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Industrial CO_2 transport in Germany: Comparison of pipeline routing scenarios

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ABSTRACT

Carbon capture and storage will be necessary for some industries to reach carbon neutrality. One of the main associated challenges is the design of the network linking the CO_2 sources to the storage sites. Establishing a CO_2 network can be impacted by many uncertainties such as CO_2 amounts, pipeline routes and the locations of emitters and carbon sinks. We present a framework to investigate different scenarios of a future CO_2 network in Germany. The analyses compare the routes and associated costs of different scenarios. The developed model uses several geospatial datasets and an optimization scheme to yield realistic and cost-efficient outcomes. Parameters such as population density and existing infrastructure are integrated to calculate potential routes, which are then used as an input for the developed heuristic model to determine the optimum network. The derived framework is flexible and can be used for investigating other scenarios, regions and settings. The results show that the different scenarios have a profound impact on the optimal layout and costs. The investment costs of the investigated scenarios range between 1.3 and 3 billion EUR. The outcomes are important for academia, industry and policymaking for the ongoing discussions regarding the development of carbon infrastructure.

1. Introduction

The industrial sector is responsible for large amounts of greenhouse gas (GHG) emissions. In Germany, about 30 % of the annual emissions are caused by the energy sector and 24 % are generated by the different industrial activities (UBA, 2020). According to the national climate goals, the country is obliged to reach climate neutrality by 2045 (Agora, 2021). Reaching this goal, especially for the industrial sector, requires overcoming a series of key obstacles. First, the process emissions of certain industries, such as cement and lime are linked to the production process and cannot be mitigated in their current form regardless of the source of energy input. Second, there are uncertainties regarding ensuring supply security and transporting the required amounts of renewable energies to customers with growing demand in the future (Denholm et al., 2021; Groissböck and Gusmão, 2020).

Hence, CCS is an indispensable technology to mitigate hard-to-abate process emissions. Moreover, it can be a backup plan strategy if the supply of green electricity couldn't be secured in the future. However, a cost-efficient CCS operation cannot be realized without a CO_2 transport system in order to collect significant amounts of CO_2 from different locations and eventually store them. Transport and storage infrastructure for CO_2 is seen by governments and industries as a key challenge with all CCS projects, and it must be prioritized in order to reach CO_2 storage on gigatonne scale (GCCSI, 2023; IEA, 2024; Pathak et al., 2023; Tumara D et al., 2024). CO_2 pipeline networks in particular have been shown to be cost-efficient and safe, with functioning networks in several countries such as the USA, Norway and the Netherlands, and others planned in Algeria, China and Australia (Noothout et al., 2014; Peletiri et al., 2018). A CO_2 pipeline can be capitalized on to revitalize certain areas by granting a link to carbon-free industry. However, one potential drawback of a CO_2 network is the lack of modularity and adaptability to a constantly changing CO_2 emission landscape. Indeed, the design phase of a CO_2-transportation network is very crucial as it can influence the long-term costs significantly. CO_2 pipeline network planning must therefore be done in a multi-objective manner, combining low-costs, awareness of future emission scenarios, geographical constraints associated with the network implementation for strategic choices.

CO_2 pipeline network planning, as well as pipeline network planning in general, has already been addressed in several studies as shown in table 1. There is a wide range of aspects that have been tackled in literature. Some earlier studies opted for conceptual or strategic designs that only show the main routes of the pipeline based on the locations of

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the emissions and storage sites such as (Kjärstad et al., 2011; Neele et al., 2011). Over time, additional dimensions have been integrated into the analyses. For example, the study of (d'Amore et al., 2020) succeeded in addressing the social aspects quantitatively and integrating them into the optimization model. The study of (Gabrielli et al., 2022) focused on optimizing the prospective CCS supply chain while also considering the network resilience. The studies of (Crîstiu et al., 2023; d'Amore et al., 2019; Leonzio et al., 2020) have analyzed the risks and uncertainties associated with developing such capital-intensive infrastructure systems.

Despite the usefulness of these studies, overlooking the pipeline routing and network configuration is their major shortcoming. The routes of the existing pipelines and population should be taken into account while designing the CO_2 network, especially where the land availability and social resistance are critical themes. Constructing a CO_2 pipeline in a high-population density (e.g. Germany) is more challenging than the regions with high land availability (e.g. USA). Therefore, not only right of way and land prices should be considered, but also the potential refusal or resistance of the adjacent communities. Such concerns can be manifested in the scientific studies that focus on the public acceptance and perception in Germany and Europe such as (Benrath et al., 2020; Braun et al., 2018; Pietzner et al., 2014; Schumann et al., 2014). Additionally, other geographical factors such as terrain slope and existing infrastructure can impact the costs and configuration of the prospective network. For example, using pipelines and routes of the existing pipeline network layout (e.g. for natural gas) might provide a comparative advantage.

Therefore, specific mathematical models have been developed in order to design more accurate CO_2 networks regarding more geospatial details (Table 2). However, such studies often focus on the mathematical and programming challenges and rarely consider other aspects such as associated uncertainties and industrial strategies and implications. For example, many studies have so far focused on the CO_2 emissions of power plants, which is an unrealistic consideration. As for the coal and lignite power plants the question is not if they are going to operate in the future, but rather when they are going to be decommissioned. For example, Germany has ratified the coal phase-out plan, which implies that no lignite and coal-power plant shall operate in Germany after 2038 (BMWi, 2019; Oei et al., 2019). While it can be argued that the fate of certain industries is also uncertain, CCS studies should nonetheless give more consideration to industries with hard-to-abate emissions than emitters that are, by law, destined to cease activity.

Hence, a comprehensive framework is necessary to integrate these different aspects into one study. This paper aims at filling these thematic and methodological gaps via considering all the mentioned shortcomings and presenting more realistic analyses regarding the development of a CO_2 network in Germany. The paper is structured as follows; the methodology and framework are firstly presented in Section 2 (methodology and data). The model, scenarios and datasets are also explained. Thereafter, the results are displayed and discussed in the third section (results and discussion). Finally, the paper is concluded by highlighting the main outcomes and presenting an outlook for future analyses in the last section (conclusions).

2. Methodology and data

The derived methodological approach has been developed to address the above-mentioned gaps. As shown in Fig. 1, the framework is composed of three consecutive steps. In the first step (i.e. construction raster & path proposal), the factors affecting the pipeline construction are identified and the relevant datasets are collected. These datasets are used to transform the geospatial attributes into mathematical units and then to a raster map. Thereafter, the raster map is used to produce potential routes between the source and storage nodes (i.e. pipeline path proposals). The "Pipeline path proposals" refer to the combined potential pipeline routes based on the geospatial aspects only (i.e. without considering the CO_2vol). The amounts and locations of emissions as well as the storage sites are defined based on different scenarios investigated in the study. The pipeline cost function and amounts of CO_2 emissions are then used as inputs for the network optimization (step no 2). The cost function demonstrates the relationship between the pipeline capacities, lengths and costs. The heuristic optimization model assigns pipeline capacity to carry flow from sources to sinks and creates a network from the path proposals that ensures material balance across all network nodes at the lowest cost. After solving each scenario, the resulting CO_2 networks are then compared via different quantitative and qualitative aspects regarding the prospective CO_2 network and CCS supply chain (i.e. the third step: scenario analysis).

In order to demonstrate the derived framework, Germany has been selected as a suitable region for various reasons; first, the country has a clear political commitment to achieve carbon neutrality by 2045 despite having the highest magnitude of annual emissions in Europe (Agora, 2021; UBA, 2020). Therefore, the study's outcomes can be very relevant for the ongoing discussions regarding the required infrastructure, especially due to the limited number of studies and models on the country. Second, the German industrial sector encloses a variety of industries and spatially distant plants, which are not clustered in a clear way. Therefore, resulting network structures can be very distinct depending on the chosen inputs. Third, the country can effectively represent the main features of other European regions such as land availability, geographical obstacles and social resistance.

2.1. Datasets

A number of geospatial datasets are used in the study (Table 3 & Fig. 2). These datasets are chosen due to their relevance in infrastructure

Table 1
Studies on CO_2 pipelines.

Study (Publication)	Strategic route(s)	Route optimization	Techno-economic analysis	Scenario analysis	Germany (As example)
(Binn, 2021; Binnenschifffahrt Online, 2021; Gao et al., 2011; Haszeldine, 2009; J. Morbee et al., 2010, Morbee et al., 2011; Skagestad et al., 2011; ZEP, 2013, 2016)	Yes	No	No	No	No
(Crîstiu et al., 2023; d'Amore et al., 2020; Gabrielli et al., 2022)	Yes	No	No	Yes	No
(Keating et al., 2011; Middleton and Bielicki, 2009; van den Broek et al., 2009; Yiheng Tao et al., 2021)	Yes	Yes	No	No	No
(Benrath et al., 2020)	Yes	No	No	No	Yes
(Johnson and Ogden, 2011)	Yes	Yes	Yes	No	No
(McCoy and Rubin, 2008)	No	No	Yes	No	No
(Nimtz et al., 2010)	No	No	Yes	No	Yes
(d'Amore et al., 2019)	No	No	No	Yes	No
(Leonzio et al., 2020)	No	No	Yes	Yes	No
(Lazic et al., 2014)	Yes	No	Yes	No	No
This study	Yes	Yes	Yes	Yes	Yes

Table 2
Models for CO_2 pipeline design.

Model	Programming	Cost functions	Route	Existing networks	Population	Topography
FE NETL (NETL, 2018)	Mathematical	Yes	No	No	No	No
IEA model (IEA, 2009)	Mathematical	Yes	No	No	No	No
GIS-MARKAL (van den Broek et al., 2009, 2010)	GIS & Linear programming	Yes	Yes	No	No	No
InfraCCS (J. Morbee et al., 2011; Joris Morbee et al., 2011)	MILP	Yes	Yes	No	No	Yes
SimCCS (Keating et al., 2011; Middleton and Bielicki, 2009; SimCCS, 2022)	MILP	Yes	Yes	No	Yes	Yes
This model	GIS & Heuristic	Yes	Yes	Yes	Yes	Yes

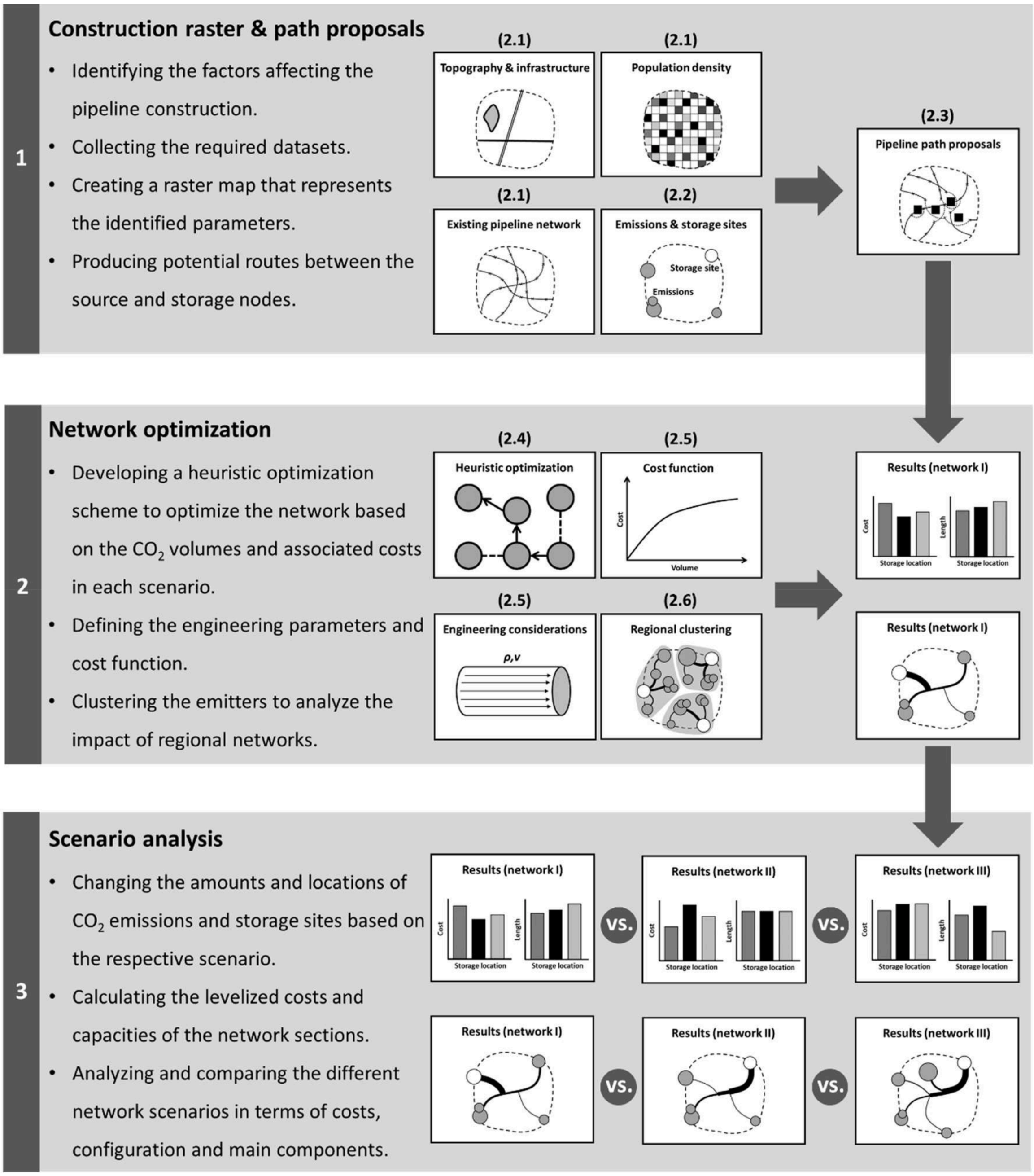

Fig. 1. Framework of the model and analyses.

planning and their inclusion in other pipeline network design studies such as (Kuby et al., 2011; Middleton and Bielicki, 2009; Middleton et al., 2011, 2012). The amounts and locations of CO_2 emissions were obtained from (DEHSt, 2021). To accommodate for the abnormal emissions occurring due to the COVID-related lockdowns in 2020, the emissions of the years 2015–2019 were averaged for each point source.

Table 3
Datasets used in the model and analyses.

Dataset	Described elements	References
Point source CO_2 Installation list 2020	Point source CO_2 emission volumes	(DEHSt, 2021; EC, 2020)
Electricity, heat, and gas sector data for modeling the German system.	Existing pipeline network	(Kunz et al., 2017)
German National census	Population density per km	(SABL, 2011)
Natural Earth	Rivers, Lakes, Motorway, Railways	(Natural Earth, 2021)
WISE	Transitional waters	(EEA, 2017b)
CCDA	CDDA protected areas, National parks	(EEA, 2021)
EU-DEM	Slope	(EEA, 2017a)

Relevant industry sectors and emitters were then filtered as desired for the different scenarios. In some cases, emitters found at the same location were grouped, depending on the studied scenario. Emitter locations and emission volumes are shown in the emitter map in Figure A1 (Supporting Information). The pre-existing pipeline data was obtained from (Kunz et al., 2017), which provides many decentralized sources to establish a georeferenced database of the German gas pipeline networks. Only larger existing pipelines, with diameters equal or larger than 350 mm, were considered for this study.

In terms of the population density, the employed data was obtained from the 2011 German National Census (SABL, 2011). The datasets of rivers, lakes, and waterways were obtained from the Natural Earth Data (Natural Earth, 2021). Transitional waters were also added to the waterways dataset from the WISE WFD Database (EEA, 2017b). The data of motorways and railways have been also acquired from (Natural Earth, 2021). Due to the high density of roads and railroads in Germany, only the larger motorways and significant railroads were selected for the study. Selecting the largest of these elements constitutes an appropriate simplification at the national scale, as they are going to be the main obstacle to further infrastructure development. Protected areas, registered under the Common Database on Designated Areas (CDDA), have been integrated in the model based on (EEA, 2021). National parks are also obtained from the CDDA dataset. Finally, the terrain slope is considered in the study as it is relevant for pipeline construction. Terrain slope is obtained from the Copernicus Land Monitoring Service - EU-DEM, housed by the EEA (EEA, 2017a).

2.2. Potential CO_2 sources and sinks

A scenario analysis has been implemented, investigating the effect of different configurations on the routes and associated costs. Scenarios depict and contrast various expectations in terms of number of emitters, locations, CO_2 quantities and CO_2 sinks. In total, 6 emitter scenarios and 3 storage cases are considered for a total of 18 distinct networks.

2.2.1. Emitter scenarios

Scenario 1: The scenario considers the hard-to-abate (i.e. process emissions) as the minimum amounts of CO_2 emissions that cannot be mitigated regardless of the source of energy input. The process emissions of the clinker and lime industry (95 plants) have been considered in the first scenario (based on (Schorcht et al., 2013; Stork et al., 2014)).

Scenario 2: The second scenario is more conservative than the first. It represents the case in which cement and lime producers, for techno-economic challenges, not only cannot mitigate process emissions, but also cannot mitigate their fuel emissions. Therefore, they have to sequester all their emissions (i.e. fuels and process emissions) via CCS.

Scenarios 3 & 4: As economies of scale play a major role in the CO_2 capture process (Kearns et al., 2021), small producers may incur more costs. Therefore, scenarios 3 and 4 apply thresholds to the emitters of scenario 2, below which the cement and lime plants are not considered. Thresholds of 100 kt and 50 kt are chosen, which result in 65 (scenario 3) and 81 (scenario 4) plants respectively being included.

Scenario 5: Achieving a carbon-neutral electricity system requires time. With the nuclear phase-out in Germany, coal and lignite-power plants will probably be needed in the midterm until 2038 according to the coal phase-out plan. Moreover, uncertain geopolitical climate has made energy security a priority on the national agenda. This scenario therefore investigates the impact of adding the coal and lignite power plants to the network as a method to achieve both energy transition and security in the midterm.

Scenario 6: Proximity to the German hydrogen network will play a key role in CO_2 emission strategies of some industries (e.g. steel), as they will find themselves with new technological options to mitigate their emissions (e.g. hydrogen-based direct reduction). According to the German hydrogen roadmap (FNB, 2020), the hydrogen network should reach most of the steel producers, but not all of them. Therefore, this scenario also considers the steel producers situated away from the hydrogen network (as well as cement and lime plants) as likely users of the CO_2 network.

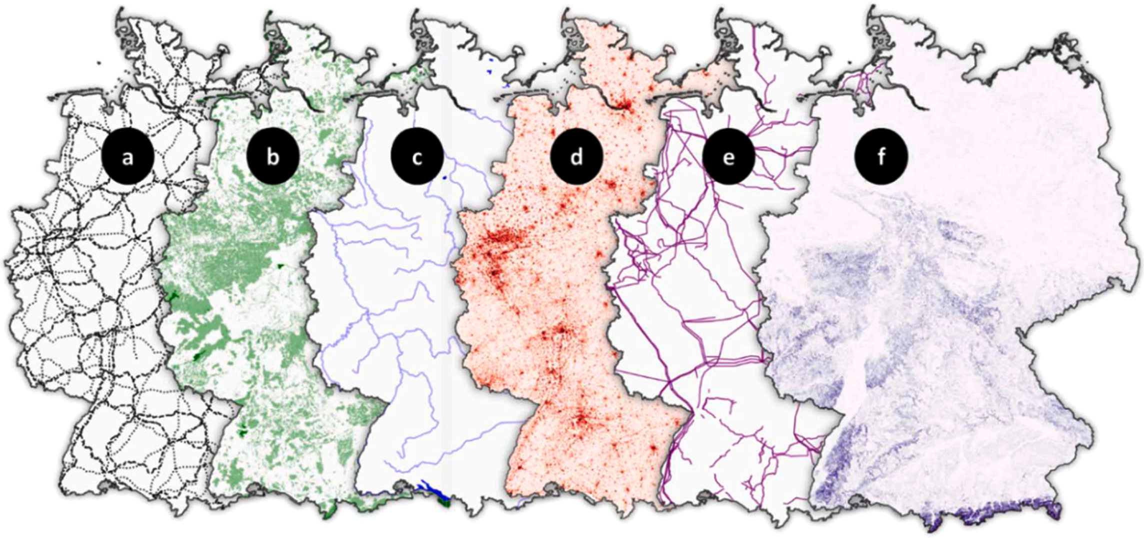

Fig. 2. Datasets used in the model. a) Main roads (dotted) and railways (hashed); b) CDDA areas (light green) and national parks (dark green); c) waterways and lakes; d) population density; e) pre-existing gas pipelines; f) terrain slope.

2.2.2. Storage cases

North Sea: As CO_2 exports still cannot be guaranteed due to the London protocol (IMO, 2006), a North Sea storage case is first evaluated, in which CO_2 does not leave the German exclusive economic zone. This storage case is represented in the study by a single sink location on the East Frisian coast, which symbolizes the final land pipeline before dedicated offshore transport to an undetermined array of North Sea reservoirs.

Netherlands: A link towards Rotterdam as a potential European CO_2 hub is provided as an alternative storage scenario. The Netherlands is developing Rotterdam as a CO_2 storage hub through the Porthos project[c] (Porthos, 2022), which is awaiting a final investment decision before construction of the infrastructure.

Regional: An option with multiple sinks taking on reduced volume is considered, combining the two German ports of Lübeck and Bremen with a connection to the Netherlands. This final scenario targets ship transport of CO_2 from German ports to alleviate the pressure on the Dutch hub. Although economies of scale can achieve significant cost reductions, establishing a single network all over Germany may also result in inefficiencies due to large distances between sources. The regional scenario is therefore valuable from a strategic and technical perspective.

We note that current German legislation, in the form of the Carbon Capture and Storage Act (BMJ, 2012) does not allow underground CO_2 storage, either onshore or offshore in Germany, and a revision would be necessary to enact the regional and North Sea storage options. Also, the final-leg transport costs (pipelines outside of German mainland, or shipping costs) have been omitted in all cases, due to significant uncertainty regarding the final CO_2 strategy.

2.3. Pipeline path proposal methodology

The pipeline path proposal methodology involves calculating weighted minimum-cost paths between network nodes using a pipeline construction raster assembled for this purpose. The pipeline path proposal consists of the three following steps: **(1)** creation of a pipeline construction raster, **(2)** calculation of elementary paths between closest neighbors, and **(3)** network simplification. The same steps are also broadly followed in (Middleton et al., 2012).

1) The pipeline construction raster assembles spatial criteria, objects or zones that are deemed relevant for the pipeline planning. The considered criteria are: population density, presence of rivers and lakes, railway lines, motorways, pre-existing gas pipelines, terrain slope, protected areas and national parks. An initial raster of the German territory is taken with uniform pixel values. Pixels intersecting each of the geospatial elements are multiplied by defined multipliers. Due to the numerous and dissimilar nature of the criteria used in the pipeline construction raster, this step does not yet use a real-world cost function, but rather identifies realistic pipeline paths. All multipliers in this work are finite, which means that pipelines can theoretically, but very improbably, be proposed at any location of the raster. If needed, an infinite value can be taken for a given multiplier in order to avoid certain locations. However, such solutions might not always be found, as some routes will inevitably need to cross a river or a motorway. Identification of the lowest-cost flow-carrying network comes at a later step, via the introduction of emission volumes and real-world cost. The raster multipliers, given in Table 4, are selected through a combination of literature examples and author estimation.

2) In the next step, elementary paths are calculated between relevant scenario locations. The georeferenced source and storage nodes are allocated to the closest corresponding pixel in the raster, forming initial network nodes. For each node, minimum-cost paths are found between the 15 other closest neighboring nodes in terms of geographical distance. Paths are calculated using a weighted Dijkstra's algorithm applied to a representative graph of the construction raster. The connections between pixels enable the pathfinding algorithm to navigate and find the lowest-cost path. Horizontal and vertical connection weights are given by the average of the two concerned pixels. An additional factor of $\sqrt{2}$ is used for the diagonal pixel connections. Proposed paths are often found to be overlapping in advantageous sections. The individual paths are then vectorized, with any overlap between them removed. This sum of all non-overlapping paths itself forms a new graph with intersections between paths representing new intersection nodes.

Table 4
Multiplication factors of the pipeline-construction-cost raster.

Criterion	Multiplier
Population density/km^2 (<250)	1
Population density/km^2 (250–500)	4
Population density/km^2 (500–2000)	9
Population density/km^2 (2000–4000)	16
Population density/km^2 (4000–8000)	25
Population density/km^2 (>8000)	36
Pre-existing pipelines	0.25
Railroads	3
Motorways	3
Rivers, lakes, and transitional waters	10
CDDA protected areas (excl. National parks)	10
National parks	30
Terrain slope [$0^\circ - 90^\circ$]	1–20

3) The resulting network of individual paths is simplified via stripping sections that create small cycles and redundant, close together intersection nodes. Cycles with an internal area of <50 km^2 only are considered. For each cycle, the longest edge is removed. The process is repeated as long as small cycles are still found. After this step, many intersection nodes are left over from broken cycles. These nodes subsequently only link two edges and will not serve a purpose in the later optimization process. Therefore, these nodes are removed, and the two pipelines attached to them are joined. Emitter nodes meeting this criterion are naturally left in place, however.

With these simplification steps, the network is strongly reduced in complexity. We provide an example of scenario 1, with the North Sea Storage location. From the 76 emitters with the additional storage location, taking the closest 15 neighbors yields 1078 unique paths on the pipeline construction raster (step 1 and 2). Each path is calculated individually. Merging the individual paths and noting the intersection points leads to 2507 segments separated by 1621 nodes. This graph is then simplified (step 3) down to 662 edges separated by 471 nodes. These numbers now become more approachable via the heuristic methods proposed in this paper. The graph simplification process is performed in less than an hour for all networks.

For the scenarios explored in this paper, the described simplifications result in a fivefold reduction in the number of edges and nodes, typically from multiple thousand to slightly >500. Fig. 3 shows the final construction raster with the resulting pipeline paths obtained after step 3, for emitter scenario 1, with the North Sea storage location.

2.4. Flow network optimization procedure

The previous pipeline path proposal methodology produces a network of potential pipeline routes without involving emission volume or real-world cost. Based on these paths, flow-carrying pipeline networks are determined in this section, considering pipeline length and capacity within a pipeline investment cost equation. All the final networks considered here are trees, or graphs without cycles, which significantly alleviates the optimization process and enables calculation of optimal networks in reasonable time. While considering exclusively tree-like networks may not be fully realistic, as complex gas networks often present cycles and auxiliary links for purposes of network stability,

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[c] Project of Common Interest (PCI) 12.3 "The Rotterdam Nucleus (Netherlands and United Kingdom)"

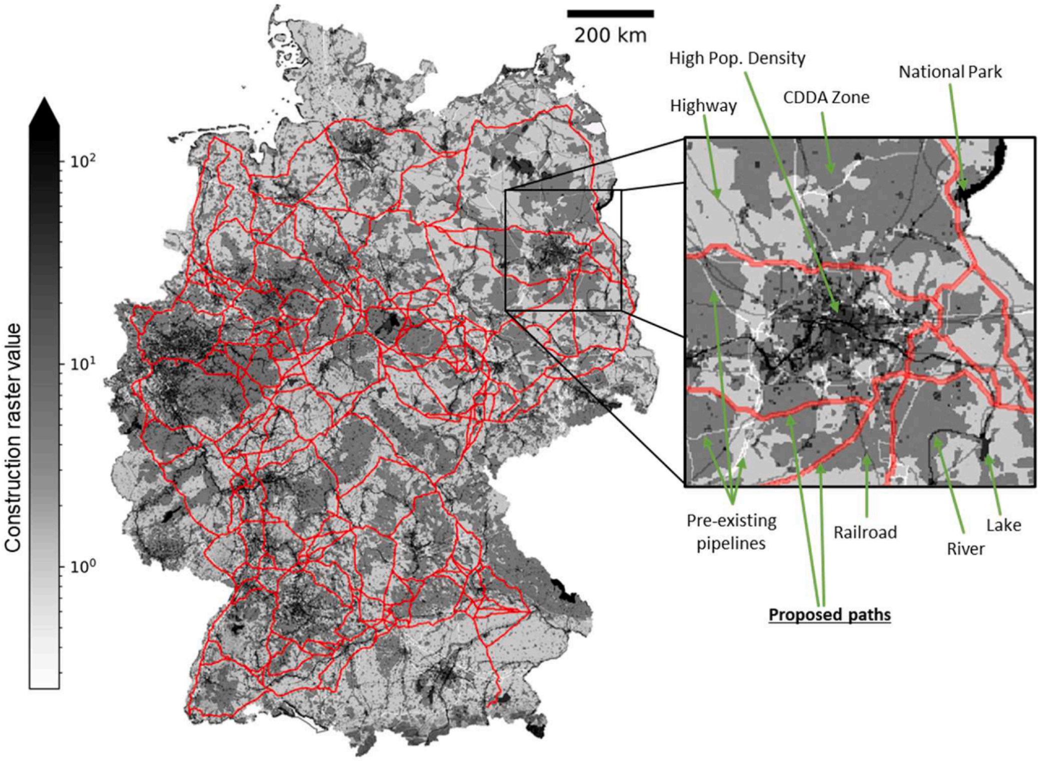

Fig. 3. Final pipeline construction raster (grey color scale), with elementary paths shown in red.

the optimal trees shown here are good candidates for network backbones, with additional links easily added in a secondary step. All calculations in this paper were performed in similar conditions on an Intel i7–8565 U CPU. The solution networks were calculated in less than a few hours each.

The network optimization procedure is described in brief here. First, for a given tree network structure, the assignment of pipeline capacity is possible via the method described in (Heijnen et al., 2020). This assignment assures material balance between sources and sink(s). A heuristic method then searches for lower-cost pipeline topologies starting from the incumbent solution, iteratively working towards the lowest-cost network available. The method is in fact composed of two heuristic algorithms working cooperatively, Algorithm A and B. Algorithm A performs a local search, based on the delta-change algorithm proposed by (André et al., 2013). Algorithm A finds at each step the single modification of the proposed network that results in the largest cost decrease. Algorithm B, a novel contribution, attempts exploratory moves outside the immediate solution neighborhood of the incumbent solution. As the local search can result in local minima, algorithm B is used only after exhausting algorithm A to find better solutions. We describe both algorithms in detail and provide pseudocode in the Supporting Information. For the input data used in this paper, using the combination of algorithm A and B results in a 10 %−25 % reduction in final cost versus using only algorithm A (i.e. local search). Calculation times are increased by a factor of 2–5, however. While the optimization methodology does not ensure a globally optimal solution, the combination of exploitative (algorithm A) and exploratory (algorithm B) approaches provides a reasonable expectation of close-to-optimal solution, usually good enough for all practical purposes. For simplicity, we will refer to final solutions as optimal solutions throughout the paper.

2.5. *Cost function & engineering considerations*

Real-world pipeline construction costs are based on the model proposed by (Parker, 2004). It has been shown that for CO_2 transportation networks, pipeline investment costs represent the largest cost incurred in the project life cycle (Benrath et al., 2020). The economic model has also been applied to CO_2 pipeline studies of (Chandel et al., 2010; McCollum and Ogden, 2006). Parker's model considers material, right of way, labor and miscellaneous costs in a combined quadratic function of pipeline diameter and a linear function of pipeline length. While Parker's model is based on North American cost data, (M. M. J. Knoope, 2015) carries out an extensive comparison of pipeline cost equations and finds Parker's model to be in a similar range to the European and global models. Furthermore, a cost-adjusted version of Parker's model has been used in a recent study focusing on the German CO_2 infrastructure design (Benrath et al., 2020), and is shown in Eq. (1):

$$I_{total} = \left(996{,}820 \times D^2 + 441{,}912 \times D + 223{,}522\right) \times L + 545{,}537 \tag{1}$$

Where I_{total} is the total investment cost in EUR (2010) for a single pipeline, D is the diameter (m) and L is the length in km.

For our study, two further modifications have been made. First, the added constant of 545,537 EUR has been omitted due to its minimal impact on the final costs for networks of the scale considered here. We estimate that for the final networks obtained in this study, the added constant would add only approximately 1 % of cost. More importantly, our study makes use of many intersection nodes, that may not modify flow throughput, but allow the optimization procedure to break up pipelines into smaller elements for more detailed route modification. An added fixed cost for each of these segments would increase the overall cost unrealistically and hinder the optimization process. The second modification of this cost function is the cost adjustment to July 2022 Euros. We estimate from the European Industrial producer price index (EUROSTAT, 2022), that an adjustment of +36 % is necessary to the 2010 prices shown in Eq. (1). The final cost equation used in our study therefore is given by Eq. (2), given in EUR_{2022}:

$$I_{total} = \left(1{,}355{,}675.2 \times D^2 + 601{,}000.32 \times D + 303{,}989.92\right) \times L \tag{2}$$

To retrieve a pipeline diameter D, we assume a constant liquid flowrate of liquid CO_2 at 3 m s^{-1}, a good practice value for CO_2 pipeline flow (M. Knoope et al., 2013). The pipeline pressure is also set to 100 bar based on (Peletiri et al., 2018), giving an approximate fluid density of 900 kg/m^3 at a temperature of roughly 15 °C. Output CO_2 mass flow is obtained by converting CO_2 output obtained from (DEHSt, 2021) in tonne/year into kg s^{-1}.

2.6. Regional clustering

In the analyses involving regional clustering and multiple storage locations, sources are grouped into clusters for each sink. This clustering is performed before the flow carrying network optimization, but after the path proposals are determined. Source clusters are determined via a two-step procedure. The number of clusters is determined by the number of sinks (here always 3). For a given emitter scenario, each emitter is initially allocated to the closest regional sink. The minimum spanning tree (MST) is then calculated for each cluster using all the available paths resulting from the path proposal procedure. For each MST, the capacity is assigned, and cost is calculated. A cluster switching step is then performed, in which emitters bordering a neighboring cluster are allowed to switch clusters. After this switch, MSTs, pipeline capacity and total cost are then recalculated for the modified clusters. The new configuration is accepted if the total cost over all clusters is lower than the initial clusters. The cluster switching process is repeated as long as cost-reducing switches are found. Using the MST rather than an optimized network structure for each cluster represents a necessary simplification due to computational constraints. As such, the clustering process is done without reference to the node capacities (i.e. emission volume).

3. Results and discussion

3.1. Network level analysis

Summarized results of all scenarios and storage cases are shown in Fig. 4, which compares the costs, lengths, and total captured CO_2vol of the results on a network level. The costs and network lengths of all three storage cases (i.e. North Sea, the Netherlands and regional clusters) are similar for a given scenario (Fig. 4–A), with small differences. North Sea scenarios are usually the most costly, due to the isolated and remote location of the North Sea sink. In contrast, the Netherlands sink is in proximity to a larger number of big sources, mostly found the state of North Rhine-Westphalia. Interestingly, splitting the network into regional sinks doesn't consistently lead to lower costs. Compared to the already convenient location of the Netherlands' sink, the regional sinks are located away from large emitters, and therefore do not contribute to reducing total network length, as also evidenced by (Fig. 2–B). Costs noticeably increase with total captured CO_2vol (Fig. 4–A and C), but less with network length (Fig. 2–B and C). To highlight the economies of scale arising with larger CO_2vol in the network, the results from Fig. 4–A are also visualized as normalized costs in Fig. 5. We observe a strong decreasing trend in normalized cost with the increasing volumes of captured CO_2 across all scenarios.

By comparing the single network and regional networks, we can notice that the capital costs are very close. The cost of regional networks is even cheaper than having one network in some scenarios. This suggests that economies of scale have their limitations and having one national network can be associated with inefficiencies. Nonetheless, it should be highlighted that the pipeline investment costs are not the only expenditures. One of the advantages of adopting a one-network approach (as opposed to regional sinks) is the cost efficiency regarding transshipment and terminal logistics. As the economies of scale also affect the transshipment (Wiegmans and Konings, 2015), regional clusters can incur higher terminal costs. Additionally, risks and uncertainties are an important factor as the number of emitters on the network affects the resilience if any problem occurs. A one-network solution implies that any problem taking place along the network can influence all upstream emitters, while regional networks can be more resilient. Hence, the stakeholders should determine which risks they have to hedge. Therefore, a cohesive view of all the supply chain elements needs to be considered in order to compare both approaches, which can be a potential extension for this study.

3.2. Scenario analysis

In order to illustrate the pipeline layout configurations, we provide corresponding maps showing the layout of optimized pipeline networks, the approximate capacity of each pipeline section and relative additional transportation costs incurred by each emitter (Figs. 6–8). Additional cost is calculated for a given emitter in an optimized network by

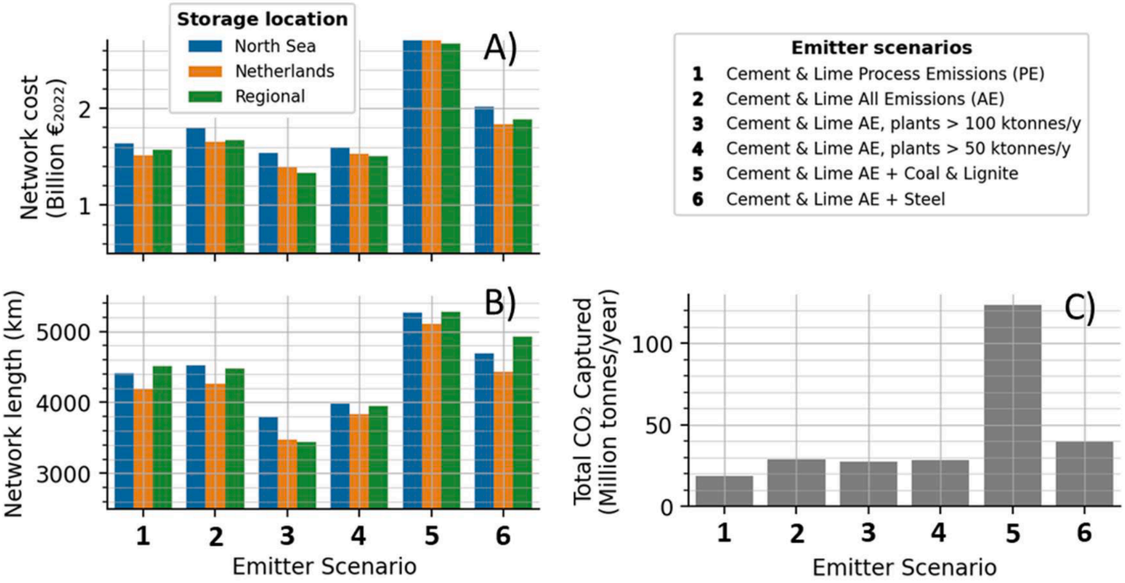

Fig. 4. Summary of the (A) total costs, (B) lengths and (C) considered yearly CO_2 emissions for scenarios 1–6.

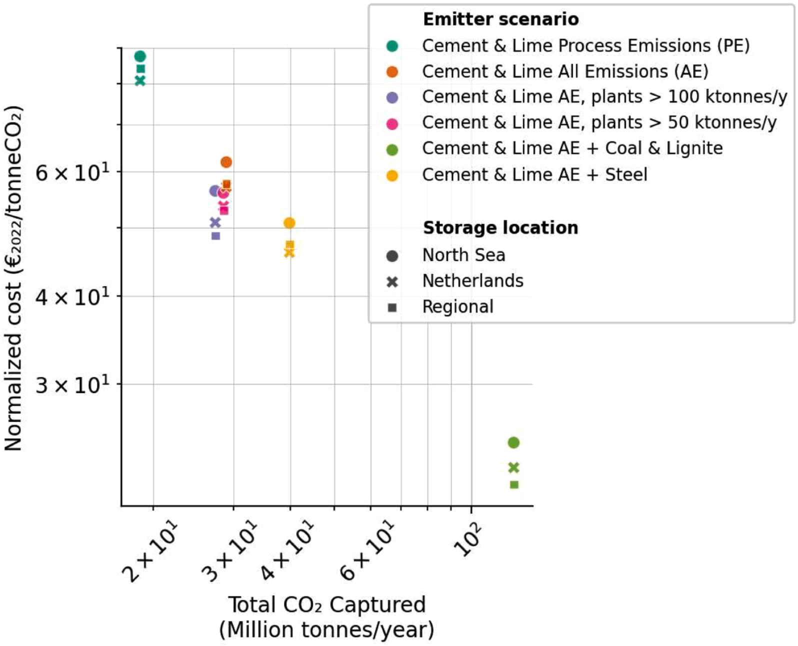

Fig. 5. Costs of different scenarios normalized by total emission volume.

setting its volume 0 and recalculating pipeline capacities and network cost. The additional cost of the emitter is then taken as the difference between this modified network cost and the original network cost. The cost difference is then divided by the annual emission volume for a relative measure of cost.

The total cost of the network in scenario 1 is approximately 1.7 billion EUR. As depicted in Fig. 6, the optimized CO_2 network links the individual pipelines into common bigger trunks with higher capacities to reduce relative costs, while fulfilling all the other constraints in the mathematical model. Broadly speaking, three main CO_2 trunks can be identified (T1, T2, T3), spanning different regions and splitting into subnetworks with a final trunk solely transporting CO_2 towards the sink (T1). The relative additional costs per emitter vary significantly for a given scenario. Although the average relative network cost is around 85 EUR/tonne CO_2, additional costs of larger emitters located close to the final trunks are very low, while smaller and isolated emitters (E100) show very high costs.

Comparing the optimal pipeline layouts for Scenario 1 between the

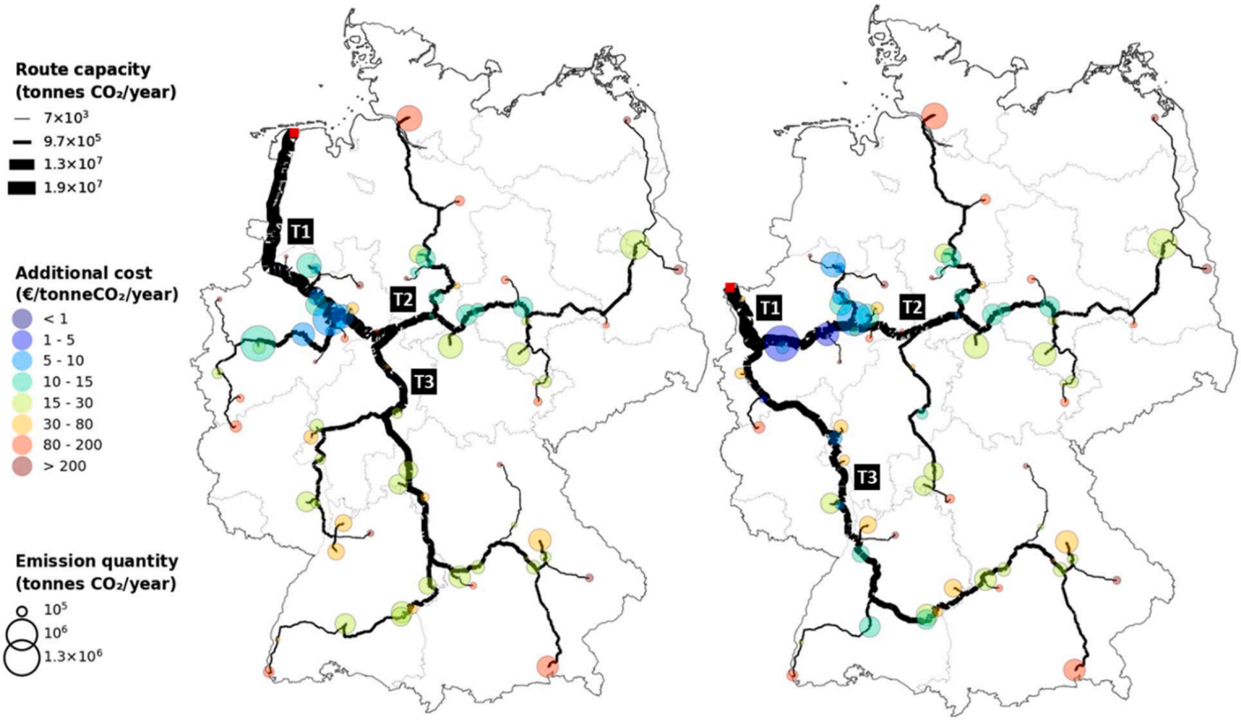

Fig. 6. Results of Scenario 1 (North Sea sink, left and Netherlands sink, right).

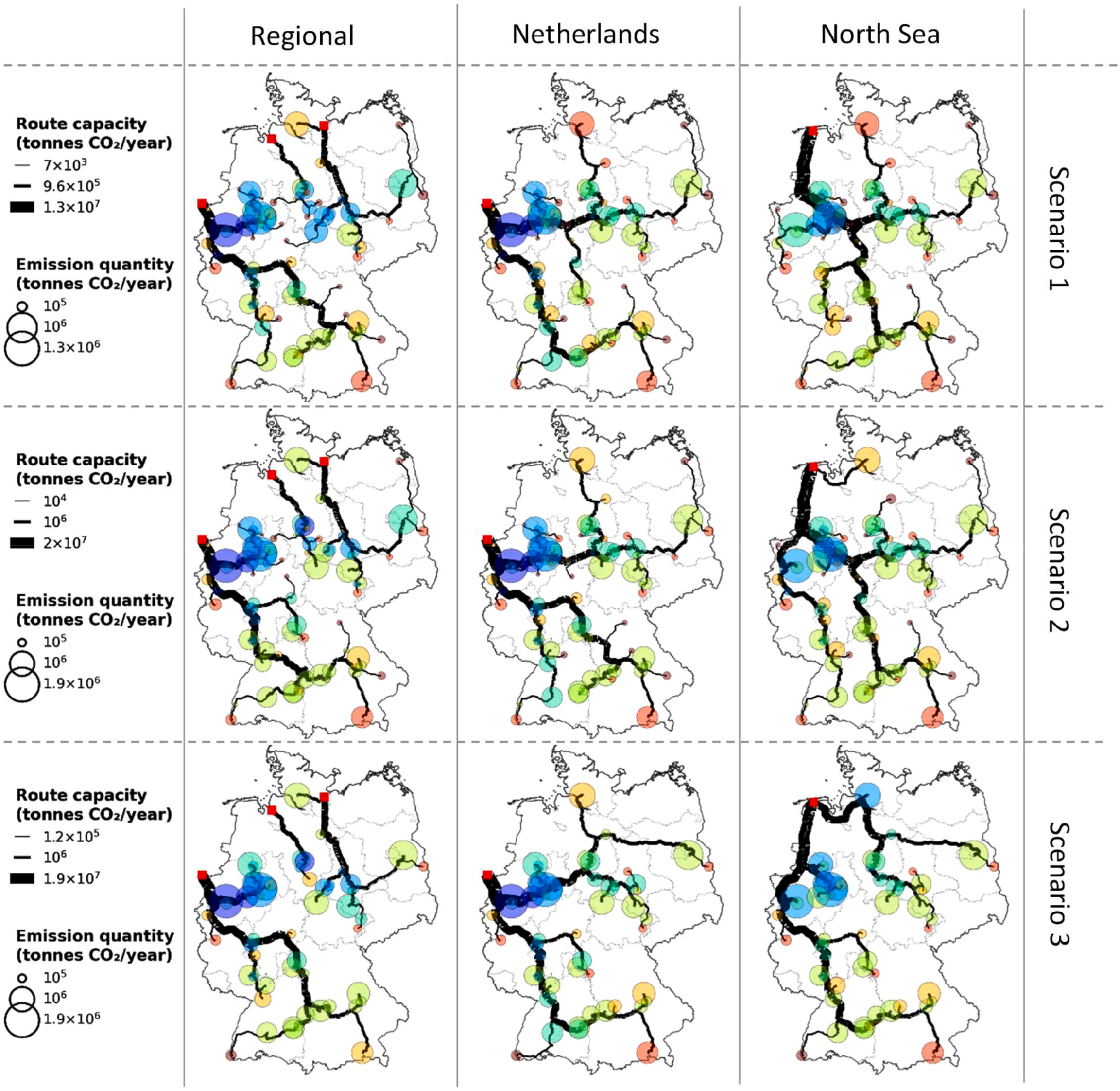

Fig. 7. Comparison of Scenarios 1–3 for all sink cases. The legend color is consistent with Fig. 6 and throughout the paper, but pipeline capacities and emitter sizes in the plots change on a scenario basis.

storage cases of the North Sea (Fig. 6, left) and the Netherlands (Fig. 6, right), we observe that emitters far away from the sink location can also be majorly affected by the flow rerouting in different configurations. The central T3 trunk of the North Sea storage case is now displaced towards the west of its counterpart in the Netherlands storage scenario. This relocation increases the additional cost of emitters that were initially positioned centrally in the network but now require dedicated pipelines. Other subsections of the network are unaffected by the storage change, such as the East of Germany, Bavaria and the Northernmost network branch.

Going from process-only emissions (Scenario 1) to total emissions of process and fuels (scenario 2) increases the total costs only by 10 %, while the total CO_2 transported increased >30 %. Therefore, the average normalized cost per CO_2 transported decreases (62 EUR/tonne CO_2). Optimal network layouts are also modified by this change in emission volumes. Additional costs are also modified when subsections of network configurations stay the same. For example, the northernmost emitter (E1, Figure A1) shows a reduction in relative additional cost for the Netherlands storage case despite having the same network subsection structure. This can be attributed to the intrinsic economies of scale of the pipeline construction cost function, as it requires in both cases a dedicated pipeline directly to the sink for the North Sea case.

Imposing a lower cut-off on emitters at 100 kt and 50 kt (i.e. Scenario 3 and 4) incurs only slight changes in the total costs. Nonetheless, as expected, the transportation costs per volume emitted (or specific transportation cost) increase as the magnitude of emissions have decreased. Scenario 3 demonstrates the necessity of having a larger network length for the North Sea case. Inspecting the network configuration, we observe that it is the only case (together with scenario 5) in which two thick trunks separately reach the sink and do not join at any point. The change of configuration has also impacted the costs of individual emitters in similar ways as before, through varying degrees of closeness to trunks and/or network centrality.

Linking the coal and lignite power plants to the CO_2 network (scenario 5) has an enormous impact on all related aspects (i.e., configuration, total costs, average specific transportation cost and individual specific transportation costs). The configuration of the CO_2 network and the main CO_2 corridors are now shaped by the biggest emitters (i.e. coal and lignite power plants) instead of the big clinker and lime plants in the previous scenarios. Therefore, a major CO_2 corridor has evolved to transport significant CO_2 amounts from East to West. Additionally, while the total costs have increased by two-thirds (2.7 billion EUR), the

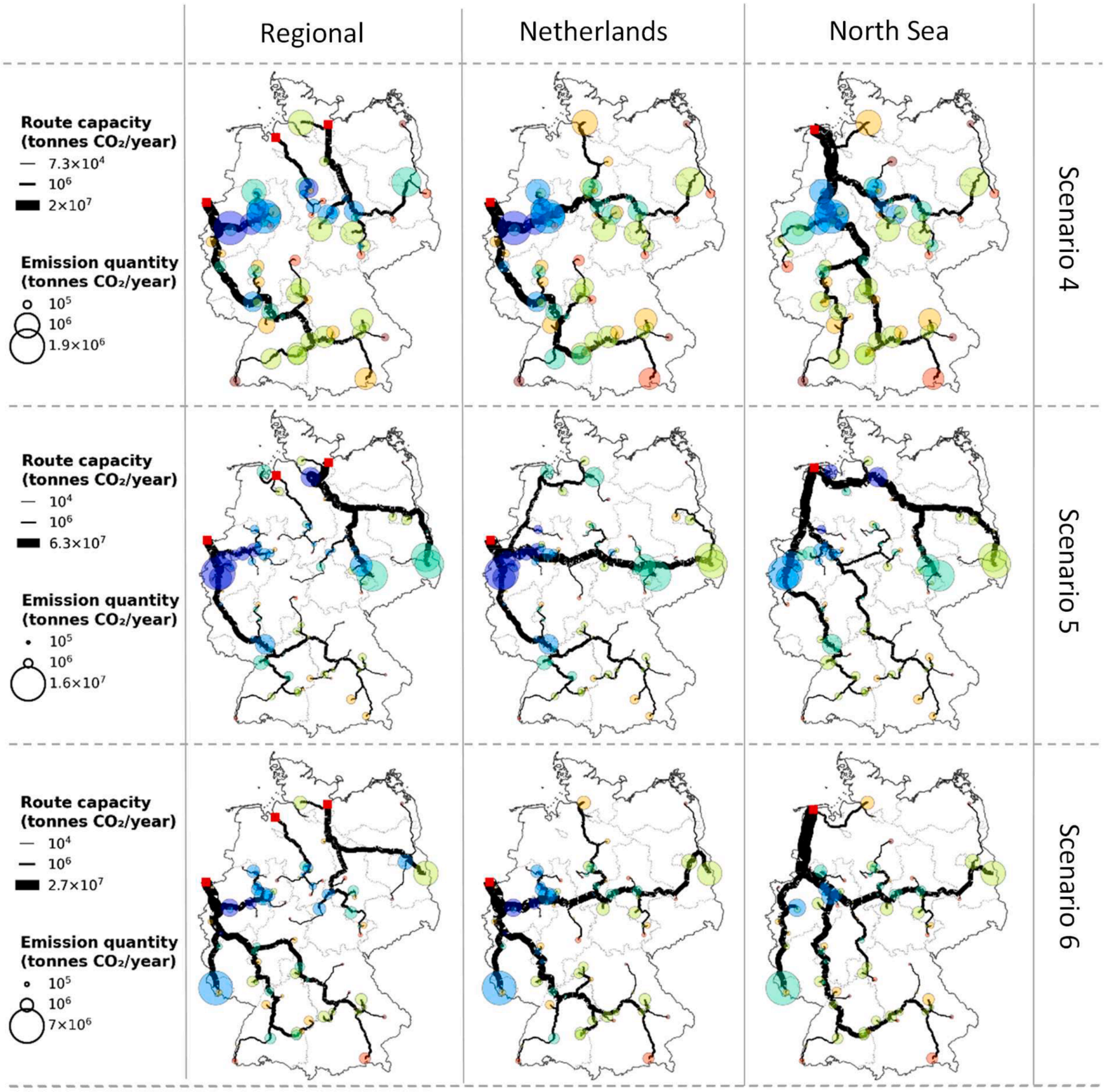

Fig. 8. Comparison of Scenarios 4–6 for all sink cases. The legend color is consistent with Fig. 6. Pipeline capacities and emitter sizes in the plots change on a scenario basis.

average specific transportation cost has decreased as the total amount of CO_2 increased by approximately 7 times (from 19 Mt CO_2 to 129 Mt CO_2,[d] Fig. 5). This change is very evident especially for the plants that are now close to the new major pipelines such as E13 (Figure A1).

For Scenario 6, additional steel plants have been added to the CO_2 network. According to (FNB, 2020), the hydrogen network should connect the main German primary steel producers located in North Rhine-Westphalia, Lower Saxony and Bremen. Nonetheless, two sites in Brandenburg and Saarland would not be covered by the network depicted by the proposed H_2 roadmap. Therefore, CCS could be a feasible option for the producers not linked to the hydrogen network. The steel production from these two sites is associated with 10.8 Mt CO_2, which means that the capacity to increase by more than one-third. A considerable capacity in Brandenburg has been added as a result, and federal state of Saarland is connected to the CO_2 network for the first time. Due to the significant magnitude of emissions from the steel industry in Saarland (approximately 7.3 Mt CO_2), a prominent CO_2 trunk emerges to connect the state towards the North. Like in Scenario 5, the increase in costs is not directly proportional to the increase in capacities due to the economies of scale.

As depicted in the presented scenarios, different optimal solutions present different costs, lengths, and routes. Some emitters are prone to considerable cost increases over most scenarios, especially the ones far away from the main CO_2 trunks. Hence, the results of the different scenarios illustrate the vulnerability of different emitters in terms of system configuration and transportation costs. Comparing additional costs on an emitter level strengthens the observations made from the previous paragraphs, as mostly small cement and lime plants show high additional costs. Note that capture costs are not considered in this paper, so only emission volume and location can contribute to network costs. We observe that larger emitters, mostly steel and power production plants, show lower additional costs. Also, as larger trunks are the most cost-efficient, minimum-cost networks emerge around them, trading off total network length with straightness of large trunks. This theoretical result shows that the largest emitters of optimal pipeline networks have reached a lower limit of relative cost that is bounded by length only.

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[d] The capacities that are going to be decommissioned before 2030 were omitted. Only the capacities that will operate in the next decade were considered, based on the governmental plans BMJ (2020); BNetzA (2021); Orsted (2020).

4. Conclusions

Designing a prospective CO_2 pipeline network with optimal configuration and capacities is of high importance to minimize the costs. The analyses have demonstrated the effectiveness of the presented approach in modelling various conditions and their implications on the pipeline network. Combining the modelling capabilities with practical questions can be interesting for both the researchers as well as the industrial sector and policymakers. For academia, the presented model has addressed research gaps of previous models while offering novel algorithms and applicable solutions. For policymakers and industrial stakeholders, the outcomes clearly highlight the influence of the pipeline configuration on the total costs as well as the specific transportation cost of each emitter. The study also highlights the associated uncertainties, as evidenced by the diverse configurations and cost variations across the different scenarios.

As demonstrated, the location has a vital impact on transportation costs. There is a high variance of additional costs of different plants in the same industry (e.g. cement) in the same scenario, which is mainly attributed to the locations of CO_2 sources and sinks. While some plants are close to the main pipeline trunks, other emitters are remotely located and require dedicated pipelines in order to be connected to the network. Therefore, similarly to the renewable pull of the energy transition, such disparity may cause plant closures or relocations in the future, which may incur considerable socio-economic challenges. The governmental role is of importance in order to achieve the required balance and stabilization (e.g. via incentives, support) as potential closures will influence the whole CO_2-transportation system negatively via increasing the specific costs of the other emitters. Careful CO_2 network design is therefore essential for minimization of the uncertainties and associated costs while securing enough time for planning and addressing the social and legal challenges. The emergence of key corridors also provides strategic insights to future opportunities for industrial development.

The derived approach is also aligned with European strategies aiming to develop future infrastructure for CO_2 transportation. The discussed emitter scenarios and storage cases also represent existing national energy policy situations in the various European countries. As reported recently by the European Commission (Tumara D et al., 2024), efforts are being made for a best-case scenario of an optimized continent-wide CO_2 transport and storage network. However, it has to be considered that such a future CO_2 network will have a large number of cross-border connections, and enabling this requires Europe-wide standards and a common framework. Resolving this obstacle will create additional opportunities for neighboring countries to work on joint cross-border solutions or to overcome potential capacity problems in regional CO_2 storage facilities. As an outlook for future research, the derived approach and analyses can be extended further to include other neighboring countries and design an optimum network in Europe. Also, other system components (e.g. buffer storage, transshipment and terminals) can be included and the weighting scheme can be replaced or adjusted to suit different geographical, social or political contexts. Moreover, geospatial features (e.g. high-risk seismic zones) can be integrated, and the heuristic methods can be further improved.

CRediT authorship contribution statement

Christopher Yeates: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Ali Abdelshafy:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Cornelia Schmidt-Hattenberger:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Grit Walther:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Christopher Yeates reports financial support was provided by Helmholtz Climate Initiative (HI-CAM). Ali Abdelshafy reports financial support was provided by SCI4climate.NRW project, the Ministry of Economic Affairs, Innovation, Digitalization and Energy of the State of North Rhine-Westphalia. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijggc.2024.104225.

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