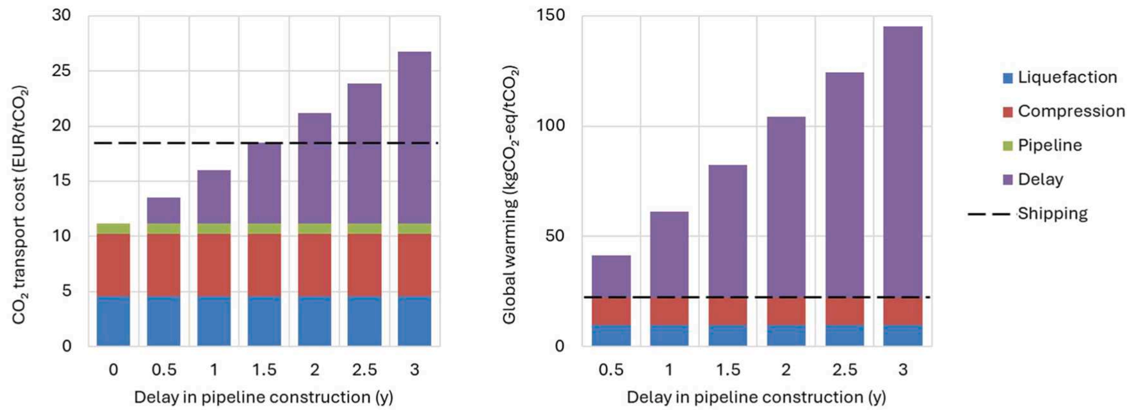

Fig. 7. The levelized cost of CO_2 transport (€/t_{CO2}) and global warming environmental impacts (kg $_{CO2eq}$) per functional unit (1 tonne of CO_2 transported) as function of the delay time in the construction of infrastructure for low-pressure CO_2 pipeline transport with Yara offtake (case 1 in Table 2). The color bars show the contributions of the different infrastructure elements. The dashed line shows reference results for the milk round shipping strategy with offtake at AMG (case 10 in Table 2). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

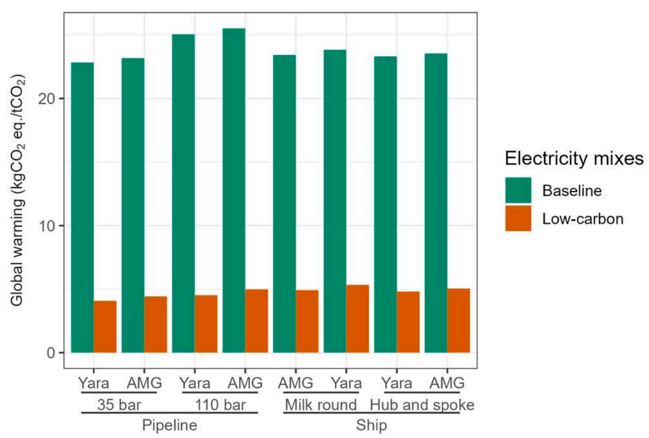

Fig. 8. The global warming impacts (kg_{CO2eq}) of CO_2 transport in the NSP cluster per functional unit (1 tonne of CO_2 transported) for the baseline and low-carbon electricity mix scenarios. In the baseline scenario, the EU-average electricity emission intensity factor (2023) is 207 (g_{CO_2eq}/kWh), which is approximately the average of the intensity factors for Belgium (150 g_{CO_2eq}/kWh) and the Netherlands (256 g_{CO_2eq}/kWh) (EEA 2025). The average carbon intensity of the low-carbon electricity mix is 36.7 g_{CO_2eq}/kWh, which is estimated assuming the electricity mix shares of 40 % offshore wind and 60 % solar power and using the carbon intensities of 6.8 and 56.6 g_{CO_2eq}/kWh for the wind and solar power respectively (Wernet et al., 2016). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

transportation cases from Table 2, calculated for the base line and the low electricity mix scenarios. It can be seen that a low carbon electricity mix leads to significant reduction in the global warming impact for all the cases. On average, across all the cases studied, the global warming impact decreased by ca. 80 %. The same conclusion was also reached for other impact categories, with the average decrease of 69 % and 70 % for the impacts on human health and ecosystems, respectively (see Figure S6 in the SI). These reductions were expected as the environmental impacts of CO_2 transport in the NSP are largely dominated by the electricity consumption in CO_2 conditioning. Although future electricity prices were not modelled, it is expected that any future changes to the price of electricity will affect all strategies similarly because electricity use dominates the CO_2 conditioning cost (Fig. 4).

4. Discussion

In the present study, a new and flexible approach to multi-objective optimization of CO_2 transport solutions, balancing cost and environmental impacts, was developed and applied to optimize CO_2 transport and conditioning within the NSP industrial cluster involving five emitters. Two main modes of transportation were compared, including a pipeline network and shipping with barges, and ten potential implementations were analyzed for the four main CO_2 transportation strategies, including low- and high-pressure pipelines, and also milk round and hub and spoke shipping strategies. The results in Section 3 showed that for the intra-cluster CO_2 aggregation, low pressure pipeline operated at 35 bar is the optimal solution, with the lowest costs and environmental impacts, followed by ship hub and spoke as a second preferable solution. A hierarchy of sub-optimal solutions was also obtained, aiming to provide the decision makers with the option of choosing alternative strategies should the optimal case be unfeasible due to criteria beyond the scope of our optimization. Across all CO_2 transport strategies and cases studied, the electricity consumption for CO_2 conditioning was the main source of costs and environmental impacts. Our scenario studies showed that (a) using a low-carbon electricity mix can help to significantly reduce the environmental footprint of CO_2 transport, and (b) the delays in construction of CO_2 pipeline infrastructure result in a significant increase in the environmental impacts and can be accompanied by an increase in CO_2 transport project costs.

4.1. Comparison with literature

The results of TEA of CO_2 transport in the cluster are in general agreement with the cost estimates reported in the literature. In particular, the capital cost contribution of the pipeline to the overall cost of CO_2 transport is ca. 0.7 €/t_{CO2}, that for the 37 km long pipeline network translates to ca. 0.02 €/(t_{CO2} km), falling in the range of costs reported in the IPCC report (Doctor et al., 2005) (0.018 €/(t_{CO2} km), upon the currency conversion) and in the study by Smith[1] (Smith, 2021) (0.006 – 0.025 €/(t_{CO2} km), upon the currency conversion). It can also be noted that our estimates of the capital cost of the cluster high-pressure pipeline transport are ca. 86 M€, which is slightly less conservative than ca. 60 M€, reported in (CUST, 2019).

The finding of lower costs for CO_2 pipeline transport versus shipping

[1] In the present analysis, the Yara-AMG pipeline in the Yara offtake strategy has a cost of 14.2 M€, compared to a range of 4 M€ to 31 M€ using the expression in the cited article (when converted to 2023€).

is broadly consistent with the existing recommendations, e.g., that shipping can only become more economical than pipeline transport at break-even distances greater than 320 km (IEAGHG, 2020). Indeed, the transport distances in the NSP cluster region are ca. 30 - 60 km, which are considerably shorter than the above reported break-even distances.

The model for levelized liquefaction CAPEX did not account for economies of scale, which is a crude approximation compared to that used for the compression process. It is possible that the 35 bar pipeline transport case would achieve a cost reduction compared to the other strategies by concentrating all liquefaction at the cluster offtake point. Similarly, efficiency gains may lead to reduced variable OPEX. As the 35 bar pipeline strategy is already estimated to be the cheapest, this would not change the conclusions.

The LCA results of this study are comparable to those in (Zanobetti et al., 2023), with global warming impacts of 24 and 26 $kg_{CO2\text{-}eq}/t_{CO2}$ transported, respectively. The global warming impacts were dominated by CO_2 conditioning in both studies. Comparing our LCA results with those of other studies is challenging. This is due to differences in scope and system boundaries. Moreover, in LCAs of carbon capture, the impact of CO_2 transport is often negligible compared to other processes and therefore tends not to be discussed in detail (de Kleijne et al., 2022; Koornneef et al., 2008; de Kleijne et al., 2020; Petrescu et al., 2019; Cuéllar-Franca and Azapagic, 2015). One notable exception is the study (Burger et al., 2022) that showed CO_2 transport as the main contributor to global warming impacts (ca. 56 % of the CCS chain).

4.2. Uncertainty of the results

As stated in Section 2.4, in the study, we have evaluated the environmental impacts using LCA method implemented following the ISO standard (Knoope et al., 2014), while the CO_2 transport infrastructure costs were calculated using established correlations in turn verified against the results reported in the literature (Section 4.1). The methodology was designed to ensure consistency of the environmental impacts and cost estimates across the various types of CO_2 transport infrastructure. In particular, the uncertainties of the calculated costs can be estimated to be ca 30 % −50 % (Towler and Sinnott, 2012; ZEP, 2011). The uncertainty of the environmental impacts depends mainly on the input inventory data and the impact assessment methods. While the detailed assessment of the accuracy of LCA results must be done on a case-by-case basis, which is beyond the scope of this paper, we can expect that uncertainty in the inventory or impact assessment would affect our results equally. Given the comparative nature of our study, the influence of this uncertainty would therefore be of little practical significance. For example, changes to the carbon intensity of electricity would influence all the cases in equal extents and would not affect our case ranking or Pareto optimization results.

It also can be expected that the optimal solution for intra-cluster CO_2 transport depends on the industrial composition of the cluster, the locations of the CO_2 emitters and the amounts of CO_2 captured from the plants. While this is beyond the scope of the present study, for the practical uptake, parametric studies on sensitivity of the results to the captured CO_2 amounts would help to assess the robustness of the proposed CO_2 transport solutions.

4.3. Limitations due to the study scope and modelling assumptions

To demonstrate its efficacy, the developed methodology was applied to optimize CO_2 transport in a realistic industrial cluster. This was done by limiting the scope of the study to a relatively small number of scenarios and examining sensitivity of the results to several practically important factors.

Particular attention was paid to intra-cluster CO_2 transport, assuming a single collection point for subsequent transport of CO_2 to a more distant collection hub or geological storage location. One limitation of this approach (Fig. 2) is that it does not include an extended milk round strategy, where a larger ship would be used to service the NSP and other clusters in the North Sea before sailing to, e.g., Rotterdam in the Netherlands or Bergen in Norway, thus sharing the tonnage cost of the ship (which is the dominant shipping cost component as shown in Table 4) between multiple clusters. However, Fig. 4 shows that the ship tonnage cost would have to be shared by approximately 10 clusters of the NSP cluster size to reach parity with the 35 bar pipeline strategy. Part of the saving would also be offset by increased mileage and storage costs, although these are small.

Another potential limitation of the chosen approach is the choice of scope and system boundaries. Focusing on optimization of a shared CO_2 transport infrastructure for a cluster may lead to overlooking of burden shifting within the CCS chain. For example, opting for a shared CO_2 transport infrastructure collecting relatively pure CO_2 streams and transporting them to a hub set up at an emitter where captured CO_2 has relatively large amount of contaminant components (that may, e.g., pose risks of corrosion of carbon steel pipelines) may help in adopting less costly solutions for the intra-cluster CO_2 transport. Mixing of CO_2 streams at the hub would result in dilution of the contaminants, which can become advantageous, e.g., for meeting more stringent CO_2 stream specifications for subsequent longer-distance transport to the destination of geological storage. The different offtake points may also impact the design and operation of the intra-cluster and wider CO_2 transport system (e.g., the pipeline diameters and the pressure drop). For example, the benefits from a Yara offtake may be counterbalanced by a marginally longer distance to transport downstream. Also, future research should expand the work presented here to an analysis of the costs and environmental impacts of a complete CCS chain.

In the present study, we have set the amount of CO_2 captured in the cluster based on the NSP 2030 decarbonization targets (SDR 2020) assuming industries join the project simultaneously. Although this assumption is plausible, investment decisions on pipelines and vessels may practically require consideration of a gradual increase in the number of emitters committed to joining the infrastructure. This can become a serious obstacle to the implementation of CCS, especially in the case of pipeline projects. Also, in this study, we assumed a constant rate of CO_2 capture in the cluster, while in the longer term, emissions from the five industries considered are most likely to diminish from 2030 to the end of the infrastructure's lifetime in 2055, given other decarbonization measures that are being implemented along with CCS to meet the European net-zero carbon target of 2050. Moreover, while we modeled a future electricity mix, we did so only for the foreground system. The impact of a change in electricity mix in the background system would be minimal compared to that of the foreground, as environmental impacts are largely caused by foreground electricity consumption.

Furthermore, we also did not include the transport network route optimization, using pre-set design cases as the basis for the study. While this is justifiable, given a relatively small number of industrial CO_2 emitters in the cluster region, prescribed transportation routes and preferred transportation modes, in practice, constructing the feasible CO_2 transport chains for industrial clusters involving large number of industries and spread over a bigger area, may require applying optimization methods. Such models are being developed to aid optimal routing for pipeline transportation networks and optimizing multimodal CO_2 transport chains (see, e.g., (Ejeh et al., 2022)).

The impact of lead time (the delay in pipeline construction) is investigated in a parametric study. Alternatively, minimizing the lead time can also be included in the multi-objective optimization problem. Here, balancing the risks of potential delays against the CO_2 infrastructure project costs can help choosing the right type of transport infrastructure for a cluster over the specified time horizon. Other important decision criteria to consider when optimizing the CO_2 transport chains and networks may also include safety and reliability factors (CaLby2030 2022) and also resilience and public acceptance (Oeuvray et al., 2024).

In summary, although the methodology proposed in the present study was applied to a single industrial CCS cluster, it can potentially be extended to more complex CO_2 transport systems. Such extensions could include accounting, e.g., for the CO_2 purity requirements for transport system, the introduction of hubs and interim CO_2 conditioning and purification. They may also consider existing regional infrastructure, optimal routing for networks connecting many emitters, and scenarios with several offtake points. The method developed in the present study can be extended by adopting suitable TEA and LCA models for strategies involving other mobile modes of CO_2 transport, e.g., using road or railway transport or using subsea pipelines. Although we focused on the intra-cluster transport infrastructure, the approach can be easily applied to longer distance CO_2 transport beyond the cluster region.

5. Conclusions

Efficient and timely deployment of CCS is critical to decarbonize energy-intensive industries and the power generation sector during the energy transition towards climate neutrality. In this work a TMOO method was developed to determine a hierarchy of economically and environmentally balanced transport solutions for collecting CO_2 from industrial emitters in a CCS cluster. This method was applied to the five-emitter NSP cluster in Belgium/Netherlands, showing that transporting CO_2 via 35 bar pipelines is the optimal strategy with the cost and the global warming impact of €12.5/t_{CO2} and 22.9 $kg_{CO2\text{-}eq}/t_{CO2}$, respectively. These are lower than the cost and global warming impact of the alternative optimal CO_2 transport using barges by 37 % and 2 %, respectively.

Electricity consumption for CO_2 conditioning, in particular compression and liquefaction, dominates both the costs (44 %) and environmental impacts (96 %) for CO_2 transport in the NSP across the strategies modeled. Using a low carbon electricity mix can lower the global warming impact of CO_2 transport in the NSP by 80 %, on average across the strategies modeled.

Longer anticipated timeframes for pipeline construction compared to barge deployment may have a significant impact on both CO_2 emissions and cost (via ETS), directly impacting the order of priority of the candidate CO_2 transport solutions. Assuming an ETS price of 50 €/t_{CO2} (Ember, 2024), it was shown that a delay in pipeline construction of longer than 2 years would make barge transport less costly than implementing a low-pressure pipeline infrastructure, while a delay of only half a year would make the pipeline transportation costlier in terms of the global warming impact. This finding highlights the urgency of CO_2 infrastructure implementation, and suggests that further work is required to understand the deployment timeframes for both options, and factor these into the decision-making process.

CRediT authorship contribution statement

Thomas Hennequin: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Diarmid Roberts:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Rosalie van Zelm:** Writing – review & editing, Supervision, Funding acquisition. **Solomon F. Brown:** Writing – review & editing, Funding acquisition. **Richard T.J. Porter:** Writing – review & editing, Funding acquisition, Conceptualization. **Haroun Mahgerefteh:** Writing – review & editing, Project administration, Funding acquisition. **Sergey B. Martynov:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, 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.

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Supplementary materials

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