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A Mixed-Integer Linear Programming Model for Multi-Modal CO_2 Transport

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Abstract

This study describes a Mixed-Integer Linear Programming (MILP) model for optimizing the costs of CO_2 transport network infrastructure, involving multiple modes of transport (pipelines, trucks, trains, and ships) and the required conditioning and processing steps, for industrial Carbon Capture, Utilization and Storage (CCUS) projects. The model assumes varied amounts of CO_2 transported from the emission sources and accounts for essential factors, such as geographical locations of CO_2 emitters, injection points of geological storage, interim storage locations at seaports, and CO_2 transportation routes. To be more accurate and realistic, the model involves conditioning functions based on the pressure requirements of upstream and downstream transport systems, offering a precise representation of conditioning change processes. A case study is constructed to compare the costs and optimal transport network designs for various amounts of CO_2 transported from a set of industries in Western Europe. The results highlight the economic viability of flexible, multi-modal systems for small-scale applications, transitioning to pipelines for larger volumes. This work offers critical insights into scalable CO_2 transport solutions, supporting efficient CCUS deployment in the near future.

Keywords: Multi-modal transport; CO_2 transportation; Mixed-integer linear programming; Carbon capture, utilization and storage

1. Introduction

The rapid increase in global anthropogenic CO_2 emissions over the past century has intensified the urgency of implementing effective mitigation strategies to combat climate change [1]. Carbon capture, utilization, and storage (CCUS) technologies have emerged as pivotal tools in reducing atmospheric CO_2 levels by capturing CO_2 from industrial emissions sources to convert it into valuable chemical products or injecting into geological formations for long-term storage [2]. The design of efficient and cost-effective CO_2 transport networks is crucial to the overall success of CCUS projects [3].

CO_2 transport systems can use a variety of transport modes, including pipelines, trucks, trains, and ships, each with distinct characteristics and costs [4]. Many studies have focused on the design of single-mode transport systems considering the hydraulic model and right sizing [5, 6], due to their established role in natural gas transport. Pipelines, in particular, offer cost advantages for large-scale, long-distance onshore CO_2 transport [7]. However, deploying

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pipelines for small-scale CO_2 transport in the near future may not be economically viable [8]. For example, the levelized cost of gas-phase CO_2 pipeline transport depends significantly on the transported flowrates, ranging from €0.24/t_{CO2}/km for 0.1 Mt/y to €0.015/t_{CO2}/km for 10 Mt/y [9], making the pipeline transport of CO_2 for small-scale CCUS deployment economically challenging. In the near future, with the deployment of small-scale CO_2 transportation, more flexible modes of transport, such as trucks and trains, could offer viable alternatives for pipelines [10]. Furthermore, designing multi-modal CO_2 transport chains can potentially enhance the CO_2 transport networks' flexibility and economic efficiency, particularly for regions with diverse geographic and infrastructure constraints [11–13]. Becattini *et al*. presented an optimization framework formulated as a Mixed-Integer Linear Programming (MILP) model for the optimal design of carbon capture, transport, and storage supply chains while complying with different emissions reduction pathways over a deployment time horizon of 25 years [11]. Gabrielli *et al*. developed an advanced MILP model to design CCUS supply chains that ensure a specified level of resilience while minimizing total system costs and CO_2 emissions [12]. Zhang *et al*. also employed a MILP model to propose comprehensive transportation routes as well as the resultant system deployment schemes [13]. Although these studies consider the full-process simulation of CCUS, they lack detailed calculations for the transportation process. In particular, it is essential to account for conditioning costs during transportation mode transitions and the interim storage costs to quantify the benefits of the multi-modal transport network.

This study develops a steady-state mixed-integer linear programming (MILP) model to optimize the economic performance of multi-modal CO_2 transport networks, and provides a detailed calculation of transportation cost and conditioning cost. The model assumes four transport modes—pipelines, trucks, trains, and ships—and accounts for the locations and annual emissions of CO_2 sources, onshore and offshore transport conditions, and temporary storage at ports. A key innovation of this model is the integration of conditioning between different transport modes, for which the costs are calculated based on the upstream and downstream pressures, thereby enabling a detailed representation of mode-transfer processes. The model is then applied to a European case study, demonstrating its capability to identify optimal transport configurations for varying CO_2 transport volumes and providing detailed insights into the capital expenditures (CAPEX) and operational expenditures (OPEX) associated with transport and conditioning. This study aims to develop design tools for planning scalable and flexible CO_2 transport solutions that address the transitional needs of near-term CCUS deployment, paving the way toward a sustainable and low-carbon economy.

2. Methodology

In this part, a MILP model is constructed to optimize the design of a multi-modal CO_2 transport network based on the project costs, subject to the transport system operation and design conditions and constraints. The latter is introduced to account for the geographical distribution of CO_2 emitters and storage sites, the accessibility of routes and infrastructure for different modes of transport, and the specific quantities of CO_2 to be transported.

2.1. System description

The present study concerns the development of a design optimization model for a generic multi-modal CO_2 transport collection/ distribution network connecting onshore industrial CO_2 emitters with offshore geological storage sites via a set of transition ports. Fig. 1 shows schematically the sets of CO_2 industrial emitters $\boldsymbol{N_c}$ distributed in a geographical region, geological sequestration sites $\boldsymbol{N_s}$ and interim storage locations at the ports $\boldsymbol{N_b}$ are to be connected via different CO_2 transport modes. The circles represent the locations of onshore emission sources, with larger circles indicating higher emission volumes. Shipping is assumed to be the mode of transport between the ports and the storage sites. The total set of the network nodes, $\boldsymbol{N}$, combines the sets $\boldsymbol{N_c}$, $\boldsymbol{N_b}$ and $\boldsymbol{N_s}$, and can be expanded to include additional interim nodes resolving the geographical transportation routes. The arrows show schematically potential connections and direction of CO_2 transport between some of the onshore nodes using one of the transport modes, selected from a given set of modes, $\boldsymbol{Y}$, including pipeline, truck, train, and ship, represented by different colors.

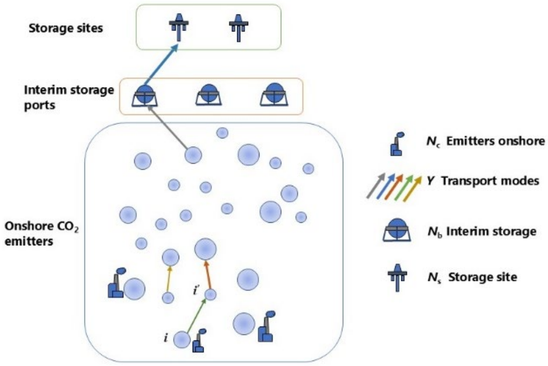

Fig. 1. Schematic diagram of multi-modal CO_2 transport system.

In this study, we included five common modes of transportation, including pipelines transporting CO_2 in gas phase and dense phase, trucks, trains and ships transporting CO_2 in liquid phase. The assumed operating conditions for CO_2 transport modes are shown in Table 1. The cost of CO_2 transport for each mode, including its CAPEX and OPEX, were calculated using correlations from the literature [14–17]. Furthermore, in this study, we assumed purification of CO_2 at the emission sources to achieve the CO_2 purity of 99.8% as required for CO_2 transport [18].

Table 1. Operating conditions assumed for CO_2 transport modes

CO_2 transport mode	Pressure (bar)	Temperature (ºC)
Pipeline-gas phase	25	20
Pipeline-dense phase	130	20
Truck	15	–30
Train	20	–30
Ship	15	–30

2.2. The MILP model

The MILP optimization is particularly useful for decision-making problems involving both discrete and continuous variables [19]. Discrete variables can only take on specific, distinct values, describing, e.g., the decision whether or not to build a facility [20]. Continuous decisions, on the other hand, are described by actual variables that can take on any value within a given range, such as the amount of CO_2 to be transported through a pipeline.

The MILP problem consists of input data, decision variables, linear constraints, and an objective function, of which the general form in mathematical terms can be described as

$$\min_{\boldsymbol{x}}\left(\boldsymbol{p}^{T}\boldsymbol{x}\right) \tag{1}$$

subject to

$$\boldsymbol{A}\cdot\boldsymbol{x}\le\boldsymbol{b} \tag{2}$$

$$\boldsymbol{A}_{eq}\cdot\boldsymbol{x}=\boldsymbol{b}_{eq} \tag{3}$$

$$\boldsymbol{lb}\le\boldsymbol{x}\le\boldsymbol{ub} \tag{4}$$

where $\boldsymbol{p}$ is the vector of objective functions, such as the unit cost of transportation, and $\boldsymbol{x}$ is the column vector of unknowns that includes actual variables, representing, e.g., the transportation distance between the nodes, and the integer “binary variables”, implementing the model constraints [21]. Eqs. (2)–(4) describe the model’s additional constraints due to the nature of the problem and limits on the variables, e.g., the capacity constraints for storage.

Input data: This data includes (i) the locations and transported amounts of CO_2 emissions from the plants; (ii) the locations and capacities of CO_2 storage sites; (iii) the costs of transportation, conditioning and interim storage; (iv) the availability of CO_2 transportation modes (i.e., the connectivity between nodes).

Decision variables: These variables represent the unknowns of the MILP model and are listed in Table 2.

Table 2. Decision variables of the MILP model.

Variable description	Variables	Units	Variable ranges
Logical variable for the implementation status of the transport mode y between nodes i and i'	$c_{i,i',y} \in \{0,1\}$	–	$\forall i,i' \in \mathbf{N}, \forall y \in \mathbf{Y}$
Design capacity of the transport mode y between nodes i and i'	$R_{i,i',y} \in \mathbb{R}$	tCO_2	$\forall i,i' \in \mathbf{N}, \forall y \in \mathbf{Y}$
Flowrate of CO_2 using the transport mode y between nodes i and i'	$G_{i,i',y} \in \mathbb{R}$	tCO_2	$\forall i,i' \in \mathbf{N}, \forall y \in \mathbf{Y}$
Logical variable for the installation status of CO_2 transport mode y between nodes i and i'	$z_{i,i',y} \in \{0,1\}$	–	$\forall i,i' \in \mathbf{N}, \forall y \in \mathbf{Y}$
CO_2 stored at interim nodes	$B_i \in \mathbb{R}$	tCO_2	$\forall i \in \mathbf{N_b}$
CO_2 stored at storage sites	$U_i \in \mathbb{R}$	tCO_2	$\forall i,i' \in \mathbf{N_s}$

Constraints: The constraints are the conditions that the decision variables must satisfy for the solution to be feasible—to meet the real limitations and respect all necessary requirements for the network. These include CO_2 mass balances, limitations on CO_2 transportation capacity, connection requirements, maximum and minimum flow rates, and CO_2 storage capacities. In particular, the connections between the nodes were restricted by more constraints to ensure that there is only one transport mode between any two nodes, no two-directional transportation, the onshore nodes are connected to the interim port before the offshore transport, and the CO_2 streams can only be combined rather than split at any nodes in the network.

Objective function: The objection function of the MILP problem is the minimum cost of the system, including the capital cost and operation cost for transportation and conditioning:

$$\min\left(\text{TCAPTRA}+\text{TOPTRA}+\text{TCAPCOND}+\text{TOPCOND}\right) \quad (5)$$

where TCAPTRA is the annual CAPEX for all transport infrastructure, TOPTRA is the OPEX for all transport infrastructure, TCAPCOND is the annual CAPEX for all conditioning facilities, and TOPCOND is the OPEX for all conditioning.

The optimal design of CO_2 transportation network is determined by solving the MILP optimization problem that minimizes the total cost of the infrastructure construction and operation for a finite set of CO_2 transportation modes and the system-specific conditions and constraints.

2.3. Conditioning cost

Fig. 2 presents some of the conditioning flowsheets simulated in Aspen Plus. Fig. 2(a) shows the conditioning process from trucks (–30°C, 15 bar) to pipelines (20°C, 130 bar), which involves both pressurization and heating stages. Fig. 2(b) illustrates the process from pipelines (20°C, 130 bar) to ships (–30°C, 15 bar), consisting of depressurization and two cooling cycles, with ammonia used as the refrigerant. We assume that CO_2 has already been purified to 99.8% before entering the transport network, so no purification equipment is included in the flowsheets. Using these two flowsheets, we developed cost functions for conditioning, which were incorporated into the MILP calculations.

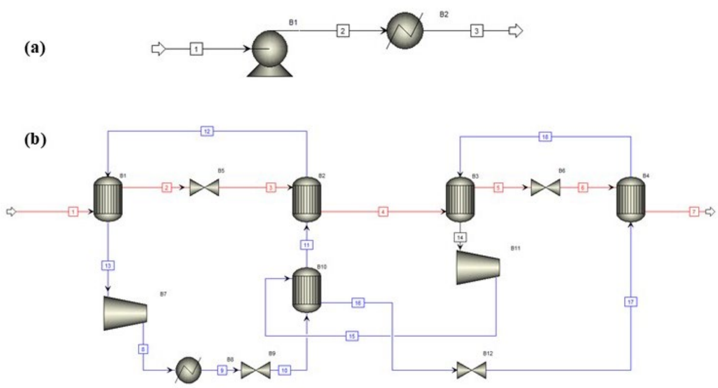

Fig. 2. Scheme of the conditioning configurations in Aspen Plus. (a) conditioning from truck to high-pressure pipeline; (b) conditioning from high-pressure pipeline to ship.

2.4. The case study

The constructed MILP model is applied to a case study in Europe. The locations of the CO_2 emitters, transition ports and the destination geological storage site assumed in the case study are schematically shown in Fig. 3. We consider six onshore CO_2 emitters in iron and steel industries, with the total CO_2 emission of 2.23 Mt/y. The bigger circle represents more CO_2 emission at the node. There are three interim storage ports, namely the Rotterdam port, the Hamburg port, and the Rostock port. CO_2 will be collected and transported to the Northern Lights storage point via one of the three interim storage ports. The location and annual emission for each emitter are listed in Table 3.

Table 3. Location and annual emission for each node.

Node no.	Node name	Latitude	Longitude	CO_2 emission ($ktCO_2/y$)
1	Integriertes Hüttenwerk Duisburg	51.3753º N	6.7268º E	514
2	Roheisenerzeugung Dillingen	49.3557º N	6.7324º E	460
3	Glocke Salzgitter	52.1579º N	10.4222º E	376
4	Einheitliche Anlage Bremen	53.1398º N	8.6883º E	248
5	Herdofenanlage Fortuna-Nord	50.9885º N	6.6620º E	128
6	Warmwalzwerk	50.6892º N	7.1867º E	504
7	Hamburg Port	53.5074º N	9.9681º E	–
8	Rostock Port	54.1514º N	12.1010º E	–
9	Rotterdam Port	51.9648º N	4.1491º E	–
10	Northern Lights	60.5548º N	4.8847º E	–

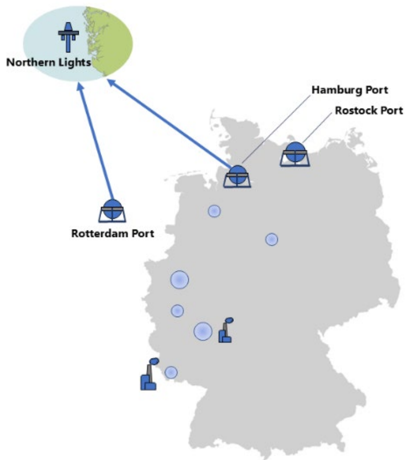

Fig. 3. Scheme of the case configuration showing the six CO_2 emitters in Western Europe, three interim storage ports, and the Northern Lights storage point.

Five transportation modes, as mentioned in Table 1, are involved in the case study, including four onshore transportation modes and one offshore shipping transportation. The conditioning cost functions for the transition of varied transport modes are developed using ASPEN Plus® to enable a more accurate estimation of the conditioning cost. The distance of transportation between any two nodes is calculated by the direct line of the two nodes. The MILP optimization model, which minimizes the total costs defined by Eq. (5) complemented by the constraints, was coded in MATLAB and solved by the commercial solver Gurobi [22].

3. Results and discussion

Fig. 4 illustrates the optimal solutions for a multi-modal CO_2 transport network under varied transport amounts. The calculation is divided into 10 scenarios, the transport amount of which varies from 10%–100% of the total CO_2 emission. It can be observed that at low transport amounts (10%–30% transported volume at each emitter node), onshore transport is entirely handled by trucks. As the transport amount increases, high-pressure pipelines start to play a role, subject to regulatory authority. When 40% of the CO_2 is transported, the optimal solution involves constructing a short pipeline to the Rotterdam port, with other nodes connected to the main pipeline via trucks. At 50% of the total transport amount, the main pipeline extends to the Hamburg port, while trucks still connect other nodes to the pipeline.

As transport amount continues to increase, the pipeline network grows longer, while the main pipeline remains unchanged, and truck usage decreases. Once the transport amounts exceed 80%, all onshore transport transitions to pipelines, with trucks no longer in use.

From the results in Fig. 4, it can be concluded that trucks provide greater flexibility and cost-effectiveness for transporting over short distances and small CO_2 amounts (less than 0.67 Mt/y in this work). As transported CO_2 amounts increase, the share of pipelines becomes progressively higher. It can be concluded that multi-modal transport systems show significant advantages for small emission sources in the near future.

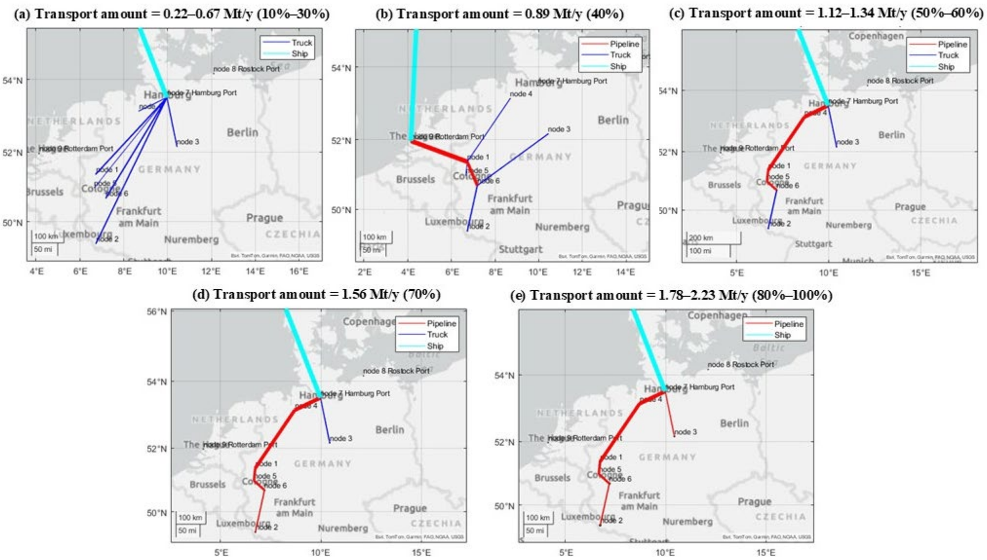

Fig. 4. Optimal solutions of multi-modal CO_2 transport networks under varied transport amounts.

Fig. 5 illustrates the annual CAPEX and OPEX of the optimal transport system under different transport volumes. From Fig. 5(a), it can be observed that CAPEX is very low when transporting small amounts of CO_2, as truck transport requires significantly less capital investment than pipelines. However, Fig. 5(b) shows that trucks incur substantial OPEX due to the high costs associated with maintenance and labor. Overall, both CAPEX and OPEX gradually increase as the transport volume grows.

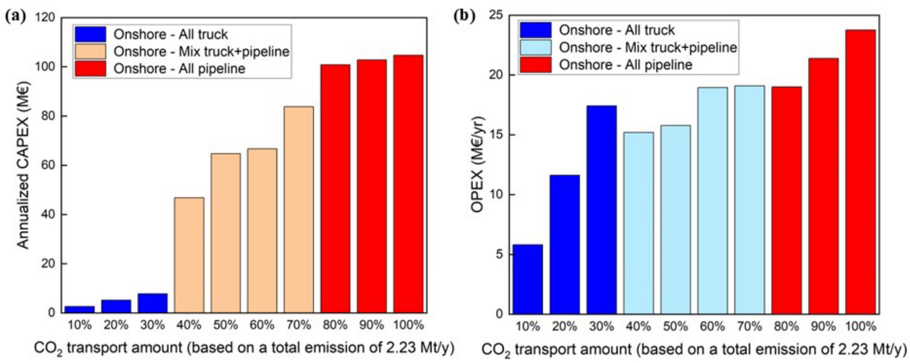

Fig. 5. CAPEX and OPEX of the optimal CO_2 transport network at varied transport amounts: (a) annualized CAPEX; (b) OPEX.

Fig. 6 illustrates the CAPEX and OPEX of conditioning under varying transport amounts. Except for the 40% transport amount scenario, both CAPEX and OPEX generally increase with higher transport amounts. This anomaly at 40% is due to the need for multiple conditioning processes in this transport network, as shown in Fig. 4, leading to relatively higher CAPEX and OPEX.

Fig. 6(b) also shows that the OPEX at 70% transport amount is lower than in other scenarios. This is because, compared to the low transport volume scenarios, it only involves pipeline-to-ship conditioning. Meanwhile, compared to high transport volume scenarios, the CO_2 conditioning amount is lower than that in the 80%–100% transport amount scenarios. As a result, the overall conditioning cost at 70% scenario is relatively low.

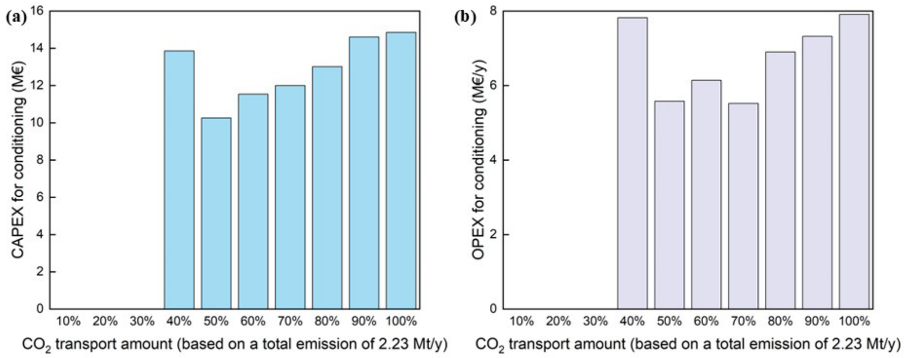

Fig. 6. Conditioning cost under varied transport amounts: (a) annualized CAPEX; (b) OPEX.

Fig. 7(a) shows the annual CAPEX for transportation and conditioning infrastructure under various scenarios. It is evident that the capital investment in conditioning equipment is minimal, while the pipeline infrastructure requires significantly higher investment compared to truck transportation. Fig. 7(b) presents the OPEX for transportation and conditioning across the scenarios. It shows that the OPEX for conditioning is non-negligible, especially in the scenario with 40% transportation volume. This scenario involves more conditioning requirements, resulting in its higher conditioning OPEX.

Moreover, Fig. 7(c) compares the total CAPEX and OPEX across all scenarios. It highlights that as transportation volume increases, the total cost rises sharply. For trucks, OPEX is higher than CAPEX (10%–30% transport amounts). In contrast, when pipelines are involved, the overall CAPEX significantly surpasses OPEX, underscoring the cost-intensive nature of pipeline infrastructure relative to its operational expenses.

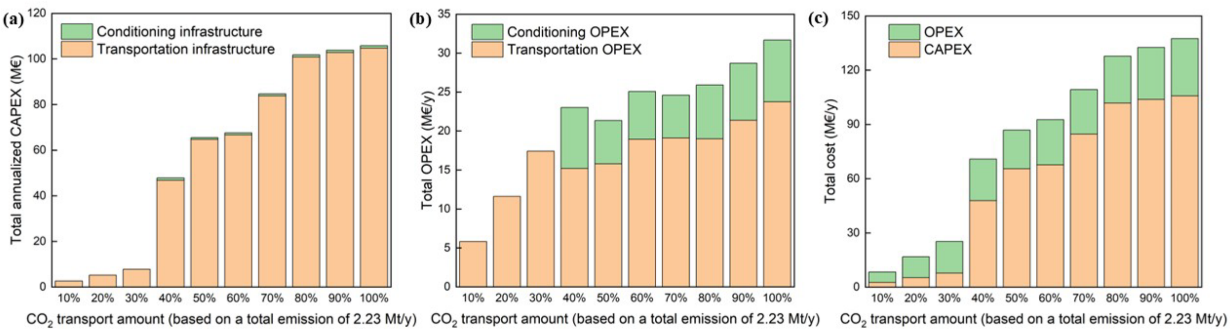

Fig. 7. Total cost of transportation and conditioning under varied transport amounts. (a) Total annualized CAPEX; (b) Total OPEX; (c) Total cost.

Furthermore, considering all the above results, the Hamburg port is commonly used as a transition port from onshore to offshore transport in most scenarios due to its geographic advantage of connecting all emitters in a short distance. For long-term investment and operation, it is recommended that the Hamburg port be selected as an interim storage point. Additionally, if there are no more emitter nodes involved in this network, pipeline segments that spread from the Hamburg port to the southwest, as shown in Fig. 4(c)–(e), can be constructed earlier to address the challenges of more CO_2 transport amounts in the future.

4. Summary and conclusions

This study developed a MILP optimization framework to aid the design of cost-effective multi-modal CO_2 transport infrastructure for future CCS projects. The MILP model includes a detailed calculation of each transport mode cost and all conditioning costs from one mode to the other. The model was implemented to include CO_2 transport by pipelines, trucks, trains, and ships, explicitly accounting for the amount of CO_2 transported and geographical constraints. Then the model was applied to a case study in Western Europe, including six onshore emitters, three interim ports at the sea, and one CO_2 storage site, to collect all onshore emissions to the storage site via one of the interim posts. The results show that trucks provide greater flexibility and cost-effectiveness for transporting over short distances when CO_2 transported amount is less than 0.67 Mt/y. The results also highlight the economic and operational advantages of transitions from trucks to pipelines for larger volumes, as pipelines offer long-term scalability and cost efficiency. Moreover, incorporating conditioning costs between transport modes provides a more comprehensive understanding of network economics, enabling a realistic assessment of infrastructure needs. This research underscores the critical role of multi-modal systems in early-stage CCUS deployment and their potential to support the transition to a low-carbon economy. By optimizing transport configurations and minimizing costs, the model provides valuable insights for policymakers and industry stakeholders, paving the way for more sustainable and scalable CO_2 transport solutions.

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