CCUS value chains: Options for Storage- and Infrastructure of CO2 in Europe

September 2022

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Agenda

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- **Techno-economic overview**
  - CO_2 specifications
  - CO_2 transportation
  - CO_2 geological storage
- **Economic, regulatory and social challenges**
- **Modeling and analysis of CO_2 networks**
  - Framework & Methodology
  - Emitters, CO_2 hubs & scenarios
  - Cost functions & Network optimization
  - Datasets & Pipeline path proposal methodology
  - Results & Outcomes
- **Conclusions & Outlook**

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CO_2 specifications

- The captured CO_2 has to meet certain specifications (e.g. minimum purity, composition, etc.)

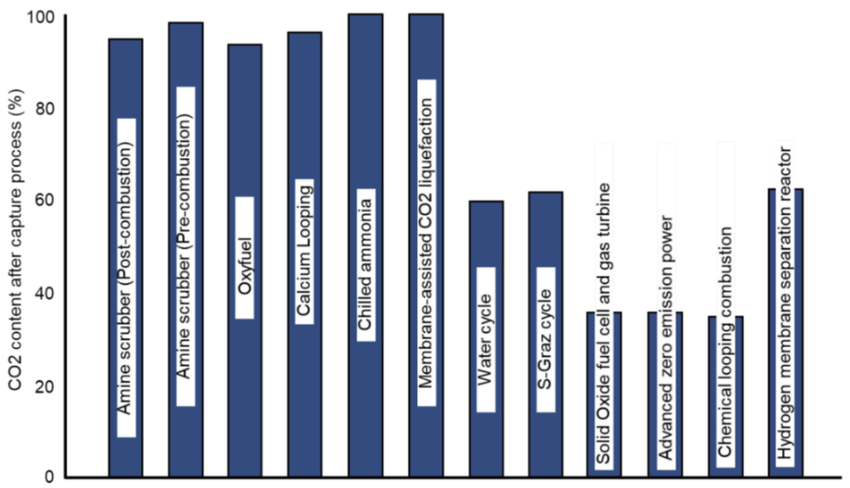
- Higher levels of impurities can cause corrosion in the pipeline system and trigger several risks during the storage phase (e.g. leakage, mineral dissolution, erosion, etc.)

- Capturing technologies don't have the same performance in terms of the final CO_2 purity.

- There are neither consensus on the required CO_2 specifications nor official standards. While the purity of the CO_2 used for EOR operations in USA is not very high (≈96%), recent CCS studies are in favor for very high purities (food-grade CO_2).

- Lack of official standards in terms of the specifications required for geological storage can increase the economic uncertainties.

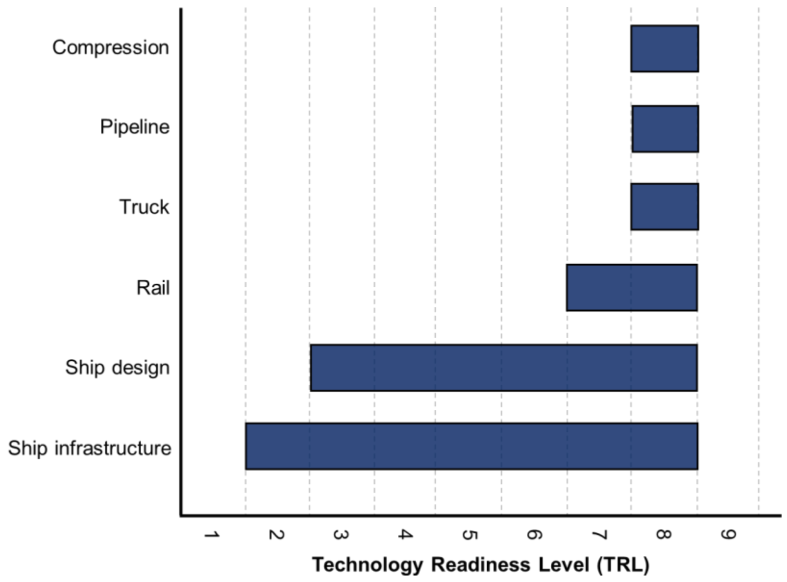
- Depending on the technology adopted, the producers may need an additional purification.

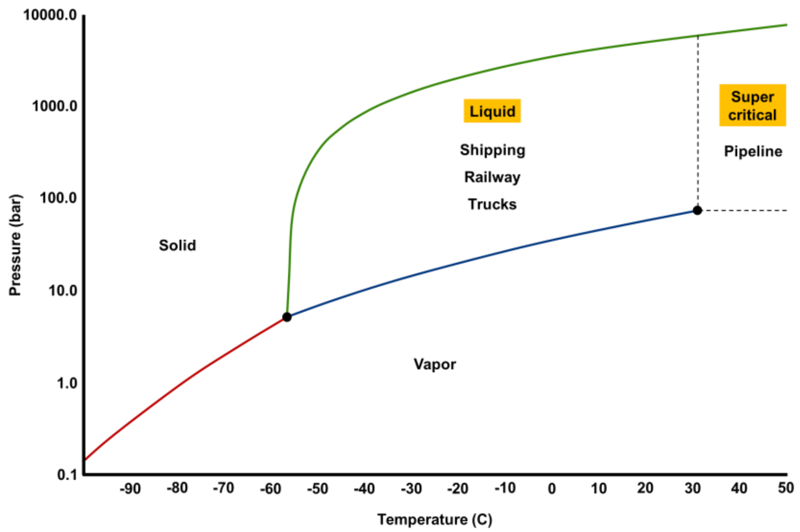


Component	Study (36)			US pipeline	Dynamis	Weyburn EOR project
	Saline Aquifer	Unmineable Coal Seams	Oil & Gas reservoirs			
H2O	300 µmol·mol−1			0.4805 g/Nm3	< 500 ppm	< 20 ppm
H2S	5 µmol·mol−1			10 - 200 ppm	< 200 ppm	< 9000 ppmv
CO	20 µmol·mol−1				< 2000 ppm	< 1000 ppm
O2	4 cmol·mol−1	10 µmol·mol−1		< 10 ppm	< 4%	< 50 ppm
CH4		1 cmol·mol−1				
N2				< 4%	< 4%	< 300 ppm
Ar					< 4%	
H2						
SOx	0.5 µmol·mol−1				< 100 ppm	
Nox					< 100 ppm	
NH3	25 µmol·mol−1					
C2H6	1 cmol·mol−1			< 5%	< 4%	< 0.7%
C3+						
Particulates						
HCl						
HF	1.8 µmol·mol−1					
HCN	0.9 µmol·mol−1					
Hg	0.02 mg·m−3					
Glycol	46 nmol·mol−1					
MEA	1 µmol·mol−1					

CO_2 transportation

- Unlike CO_2 capture, transportation technologies have high TRLs.
- In order to transport the captured CO_2 from the sources to sinks, various modes can be used (e.g. pipelines, shipping and trucks).
- Besides purity, the phase of CO_2 is also a crucial factor in the transportation process.
- The selection of transportation mode is mainly dependent on the distance and quantity.
- For long distances, pipelines and shipping are favorable for high and low flowrates respectively.
- Establishing a pipeline network is normally associated with high investments, therefore, having high flowrates is essential in order to lower the unit cost.
- For extremely long distances (e.g. > 1500 km), pipelines can be more expensive than shipping even with high flow rates.





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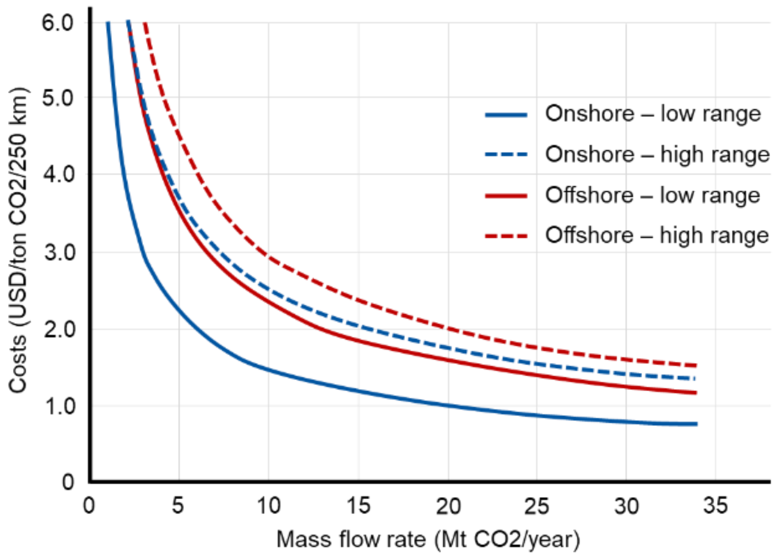
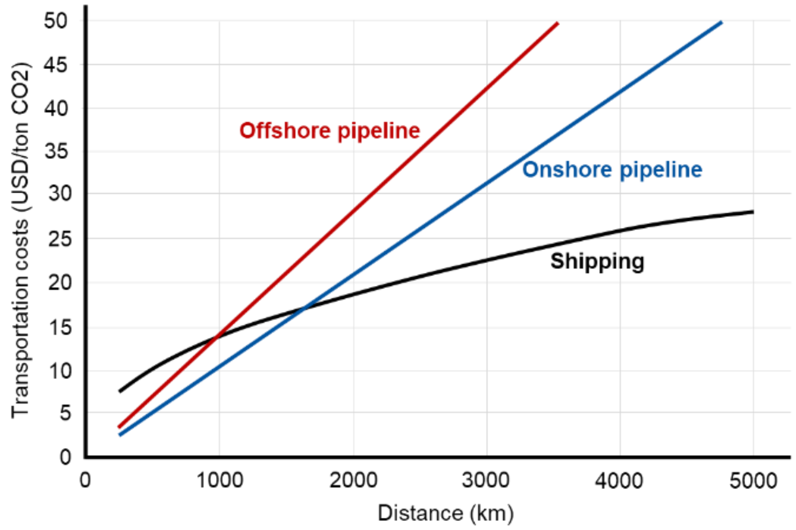
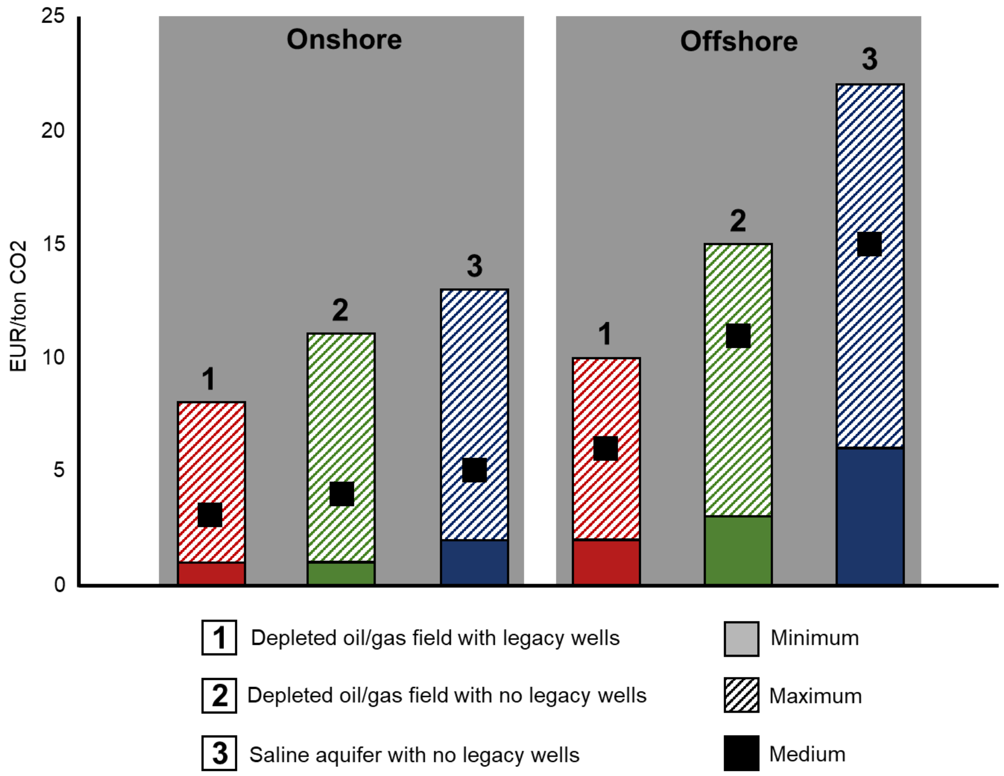


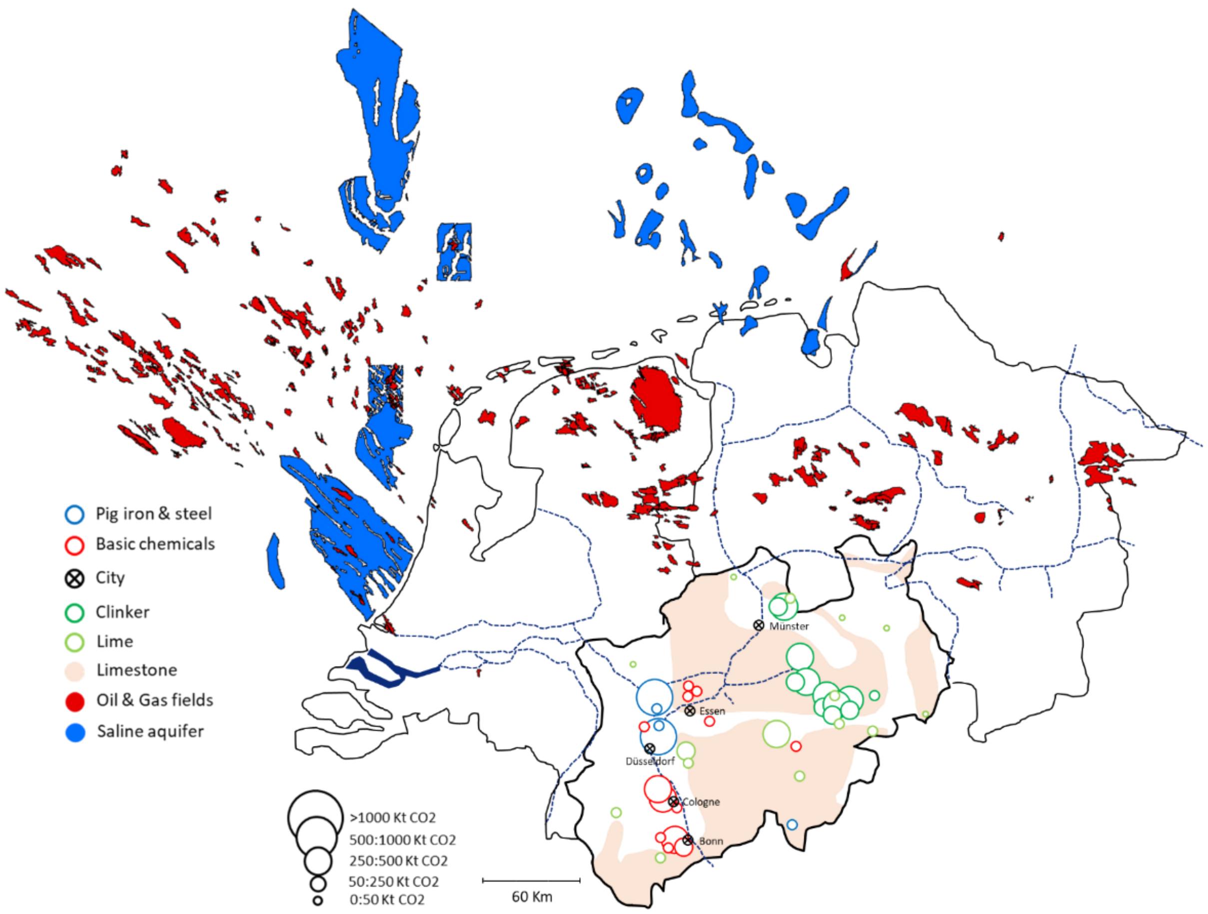


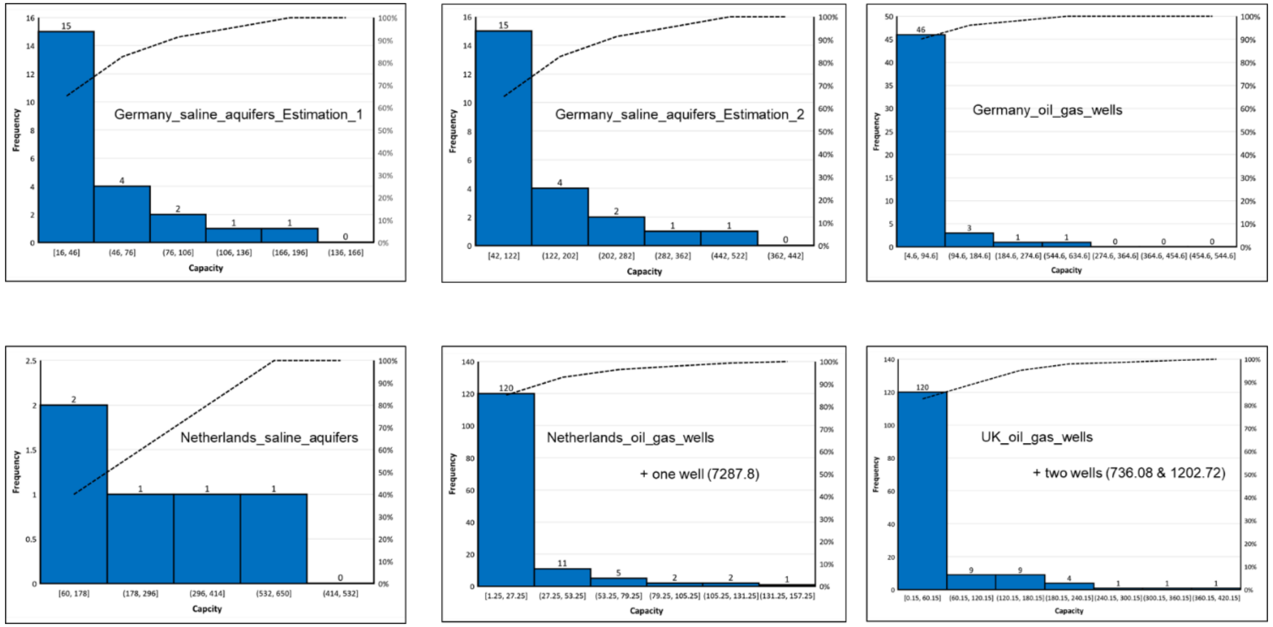
CO_2 storage

- CO2 can be geologically stored in various formations, nonetheless, two mediums have caught the attention of CCS studies (i.e. depleted oil and gas fields and saline aquifers).
- CO2 is geologically trapped via three mechanisms, namely physical residual and solubility trapping.
- Each storage site has its own characteristics which need to be studied and handled differently.
- Due to the characterization, infrastructure and monitoring costs, the economies of scale also apply to geological storage.
- Expected prices range between 1 and 22 EUR/ton CO_2.
- Offshore storage is more expensive than onshore storage.
- Also, using saline aquifers are more expensive than depleted oil and gas fields.



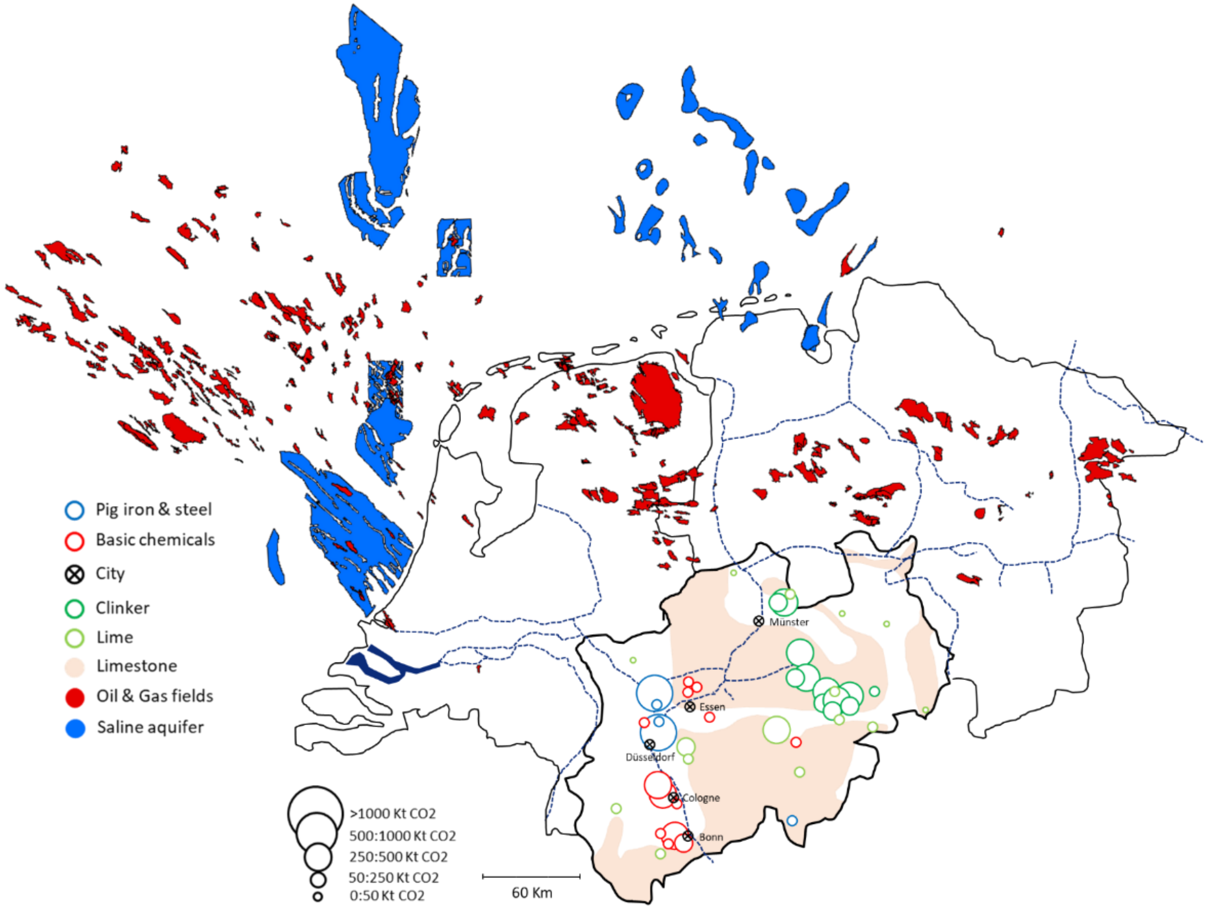
Potential storage near NRW

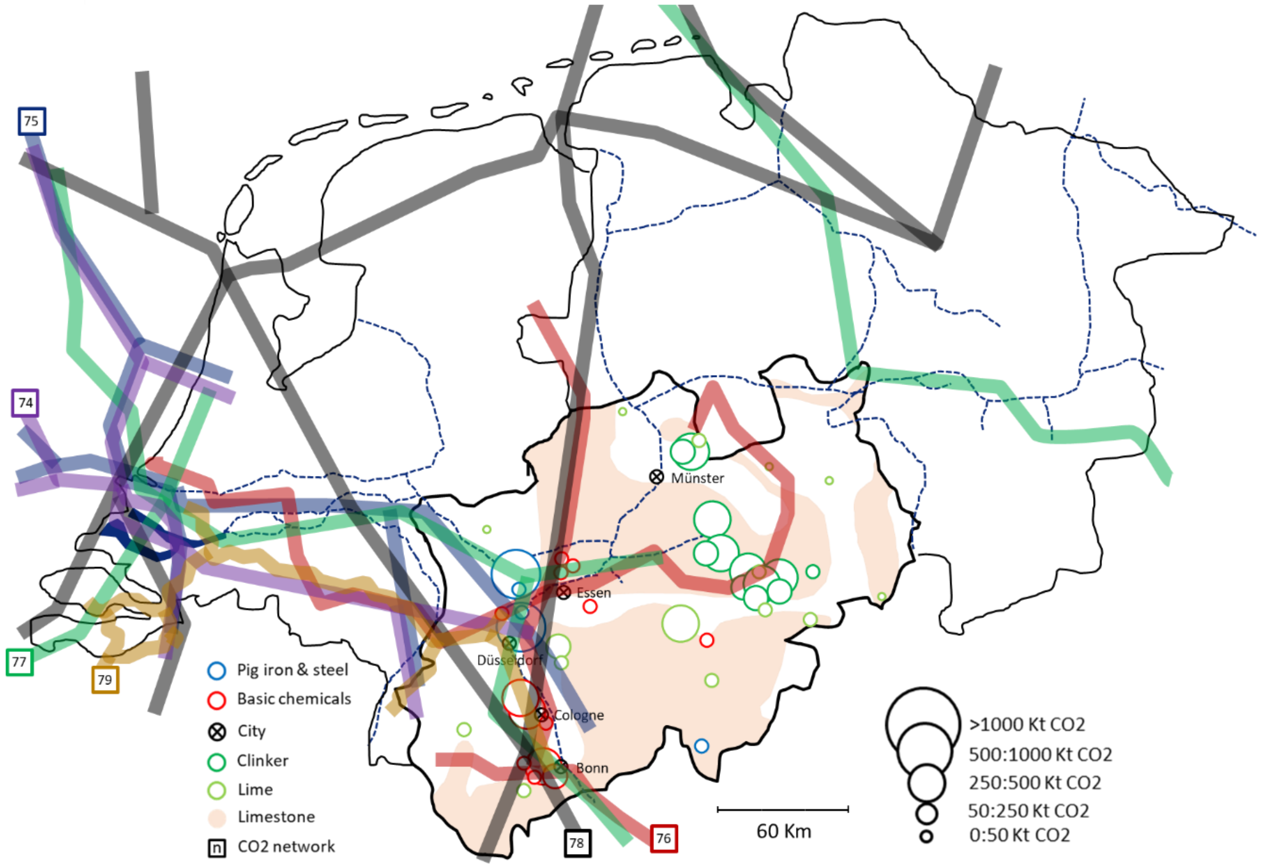




- ≈ 2.9 Gt (saline aquifers) and ≈ 9.9 Gt (oil and gas fields) in Netherlands and ≈ 7.7 Gt (oil and gas fields) in UK.
- The individual capacities, they vary significantly between the storage sites in the three countries.
- There are 28 saline aquifers (capacities between 16 Mt and 650 Mt) and 385 oil and gas fields (capacities between 0.15 Mt and 7287.8 Mt).

Potential storage near NRW





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Economic, social and legal challenges

Economic

- Long-term liability (CO_2 leakage)
- Interdependency & monopolies
- CO_2 prices & policies

Social

- Terminology
- Information & public awareness
- Public trust
- Economic background
- Incentives
- Culture

Technology		TRL (1-9) Range		CRL (1-6) Range		SRL (1-5) Range	
Capture	Direct air capture	1	5	1	3	1	2.4
	Absorption	1	9	1	5	1	4.1
	Oxy-fuel	2	4	1.5	2.9	1.6	2.6
	Adsorption	2	7	1.5	3.4	1.6	3
	Cryogenic separation	3	6	2	3.2	2.4	3.2
	Fuel cells	3	6	2	3.2	2.1	2.8
	Membranes	3	8.5	2	3.9	2.1	3.2
Transport	Shipping	3	7	2	3.2	1.8	2.8
	Rail	6	9	3.1	3.9	2.6	3.3
	Pipeline	7	9	3.6	4.3	3.1	3.6
	Truck	7	9	3.8	4.4	3.2	3.7
	Compression	8	9	4.2	4.6	3.6	3.9
Use	Electro/photochemical	1	4	1	1.9	1	1.7
	Termochemical	2	5	1.6	2.5	1.4	2.2
	Biological	3	9	2.2	3.9	2	3.2
	Carbonation	5	8	3.5	4.4	3	3.7
Storage	Other (CBM, Basalt)	2	4	1.6	2.2	1.4	2
	Unconventionals	2	5.5	1.7	2.7	1.5	2.3
	Oil & gas fields	5	8	3.5	4.4	3	3.8
	Saline formations	5	8.5	3.5	4.5	3	3.8
EOR	Unconventional EOR	3	6	2.2	3.2	2	2.8
	Storage increase by EOR design	6	8	3.1	3.7	2.4	3.1
	Conventional EOR	7	9	3.7	4.4	3.1	3.7

Economic, social and legal challenges

- The legal aspect is a key part in all the preceding challenges. This can be more obvious in the German federal system due to the various legislative spheres (e.g. state, country, European and International).

- Establishing the required pipeline infrastructure can obviously show the associated legal complexities in NRW.

- Realizing a CO_2 pipeline network necessitates several consecutive phases (planning, permission, construction, operations, safety, exports, etc.).

- These processes are governed by different laws and include several authorities and entities.

- Additionally, these procedures are unprecedented in Germany, which incur various legal uncertainties

Relevant laws for CCS in NRW

Law	Relevance
1) Gesetz zur Demonstration der dauerhaften Speicherung von Kohlendioxid Kohlendioxid-Speicherungsgesetz – **KSpG**) (carbon dioxide storage law) (BMJ, 2012)	The German implementation of the directive 2009/31/EC (European Parliament, 2009). The act addresses the major aspects related to CO_2 pipelines (e.g. construction, liability, etc.) and refers to the other respective laws.
2) Verwaltungsverfahrensgesetz (**VwVfG**) (administrative procedures law) (BMJ, 1976)	Pipeline planning and permitting procedures of the CO_2 pipelines.
3) Gesetz über die Umweltverträglichkeitsprüfung (**UVPG**) (environmental impact assessment law) (BMJ, 1990)	Environmental impact assessment during the pipeline planning and permitting procedures.
4) Gesetz über die Elektrizitäts- und Gasversorgung (Energiewirtschaftsgesetz - **EnWG**) (energy industry law) (BMJ, 2005)	As indicated by KSpG, the planning and safety requirements for CO_2 pipelines are governed by EnWG (similar to the natural gas pipelines). EnWG also refers to the rules of the German technical and scientific association for gas and water (Der Deutsche Verein des Gas- und Wasserfaches e.V. – DVGW).
5) Raumordnungsgesetz (**ROG**) (spatial planning act) (BMJ, 2008)	Regional planning of CO_2 pipelines and project compatibility.
6) Verordnung zur Durchführung des Landesplanungsgesetzes (LandesplanungsgesetzDVO – **LPIG DVO**) (Ordinance on the implementation of the state planning act) (MI NRW, 2010)	Regional planning procedures of CO_2 pipelines (>30cm) in North Rhine-Westphalia
7) London protocol (IMO, 2006)	Offshore CO_2 storage and CO_2 exports for offshore storage.
8) Verordnung über Rohrfernleitungsanlagen (Rohrfernleitungsverordnung – **RohrFLtgV**) (log-distance pipeline ordinance) (BMJ, 2002)	As there is still no ordinance for major accidents related to CO_2 pipelines, both existing ordinances can be the basis for developing a dedicated one for CO_2 pipelines.
9) Verordnung über Gashochdruckleitungen (Gashochdruckleitungsverordnung – **GasHDrLtgV**) (high-pressure gas pipeline ordinance) (BMJ, 2011).	

Relevant publications

Operations Management

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Journal of CO2 Utilization 57 (2022) 101866

Contents lists available at ScienceDirect

Journal of CO2 Utilization

journal homepage: www.elsevier.com/locate/jcou

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Coupling carbon capture and utilization with the construction industry: Opportunities in Western Germany

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A R T I C L E I N F O

Keywords:
Carbonation
Carbon capture and utilization (CCU)
Construction industry
Process emissions
Concrete products
Waste concrete

A B S T R A C T

Carbon capture and utilization (CCU) is an essential method to sequester unavoidable CO_2 emissions in regions with insufficient geological storage capacities. Nonetheless, there are several uncertainties and knowledge gaps in terms of the future value chains of some CCU technologies (e.g. carbonation). This paper analyzes the potentials of coupling CCU with the supply chains of the construction industry by means of carbonating the concrete products and waste concrete in the German federal state of North Rhine-Westphalia. Based on extensive data and statistical analyses, the locations and outputs of the concrete and recycling plants have been determined in order to quantify their CO_2 sequestration capacities. Location-allocation models have been applied to allocate the carbon sources to the potential carbon sinks and calculate the minimum transportation costs.

The analysis shows that the total annual sequestration capacity is up to 1 Mt CO_2 with an average transportation distance of 37.4 km (8.3 EUR/ton). Nonetheless, some emission sources have a clear comparative advantage in terms of their proximity to the carbon sinks as the distance ranges between 0.7 km and 99.7 km. Also, some carbon sinks have a comparative advantage in terms of capacities and technology readiness levels. Therefore, the paper also presents models for the different products in order to display the potentials of each category separately and offer more flexibility to the stakeholders.

1. Introduction

According to the energy transition policy (Energiewende), Germany plans to reach carbon neutrality by 2045 [1]. Nevertheless, the industrial process emissions are one of the major challenges to reach this goal as they result from the production process and cannot be mitigated even by using carbon-neutral energy resources. Hence, permanent carbon storage sinks will be needed in order to sequester the extensive amounts of process emissions in Germany (65 Mt in 2018 = 8% of the total GHG emissions [2]).

Although carbon capture and storage (CCS) is a feasible route due to the experience gathered from many enhanced oil recovery (EOR) projects in the last decades especially in Northern America [3], there are various challenges associated with deploying the technology such as public acceptance and environmental concerns. Therefore, CCU can be favorable in regions where social resistance and land use challenges exist [4]. Moreover, some additional costs associated with CCS such as purifying the CO_2, infrastructure and liability & monitoring after storage [5–7] can be avoided in case of adopting certain CCU technologies.

According to [8–10], Carbonation, mineralization and EOR are the only permanent CCU storage technologies. Other techniques like synthetic fuels and chemicals can be considered as temporary storage sinks as the CO_2 will be released again in the atmosphere after consumption. While the concept of EOR is based on utilizing the CO_2 to yield the hard-to-recover oil and eventually storing it geologically, the concept of mineralization and carbonation is based on the reaction of CO_2 with the oxides found in certain minerals and cementitious materials to generate carbonates as stable compounds. The EOR is characterized by a high technology readiness level (TRL) and there is already an existing robust supply chain with more than 7,000 km of CO_2 pipelines connecting the CO_2 sources and oil fields in the USA [11,3,12], but not in Europe. Recently, carbonation and mineralization are getting more attention due to the necessity of finding CO_2-mitigation techniques. Therefore, many related research questions started to be addressed in the literature.

Although the chemical principal of mineralization and carbonation is analogous, their value chains are different. As shown in Eqs. (1) and (2), the mineralization technique depends on fixing the CO_2 in the oxides of natural minerals (e.g. olivine, serpentine, etc.) [13]. These minerals are

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https://doi.org/10.1016/j.jcou.2021.101866
Received 15 October 2021; Received in revised form 8 December 2021; Accepted 16 December 2021

THE OXFORD INSTITUTE FOR ENERGY STUDIES

MAY 2022

The role of CCUS in decarbonizing the cement industry: A German case study

1. Introduction

Germany has set an ambitious plan to reach carbon neutrality by 2045 despite being the biggest emitter
in Europe (810 Mt CO_2 in 2019
and, more specifically, energy-i
involved, emissions cannot be ab
et al.,[2] four industries (cement, li
process emissions in Germany.

While the steel and chemical indu
(e.g. hydrogen), the production p
process. That is why the ceme
international roadmaps. It is very
carbon capture and utilization an
that have significant amounts of

This paper investigates the role
prospective supply chains, the
emissions and their techno-e
challenges. Some of these them
geographical features of a certain
from the German federal state
NRW has been selected due
considered to be the hub of Germ
Europe.

The paper presents the current r
NRW and the existing efficienc
Section 3 then investigates the
technologies while considering
focuses on the economic, social

[1] Agora (2021). Studie: Klimaneutrales D
Umweltbundesamt (UBA). (2020). Jährlic
Germany
[2] Lösch, O., Toro, F., Ashley-Belbin, N., F
ihre Bedeutung für die nationalen Klimaschutzziele – Problemdarstellung und erste Lösungsansätze. Institut für Ressourceneffizienz und Energiestrategien GmbH (IREES)

Energy Insight: 115

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OIES Podcast – The Role of CCUS in Decarbonising the Cement Industry

In this latest OIES podcast James Henderson talks to Martin Lambert and Ali Abdelshafy about their recent paper entitled "The Role of CCUS in Decarbonising the Cement Industry: a German case study." The authors discuss why CCUS is so important in the cement industry, and having outlined the general process of carbon capture and storage and its use in the cement industry they talk in detail about how CO2 is captured in the various parts of the cement manufacturing process. They also review how the CO2 is then transported to various storage points and discuss how the creation of industrial clusters for CCUS can enhance synergy benefits, using the North Rhine Westphalia region of Germany as an important case study. They also consider how common infrastructure can therefore become a critical element of the business model, while also discussing how social and legal issues need to be addressed to ensure the feasibility of any project. Finally, they outline the future plans for further research on this topic, including work on other hard to abate sectors.

00:00 00:00

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Categories:
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Tags:
carbon capture, CCUS, cement, CO2, Germany, Westphalia

Modeling and analysis of CO_2 networks: A German case study

September 2022

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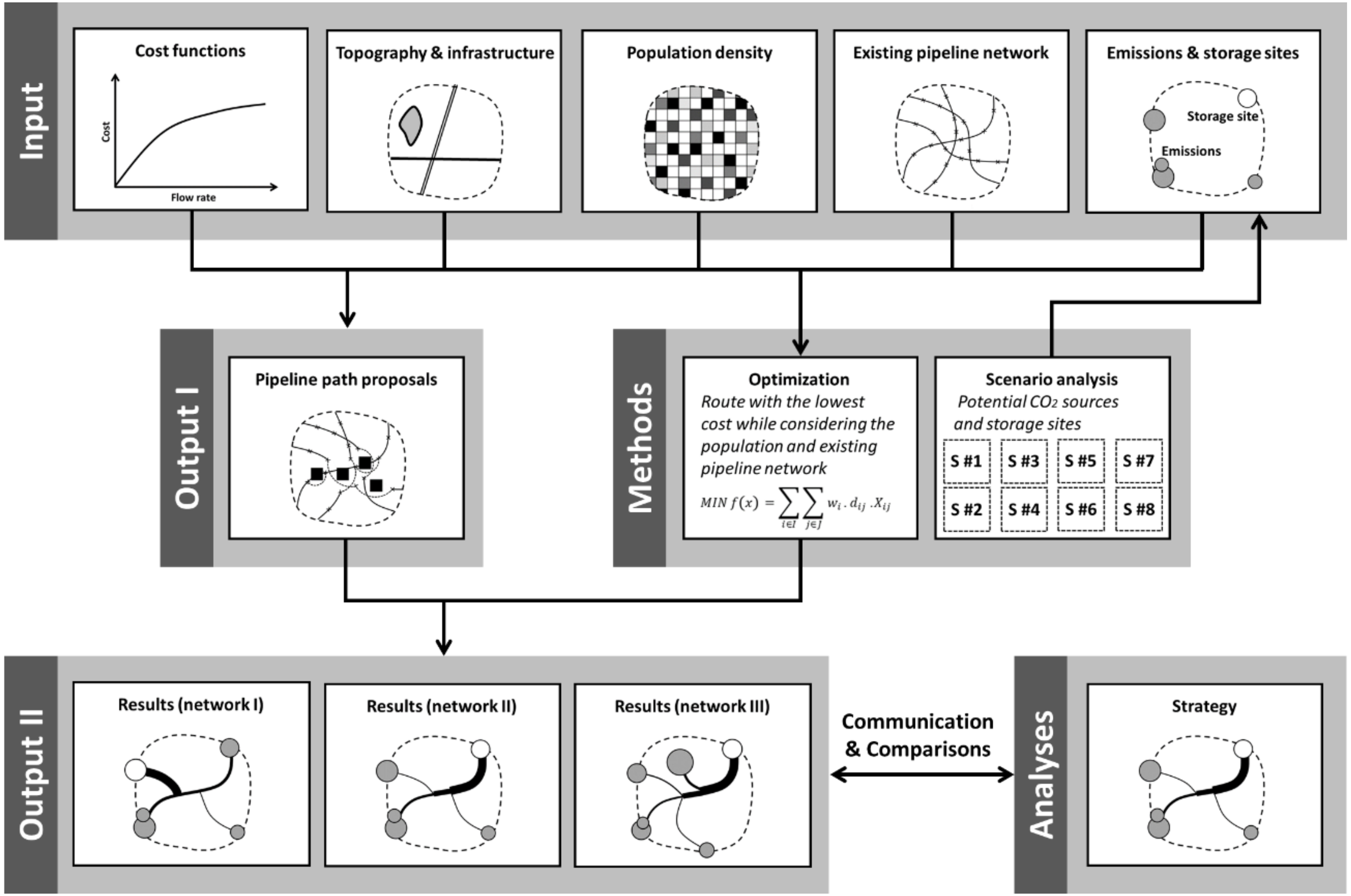
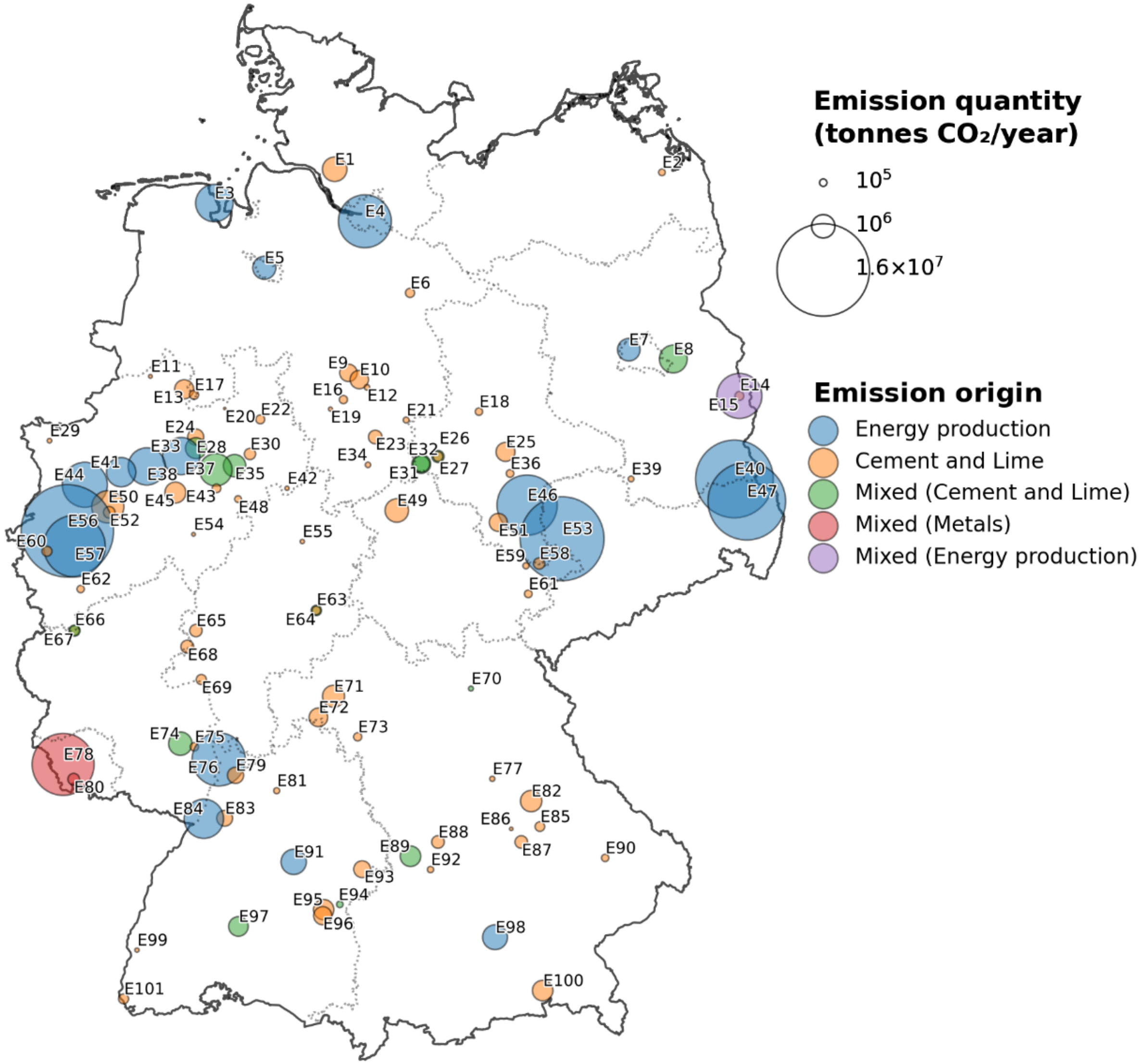
Framework & Methodology



Emitters, CO_2 hubs & scenarios

- **<u>Scenario 1</u>:** hard-to-abate/process emissions of clinker and lime industries (95 plants).
- **<u>Scenario 2</u>:** All emissions (fuel & process) of clinker and lime industries (95 plants).
- **<u>Scenario 3 & 4</u>:** consider a threshold, below which the cement and lime plants will not be a part of the network (i.e. 100 kt and 50 kt respectively), which result in 65 and 81 plants respectively.
- **<u>Scenario 5</u>:** 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 short term.
- **<u>Scenario 6</u>:** considers the steel plants away from the hydrogen network as potential users of the CO_2 network



Cost functions & Network optimization

- 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.

- A cost-adjusted version of Parker's model has been used in a recent study focusing on the German infrastructure design

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

- I_{total} is the total investment cost in € (2010) for a single pipeline in which, D is the diameter (m); L is the length in km

- Including an added fixed cost for each of these segments would increase the overall cost unrealistically and hinder the optimization process.

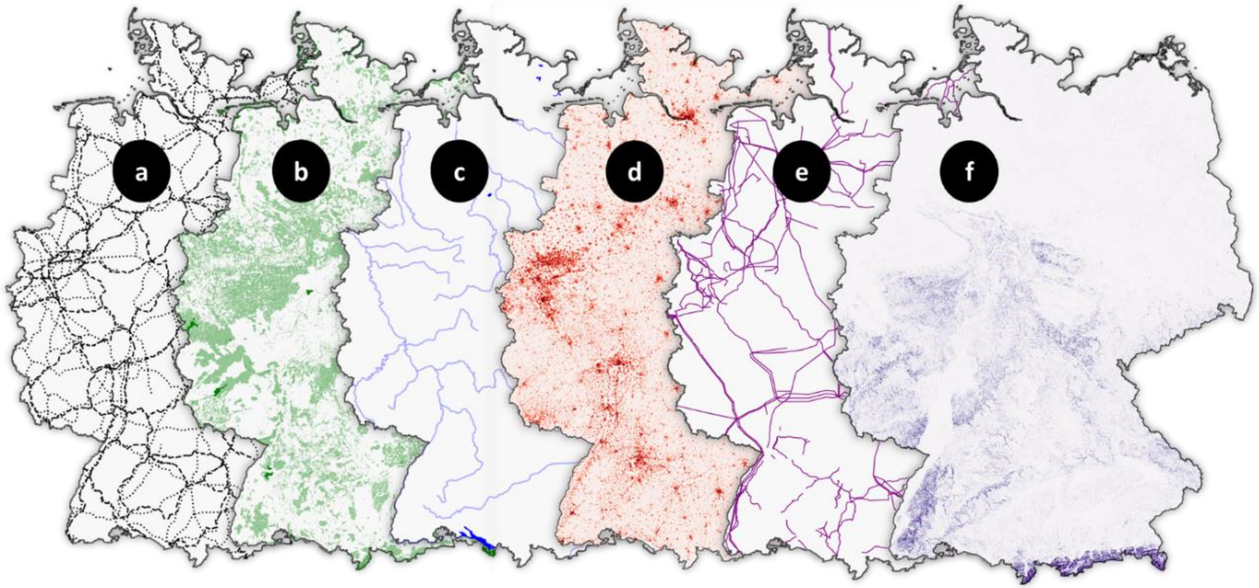
$$I_{total} = (1{,}355{,}675.2 \times D^2 + 601{,}000.32 \times \mathrm{D} + 303{,}989.92) \times \mathrm{L}$$

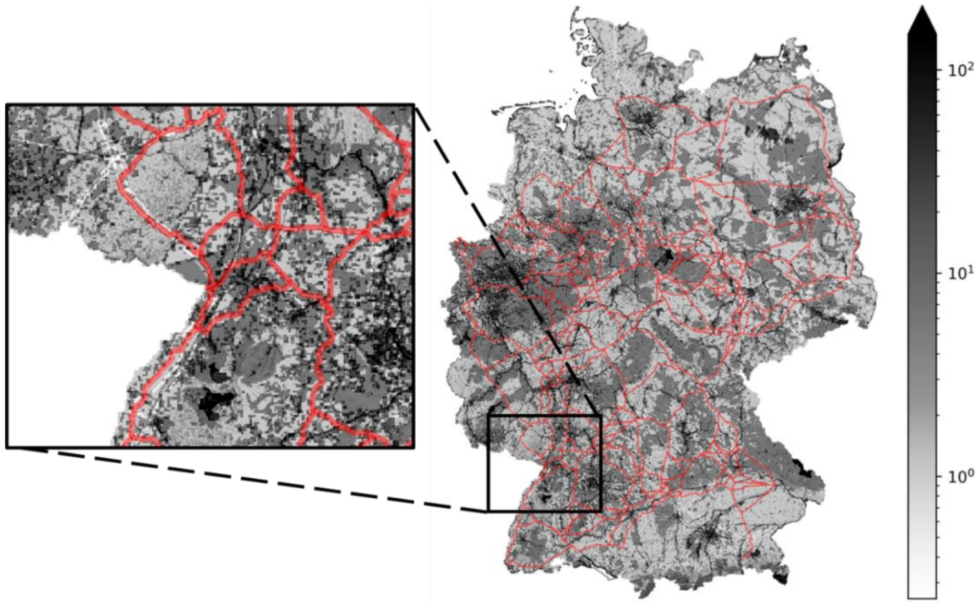
- We assume a constant flow rate of liquid CO2 at 3 m/s, pipeline pressure is also set to 100 Bar, giving an approximate fluid density of 900 kg/m³ at a temperature of roughly 15°C

Step A0:	Start from solution obtained by taking the Minimum Spanning Tree
Step A1:	Initiate empty solution list
Step A2.1:	Identify unused edges E_U in incumbent solution ***For*** each edge e_U of the set E_U: - Add edge e_U to the tentative solution - Identify edges E_c in created cycle,
Step A2.2:	***For*** each edge e_C of the set $E_c \setminus \{e_{Ui}\}$: - remove e_{Ci} from the tentative solution - Calculate capacity and cost - Add tentative solution to solution list
Step A3:	Find minimal-cost solution from solution list
Step A4:	***If*** this solution is better than current incumbent solution: - Set this new solution as incumbent solution - Restart from **Step A1** ***Else:*** - Use **Algorithm B**

Step B0:	Start from solution obtained from **Algorithm A** as incumbent solution
Step B1:	Initiate empty solution list
Step B2.1:	***For*** each emitter node n_e in the network: - Identify all neighbouring nodes N_3 in the full graph up to a graph distance of 3
Step B2.2:	***For*** each neighbouring n_3 node in N_3 - Find shortest Euclidean distance path in full graph between n_e and n_3, made of edges E_p - Add edges from E_p to a tentative solution - Find all cycles in tentative solution
Step B2.3:	- Repeat recursively **Step A2.2** from **Algorithm A** until all cycles are explored, and solution trees added to solution list
Step B3:	Find minimal-cost solution from solution list
Step B4:	***If*** this solution is better than current incumbent solution: - Set this new solution as incumbent solution - Restart from **Algorithm A, Step A1** ***Else:*** - Return incumbent solution

Datasets & Pipeline path proposal methodology

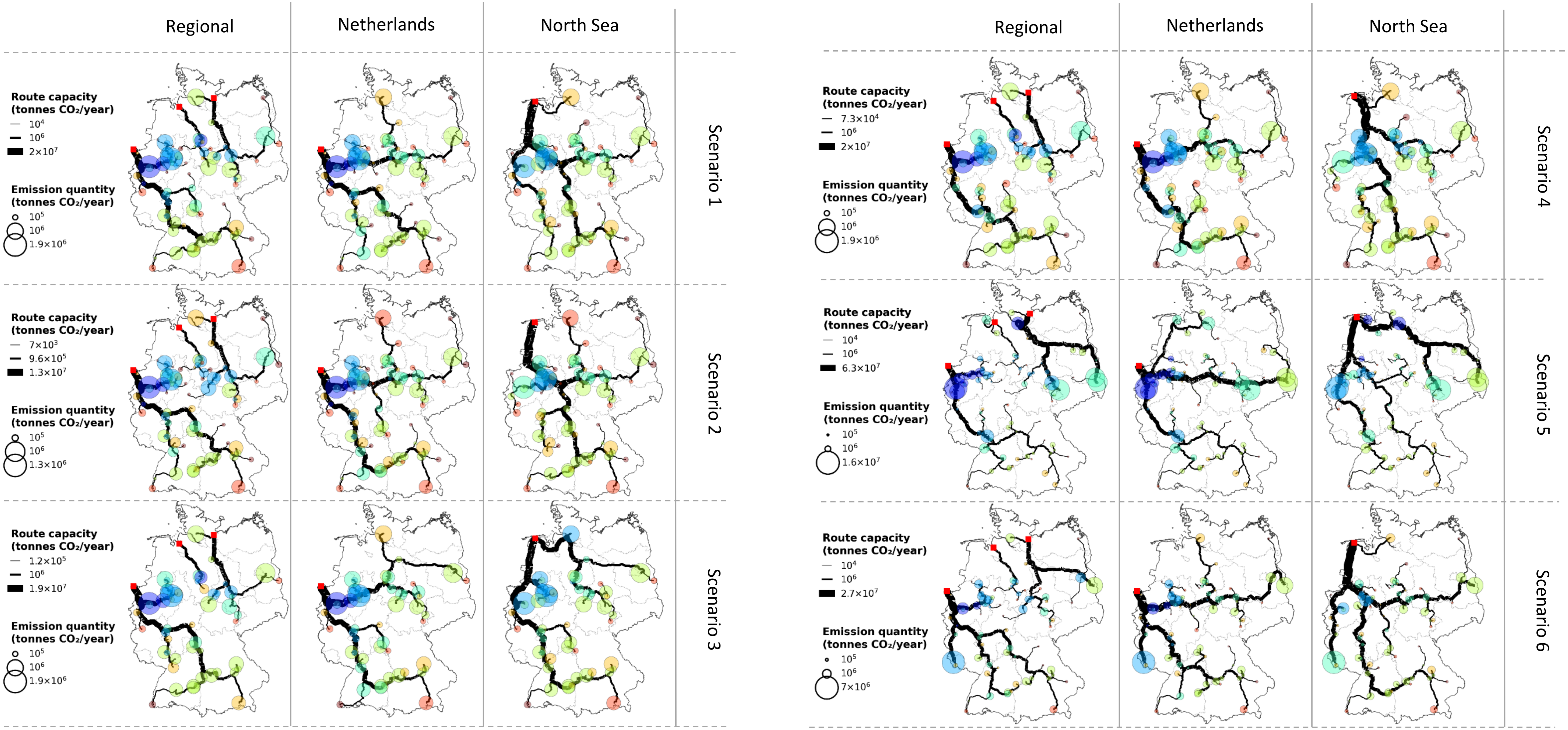




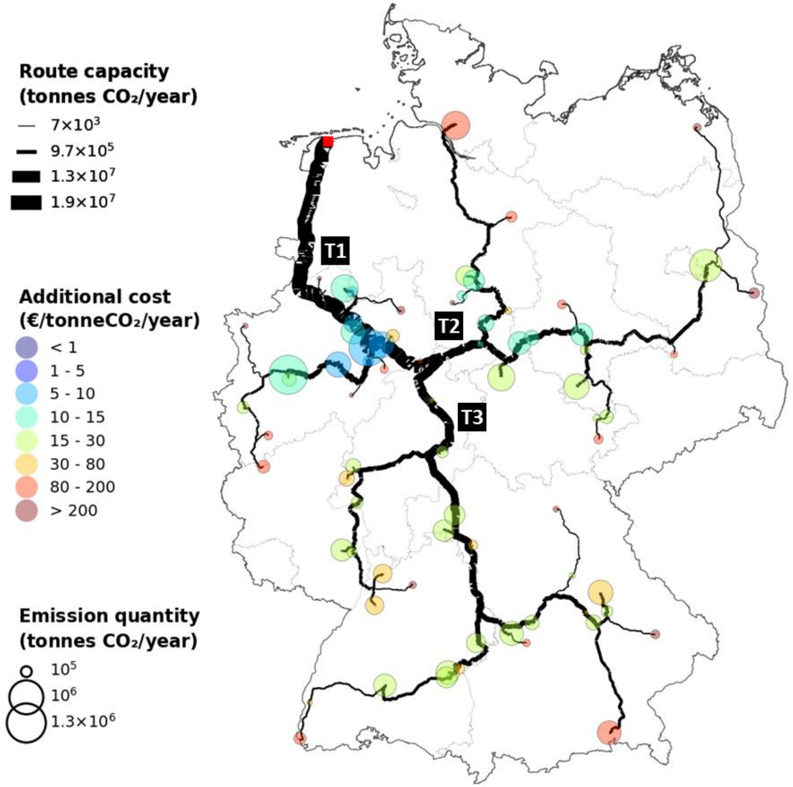
Dataset	Described elements
Point source CO_2 Installation list 2020	Point source CO2 emission volumes
Electricity, heat, and gas sector data for modeling the German system.	Existing pipeline network
German National census	Population density per km
Natural Earth	Rivers, Lakes, Motorway, Railways
WISE	Transitional waters
CCDA	CDDA protected areas, National parks
EU-DEM	Slope

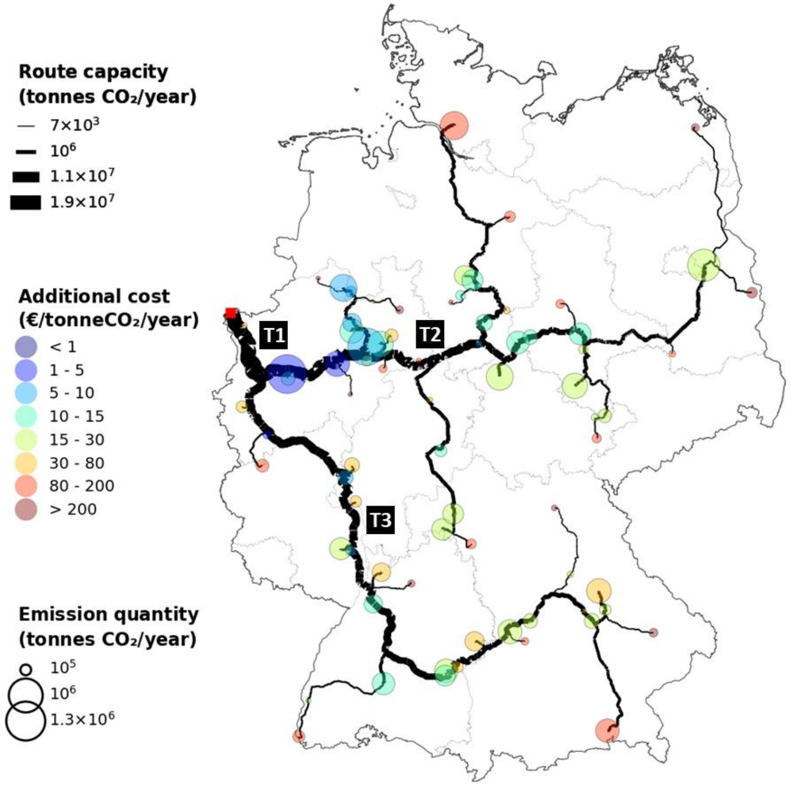
Feature	Multiplier
Population density/km² (<250)	1
Population density/km² (250-500)	4
Population density/km² (500-2000)	9
Population density/km² (2000-4000)	16
Population density/km² (4000-8000)	25
Population density/km² (>8000)	36
Pre-existing pipelines	0.25
Railroads	3
Motorways	3
Rivers, lakes, and transitional waters	10
CDDA protected areas (excl. National parks)	10
National parks	30
Terrain slope	1-20

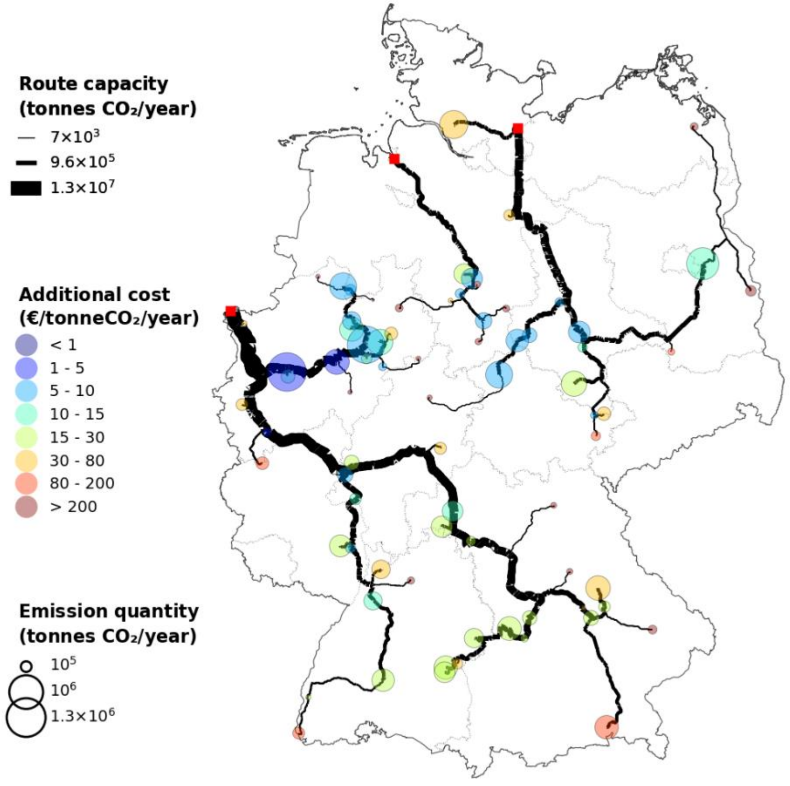
Results



Regional
Netherlands
North Sea
Scenario 1
Scenario 2
Scenario 3
Scenario 4
Scenario 5
Scenario 6
Route capacity (tonnes CO_2/year)
10^4
10^6
2×10^7
Emission quantity (tonnes CO_2/year)
10^5
10^6
1.9×10^6
Route capacity (tonnes CO_2/year)
7×10^3
9.6×10^5
1.3×10^7
Emission quantity (tonnes CO_2/year)
10^5
10^6
1.3×10^6
Route capacity (tonnes CO_2/year)
1.2×10^5
10^6
1.9×10^7
Emission quantity (tonnes CO_2/year)
10^5
10^6
1.9×10^6
Route capacity (tonnes CO_2/year)
7.3×10^4
10^6
2×10^7
Emission quantity (tonnes CO_2/year)
10^5
10^6
1.9×10^6
Route capacity (tonnes CO_2/year)
10^4
10^6
6.3×10^7
Emission quantity (tonnes CO_2/year)
10^5
10^6
1.6×10^7
Route capacity (tonnes CO_2/year)
10^4
10^6
2.7×10^7
Emission quantity (tonnes CO_2/year)
10^5
10^6
7×10^6

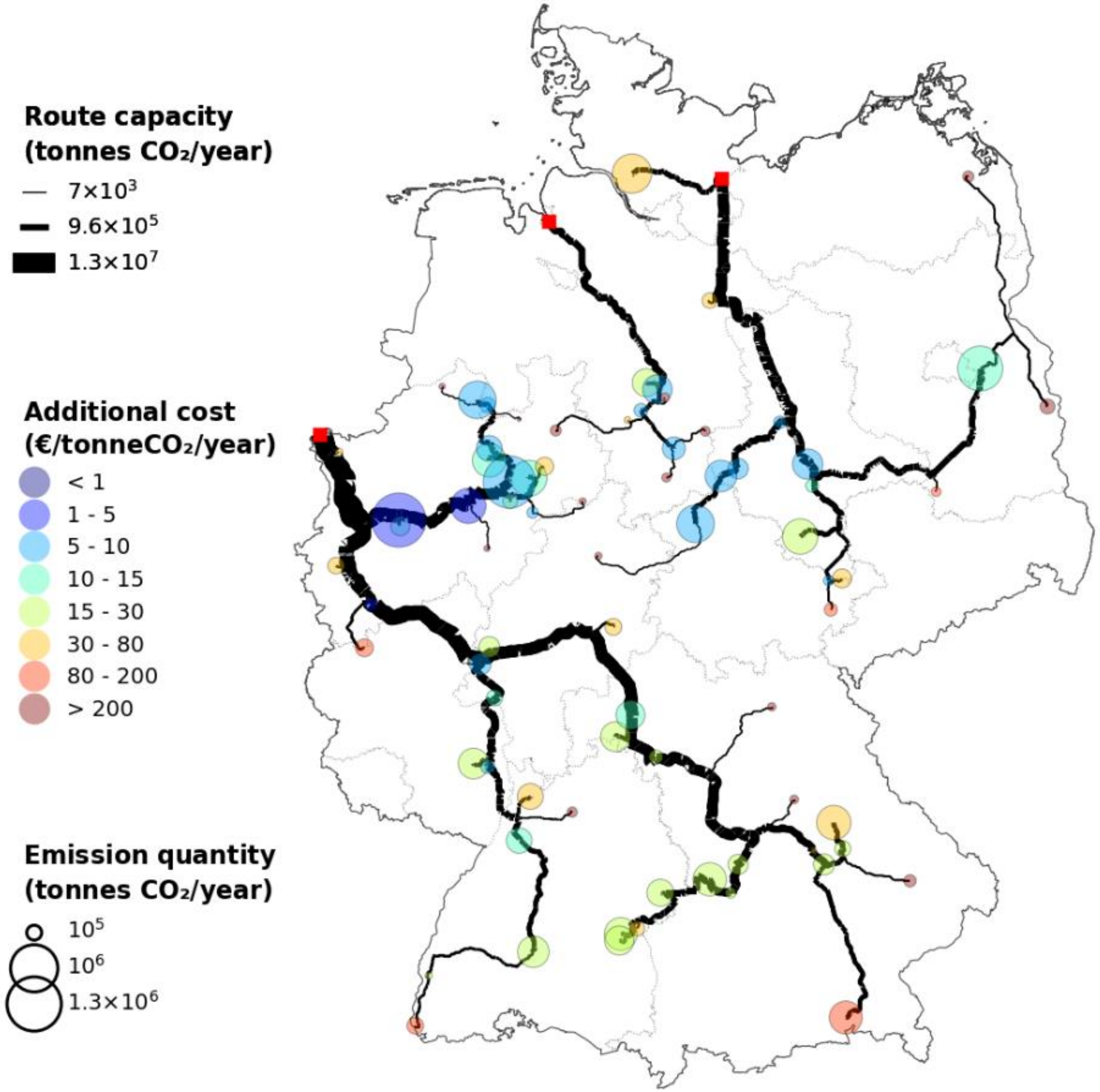

Route capacity
(tonnes CO_2/year)
7×10^3
9.7×10^5
1.3×10^7
1.9×10^7
Additional cost
(€/tonneCO_2/year)
< 1
1 - 5
5 - 10
10 - 15
15 - 30
30 - 80
80 - 200
> 200
Emission quantity
(tonnes CO_2/year)
10^5
10^6
1.3×10^6
T1
T2
T3


Route capacity
(tonnes CO_2/year)
7×10^3
10^6
1.1×10^7
1.9×10^7
Additional cost
(€/tonneCO_2/year)
< 1
1 - 5
5 - 10
10 - 15
15 - 30
30 - 80
80 - 200
> 200
Emission quantity
(tonnes CO_2/year)
10^5
10^6
1.3×10^6
T1
T2
T3


Route capacity
(tonnes CO_2/year)
7×10^3
9.6×10^5
1.3×10^7
Additional cost
(€/tonneCO_2/year)
< 1
1 - 5
5 - 10
10 - 15
15 - 30
30 - 80
80 - 200
> 200
Emission quantity
(tonnes CO_2/year)
10^5
10^6
1.3×10^6

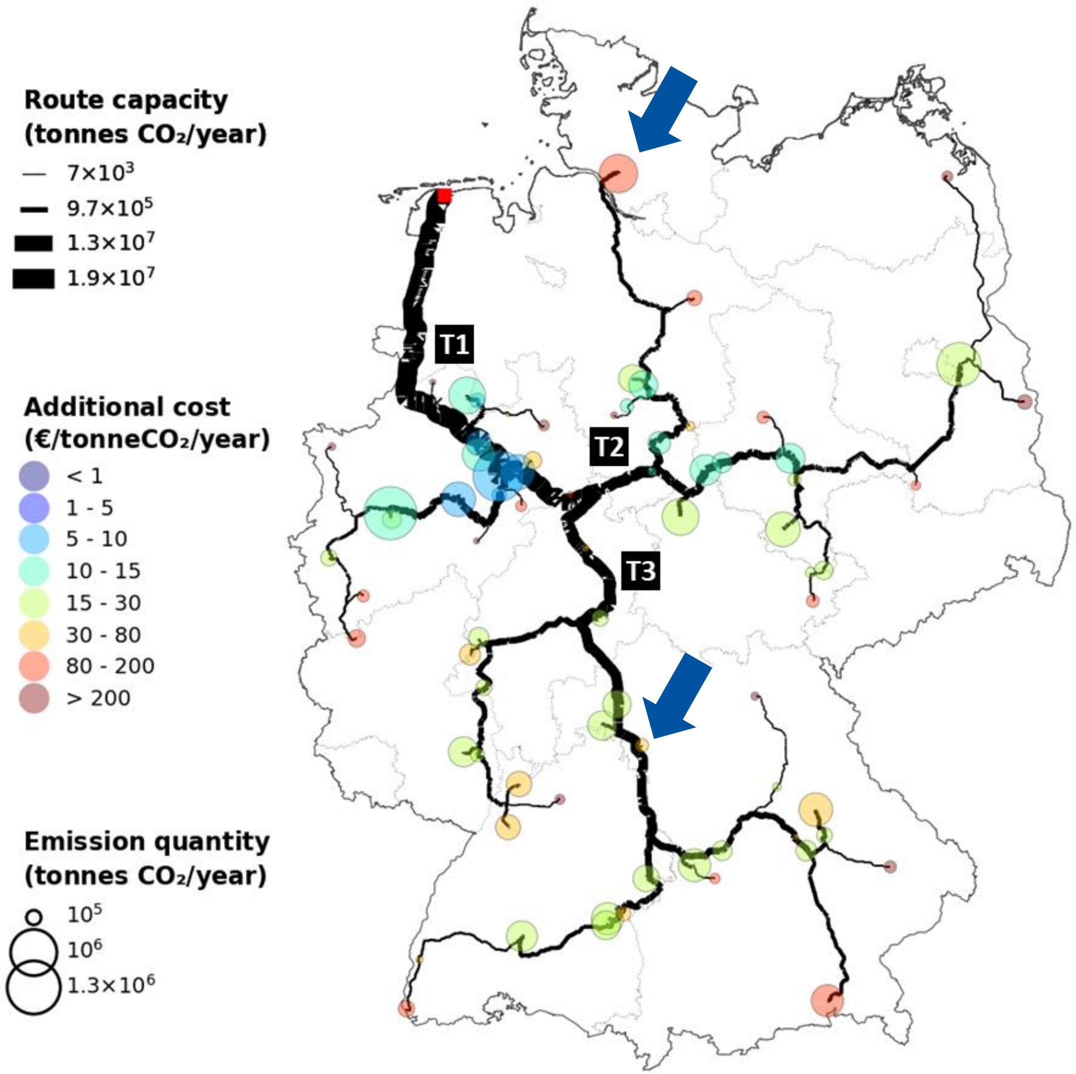
Results (scenarios 1 & 2)

- The total cost is approximately 1.7 B EUR & average transportation cost is more than 85 EUR/tone CO_2
- The optimized CO_2 network links the individual pipelines into common bigger trunks with higher capacities in order to exploit the economies of scale.
- The specific transportation costs vary significantly.
- Increasing the emissions from scenario 1 to scenario 2, increases the total costs only (10%), while the total CO_2 transported increased more than (30%).
- Therefore, the average specific cost per CO_2 transported has decreased (≈ 62 EUR/tone CO_2).
- Some plants have been impacted by this change such as plant, while other have been barely impacted.
- Changes in the configurations can be identified

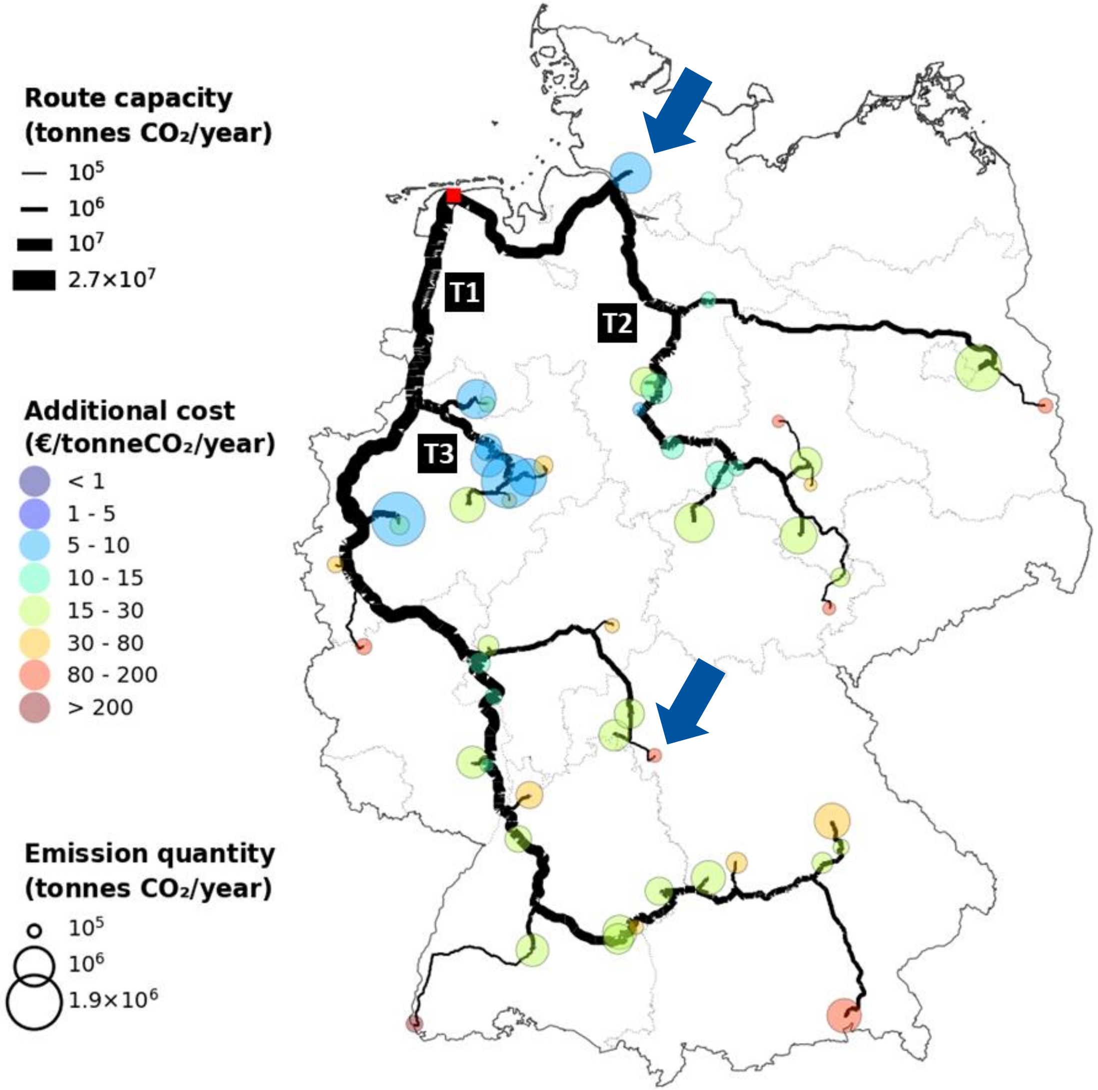


Results (scenarios 3 & 4)

Scenario 1

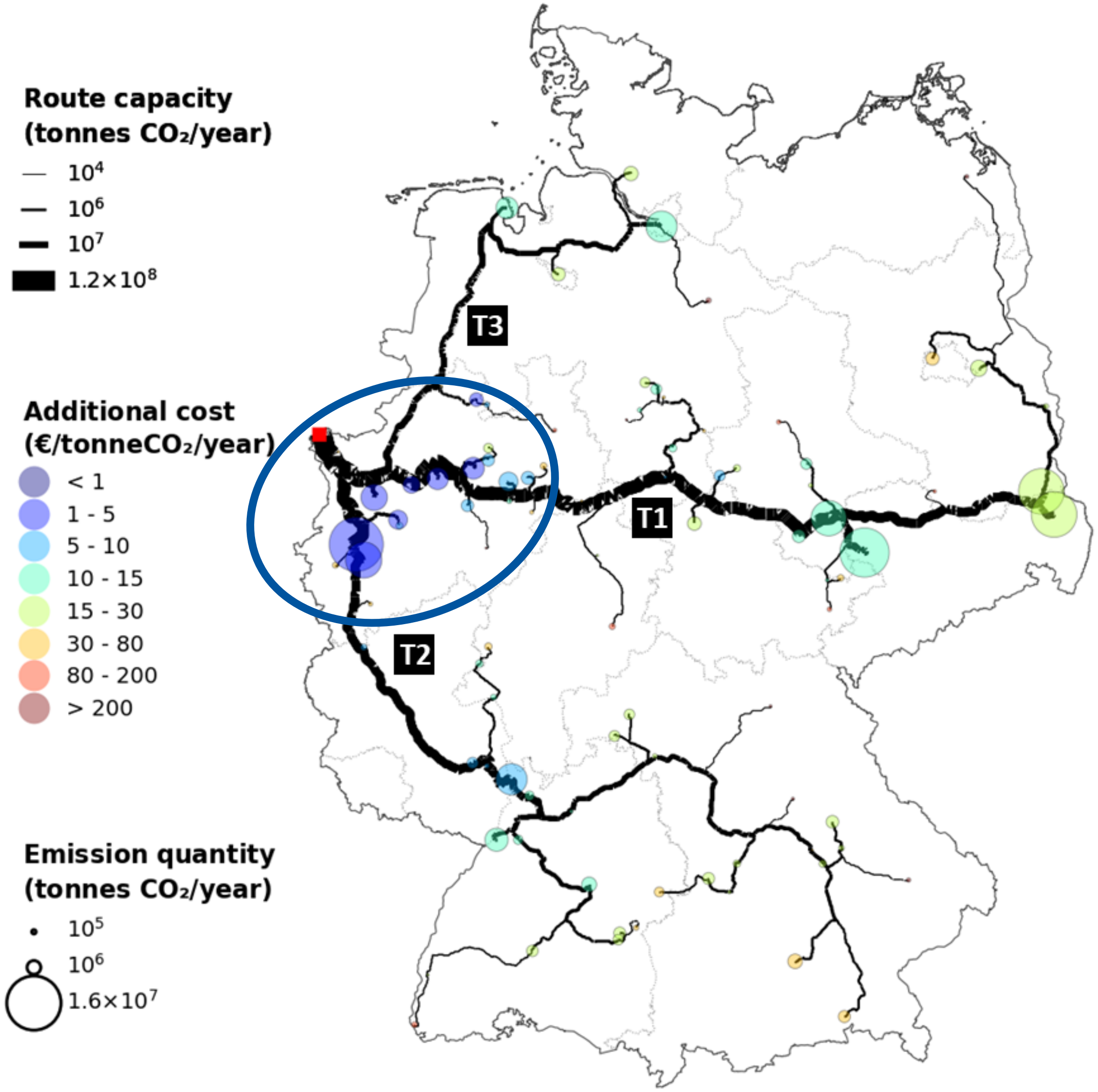


Scenario 3



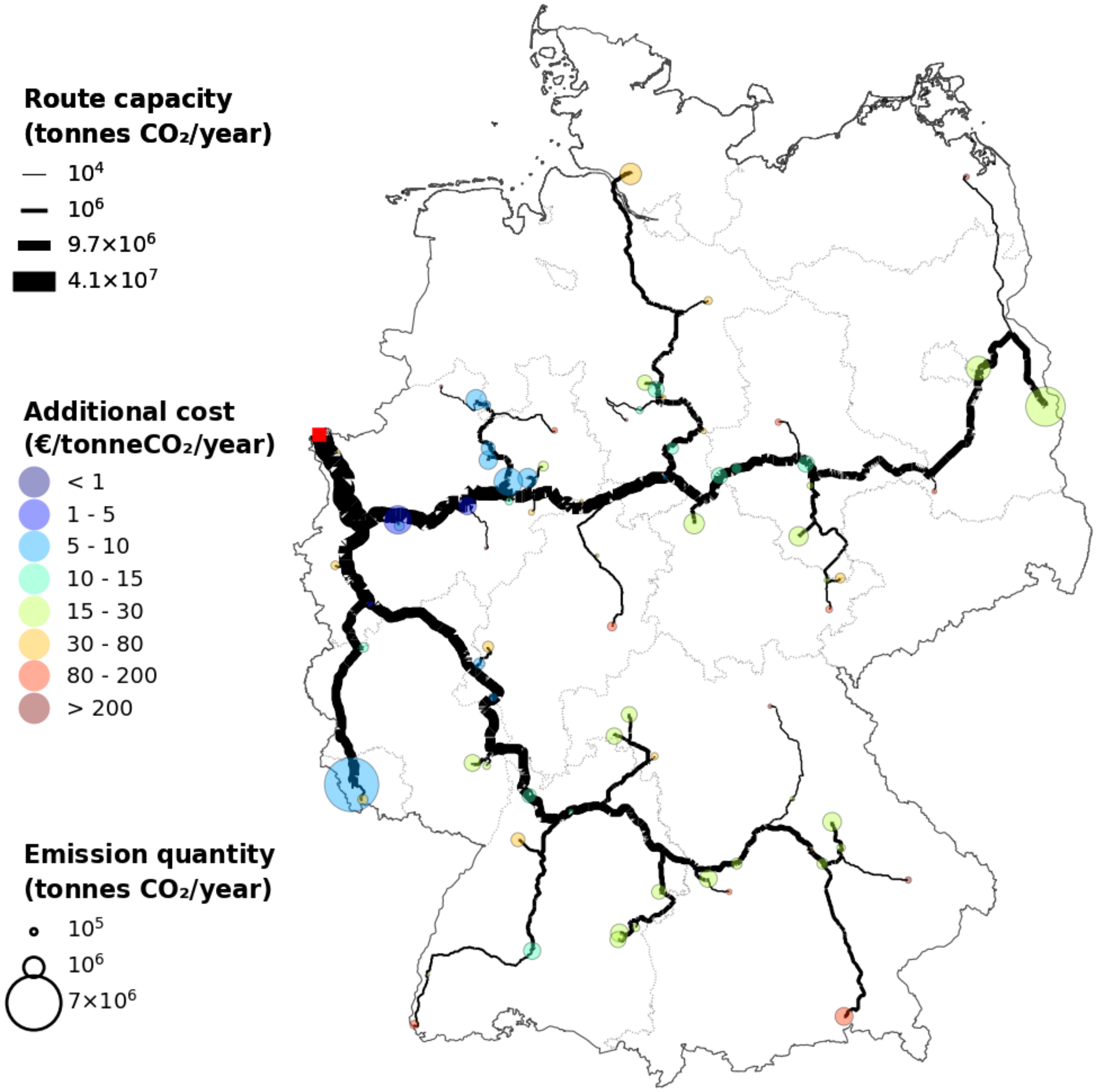
Results (scenario 5)

- Linking the coal and lignite power plants to the CO_2 network has an enormous impact on all related aspects:
  - Configuration
  - Total costs & average specific transportation cost
  - Individual specific transportation costs
- The configuration of the network and the main corridors are shaped by the biggest emitters (i.e. power plants).
- Therefore, a major CO_2 corridor has evolved to transport the significant CO_2 amounts from east to west.
- While the total costs have increased two thirds (≈ 2.7 B EUR), the average specific transportation cost has significantly decreased as the total amount of CO_2 have increased approximately 7 times.
- This change is very evident especially for the plants that became close to the new major pipelines.



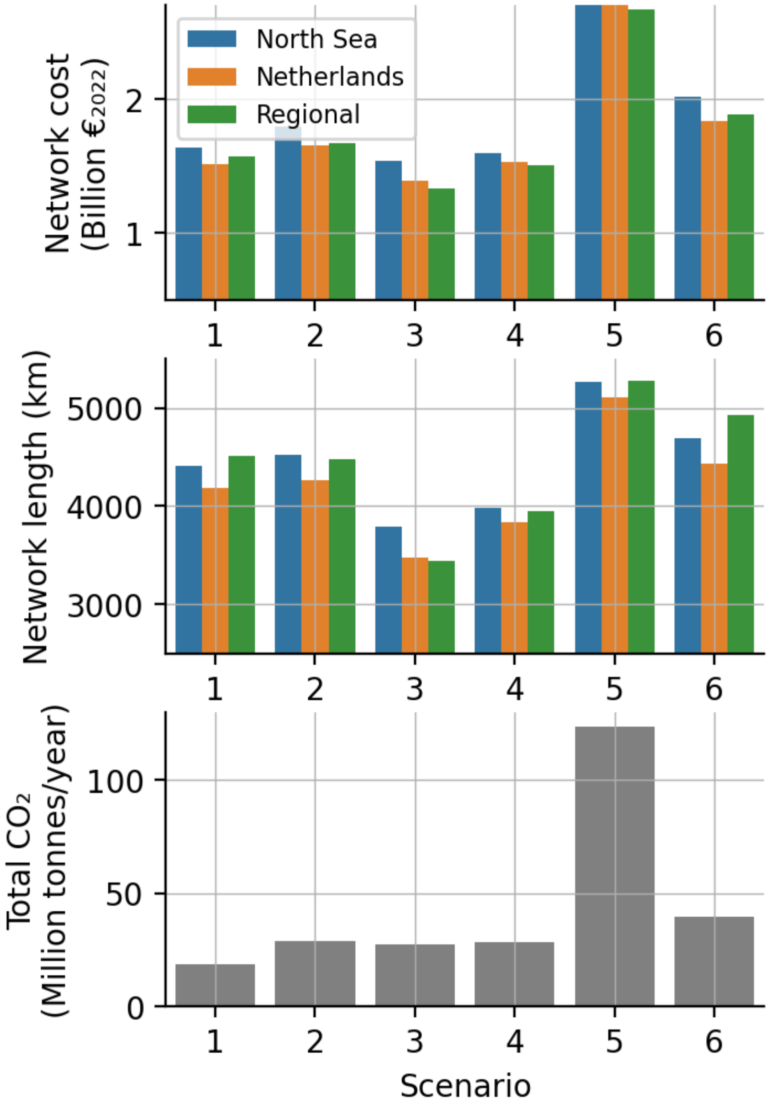
Results (scenario 6)

- The hydrogen network should reach the main German primary steel producers located in NRW, Lower Saxony and Bremen.
- Nonetheless, two sites in Brandenburg and Saarland would not be covered by the network depicted by the roadmap.
- 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.
- Herein, a considerable capacity in Brandenburg has been added, also the federal state of Saarland has been connected to the CO_2 network for the first time.
- Similar to scenario 5, the increase in costs is not directly proportional to the increase in capacities due to the economies of scale.

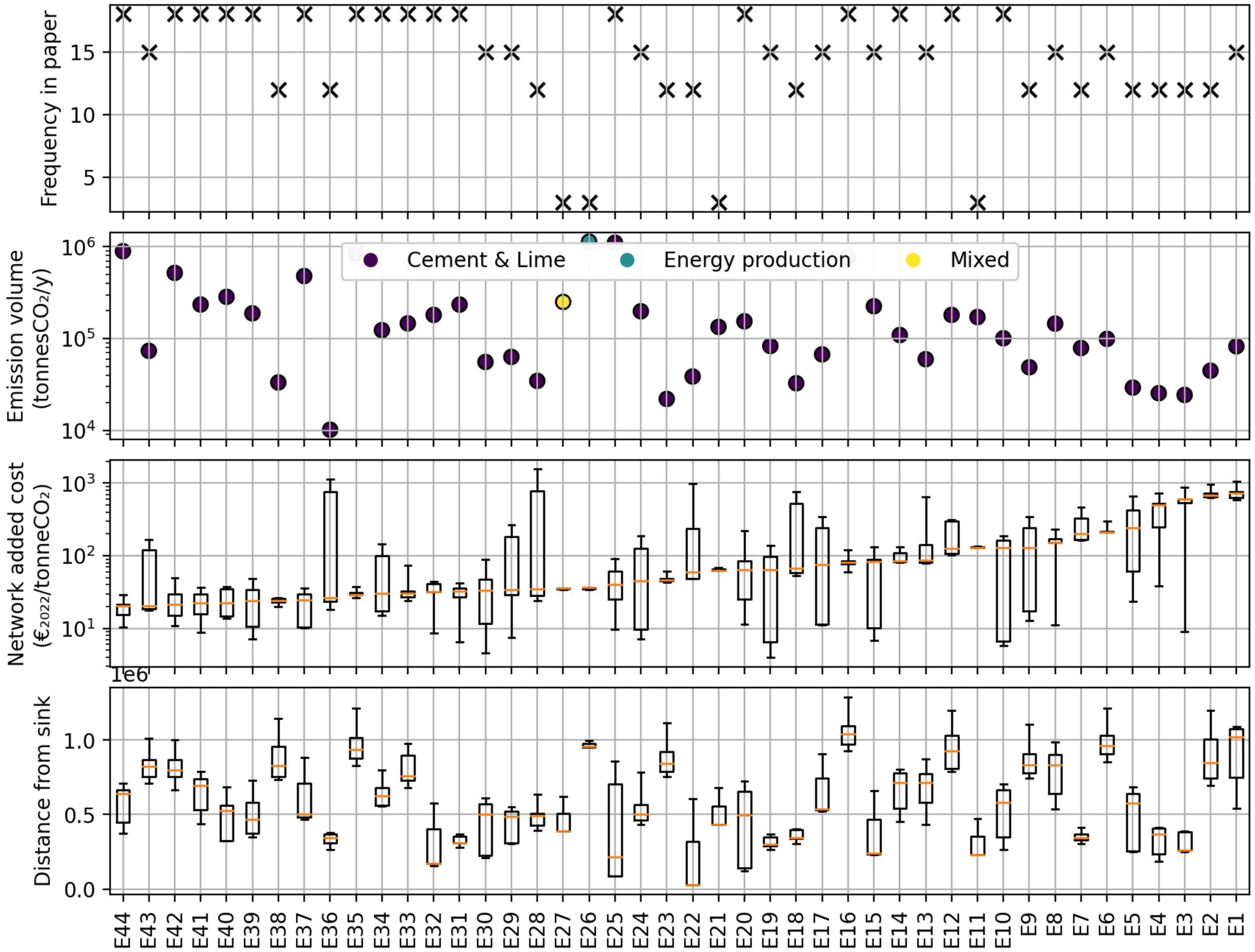


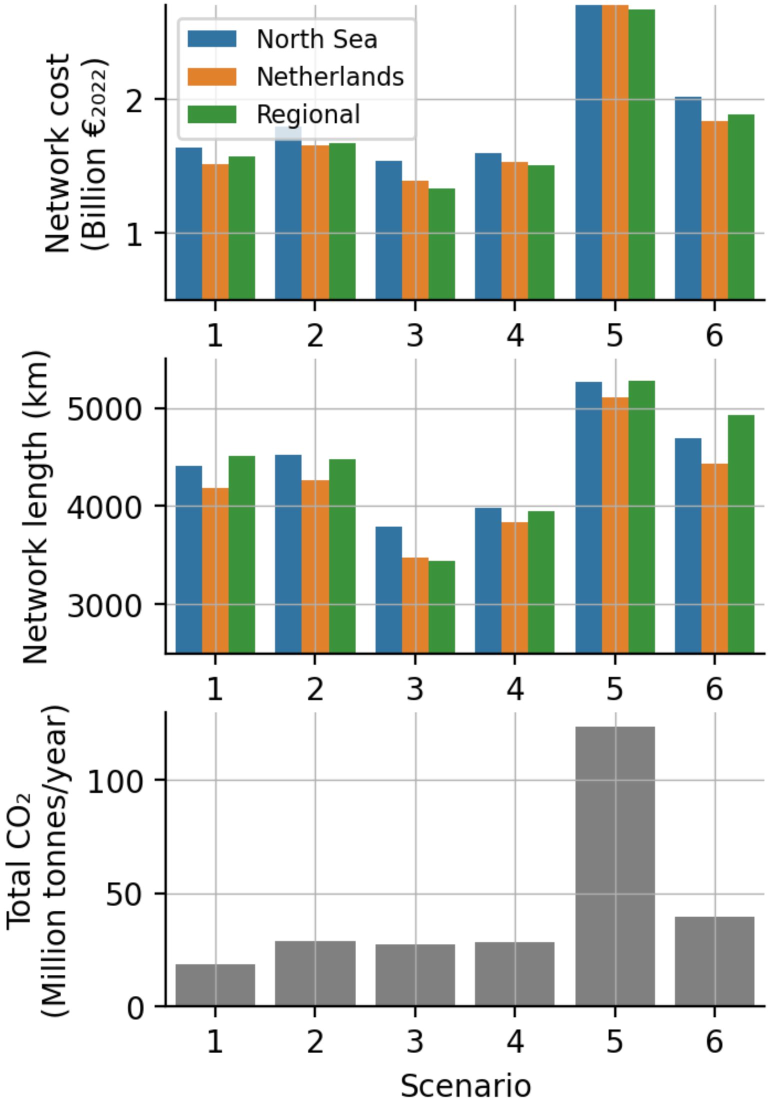
Results (comparisons)

- 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, with small differences.
- Interestingly, splitting the network into regional sinks doesn't consistently lead to lower costs.
- Economies-of-scale effect is not limited to the national-scale CO_2 backbone, regional networks can also achieve cost efficiencies.
- Pipeline is not the only costs, additional costs and factors have to be taken into consideration while considering both strategies.
- As the economies of scale also affect the transshipment, one-network approach is more cost-efficient.
- However, one network implies that any problem takes place along the network can influence all the emitters, while regional networks can be more resilient.



Results (comparisons)

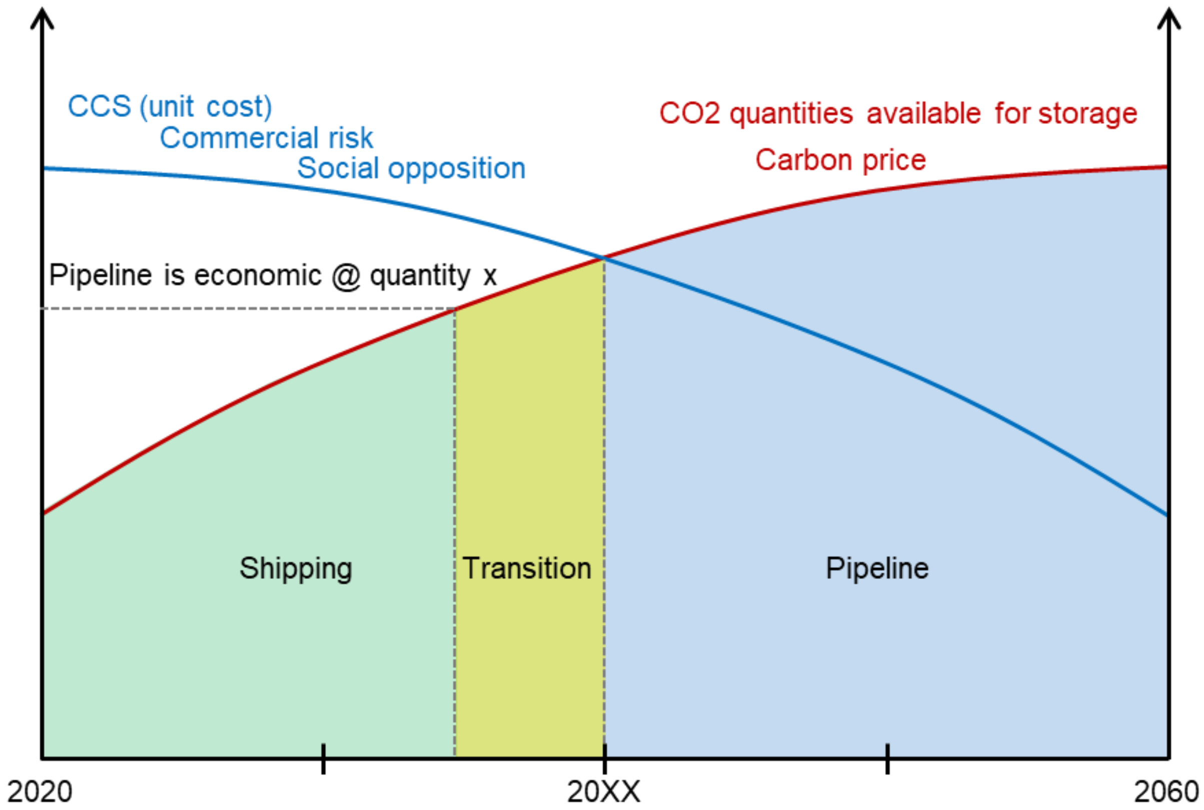




Agenda

- **Techno-economic overview**
  - CO_2 specifications
  - CO_2 transportation
  - CO_2 geological storage
- **Economic, regulatory and social challenges**
- **Modeling and analysis of CO_2 networks**
  - Framework & Methodology
  - Emitters, CO_2 hubs & scenarios
  - Cost functions & Network optimization
  - Datasets & Pipeline path proposal methodology
  - Results & Outcomes
- **Conclusions & Outlook**

- Establishing a CCS supply chain implies that various components have to develop simultaneously and various challenges to be overcome until a fully-functioning system is gradually realized.



- Establishing a CCS supply chain implies that various components have to develop simultaneously and various challenges to be overcome until a fully-functioning system is gradually realized

- The CO_2 infrastructure is vital to unleash the potentials of CCS via achieving economies of scale and reducing the specific CO_2 transportation costs.

- Constructing such system is a capital-intensive and major modifications with significant additional costs. Hence, envisaging an optimum system is of importance in order to minimize the costs.

- The location has a vital impact on transportation costs. There is a high variance between the plants of the same industry (e.g. cement) in the same scenario.

- While some plants are close to the main pipeline trunks, other emitters are remotely located and have to build an individual pipeline section in order to be connected to the main network.

- Therefore, similar to renewables pull, such disparity can cause closures or relocations in order to minimize the costs. Herein, the governmental role is of importance in order to achieve the required balance and stabilization.

- Economies of scale vs. storage capacities & diseconomies of scale.

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Thanks for attention

Questions