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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 = 23% Europe).[1] Nevertheless, decarbonizing the industrial system and, more specifically, energy-intensive industries, is more challenging as due to the processes involved, emissions cannot be abated even if the energy inputs are carbon neutral. According to Lösch et al.,[2] four industries (cement, lime, steel and chemicals) are responsible for more than 70 per cent of process emissions in Germany.

While the steel and chemical industries can benefit from the developments in their production processes (e.g. hydrogen), the production process of cement (i.e. calcination) cannot be replaced by an alternative process. That is why the cement industry has been on the radar of energy transition studies and international roadmaps. It is very clear that mitigating these process emissions will undoubtedly need carbon capture and utilization and storage (CCUS) technologies, which is the same for other industries that have significant amounts of process emissions (e.g. lime).

This paper investigates the role of CCUS in decarbonizing the cement industry by analyzing the prospective supply chains, the different options that cement producers will have to mitigate their emissions and their techno-economic requirements, advantages, drawbacks, boundaries and challenges. Some of these themes are universal, while others are regional and can be linked to the geographical features of a certain location. This paper discusses these topics and provides a case study from the German federal state of North Rhine-Westphalia (NRW) in order to address both aspects. NRW has been selected due to its locational characteristics and industrial profile. The state is considered to be the hub of German heavy industry and one of the most important industrial regions in Europe.

The paper presents the current material and energy flows of the cement and construction industries in NRW and the existing efficiency measures in the cement industry in NRW/Germany in section 2. Section 3 then investigates the decarbonization strategies and techno-economic overview of various technologies while considering the available resources and logistical aspects. Thereafter, section 4 focuses on the economic, social and regulatory aspects of CCUS. Finally, section 5 summarizes the

[1] Agora (2021). Studie: Klimaneutrales Deutschland 2045 - Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann. Umweltbundesamt (UBA). (2020). Jährliche Treibhausgas-Emissionen in Deutschland/Annual greenhouse gas emissions in Germany

[2] Lösch, O., Toro, F., Ashley-Belbin, N., Reitze, F., andd Schön, M. (2018). Prozessemissionen in der deutschen Industrie und ihre Bedeutung für die nationalen Klimaschutzziele – Problemdarstellung und erste Lösungsansätze. Institut für Ressourceneffizienz und Energiestrategien GmbH (IREES)

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main conclusions and presents measures to be taken by the industry and government to help in deploying the technology.

2. Cement production process, technologies and efficiency measures

Cement is an inorganic bonding substance composed of various compounds (tricalcium silicate, dicalcium silicate, tricalcium aluminate and tetracalcium aluminoferrite) in powder form.[3] Adding water results in a paste that eventually solidifies due to the emergence of calcium silicate hydrates (or calcium aluminate hydrates when using aluminous cements). Cement is a key input for concrete production, which is the second most consumed substance after water.[4] Several types of cement with different compositions, specifications and applications have been standardized and introduced to the market in the last decades. As shown in table 1, the different types of cements (i.e. CEM I, II, III, IV and V) are composed of different proportions of clinker as a key ingredient and other components (e.g. slag, gypsum, etc.).[5]

Table 1: composition of different cement types

Classification	CEM I	CEM II																CEM III			CEM IV		CEM V	
	Portland cement	Portland-slag cement	Portland - silica fume cement	Portland-pozzolana cement				Portland-fly ash cement				Portland-burnt shale cement		Portland-limestone cement				Portland-composite cement		Blast furnace cement			Pozzolanic cement		Composite cement	
	CEM I	CEM II/A-S	CEM II/B-S	CEM II/A-P	CEM II/B-P	CEM II/A-Q	CEM II/B-Q	CEM II/A-V	CEM II/B-V	CEM II/A-W	CEM II/B-W	CEM II/A-T	CEM II/B-T	CEM II/A-L	CEM II/B-L	CEM II/A-LL	CEM II/B-LL	CEM II/A-M	CEM II/B-M	CEM III/A	CEM III/B	CEM III/C	CEM IV/A	CEM IV/B	CEM V/A	CEM V/B
Clinker	95-100	80-94	65-79	80-94	65-79	80-94	65-79	80-94	65-79	80-94	65-79	80-94	65-79	80-94	65-79	80-94	65-79	80-94	65-79	35-64	20-34	5-19	65-89	45-64	40-64	20-38
Other	5-0	20-6	35-21	20-6	35-21	20-6	35-21	20-6	35-21	20-6	35-21	20-6	35-21	20-6	35-21	20-6	35-21	20-6	35-21	65-36	80-66	95-81	35-11	55-36	60-36	62-80

Source: Beton (2017), CEN (2000)[6]

Clinker production is an energy and emission intensive process. Although the basic chemical process has not changed since it was industrially adopted in the 19th century (i.e. calcination), the production technology (i.e. kiln) has improved significantly in order to increase efficiency of operation and energy consumption.[7] The cement industry has gradually shifted from shaft to rotary kiln and from wet to dry process. Also, other technologies such as preheater, precalciner and waste heat recovery have been developed and become common in the industry. Moreover, for economic and environmental objectives, the cement producers have also been striving to increase the substitution rates of alternative fuels (e.g.

[3] Schorcht, F., Kourti, I., Scalet, B. M., Roudier, S., and Sancho, L. D. (2013). 'Best Available Techniques (BAT) reference document for the production of cement, lime and magnesium oxide'. Industrial emissions directive 2010/75/EU (Integrated pollution prevention and control)

[4] Gagg, C. R. (2014). 'Cement and concrete as an engineering material: An historic appraisal and case study analysis'. *Engineering Failure Analysis*, *40*, 114–140

[5] Beton (2017). Zement-Merkblatt Betontechnik. 'Zemente und ihre Herstellung'

[6] CEN (European Committee for Standardization). (2000). EN 197-1. 'Cement - part 1: Composition, specifications and conformity criteria for common cements'

[7] Schneider, M., Romer, M., Tschudin, M., and Bolio, H. (2011). 'Sustainable cement production—present and future'. *Cement and Concrete Research*, *41*(7), 642–650. https://doi.org/10.1016/j.cemconres.2011.03.019

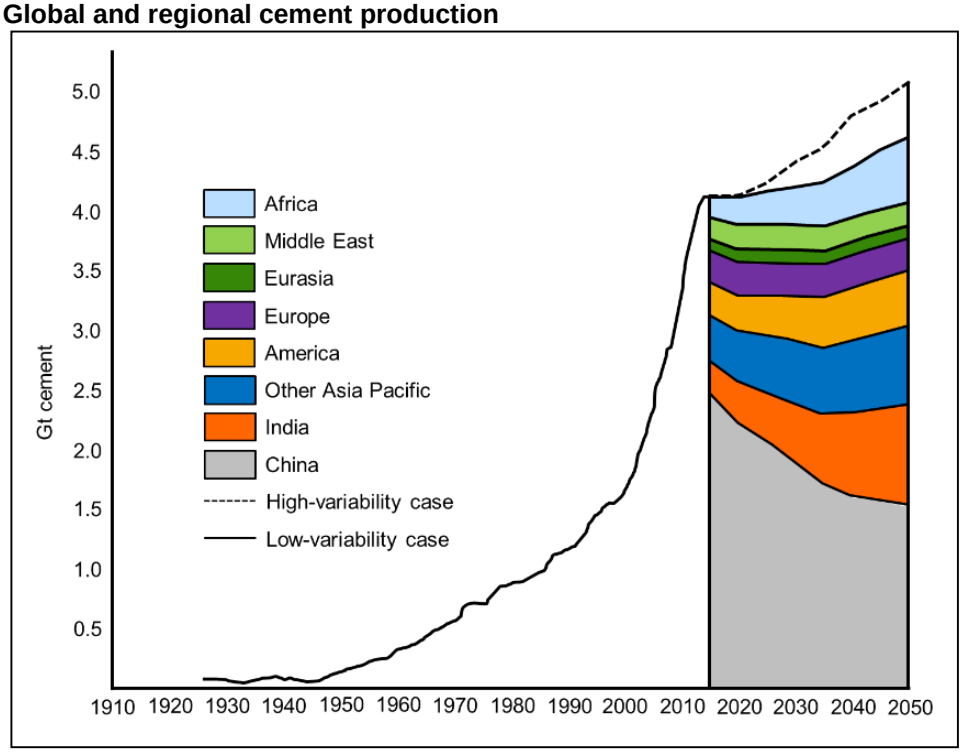
refuse-derived fuel (RDF) and plastic waste) and alternative materials. For example, substances such as blast furnace slag and fly ash are used in producing CEM II and CEM III which consume lower amounts of clinker and have a lower carbon footprint.

2.1 Global production

As an indispensable necessity for building materials and products, the demand for cement is dependent on growth in the construction industry or the economy in general. As depicted in Figure 1, the global cement production has been increasing exponentially. Since the second world war, production has increased more than eightyfold and doubled in the last fifteen years. The significant increase in the last two decades is directly linked to developing economies, for example, production in China has significantly increased from 600 megatons (Mt) in 2000 to roughly 2500 Mt in 2014 (i.e. approximately 60% of global production).[8]

However, according to the International Energy Agency (IEA), global cement production will not increase at the same rates witnessed in the last decades. Based on two scenarios (low-variability and high-variability), global production should reach between 4.5 gigaton (Gt) and 5.1Gt respectively by 2050. But regional production profiles will also change. On the one hand, the boom in the Chinese construction sector will not last and cement production in China will decrease in the coming decades. On the other hand, production will increase in other developing economies (e.g. India and Africa).

Figure 1: Global and regional cement production



Source: Author's intepretation based on IEA (2018b) and USGS (2017)[9]

2.2 Decarbonization and challenges

The cement industry is responsible for seven per cent of global greenhouse gas (GHG) emissions with specific emissions of 0.59 ton CO_2/ton cement in 2020.[10] This can vary due to the regional variations in

[8] IEA (2018b). 'Technology Roadmap - Low-carbon Transition in the Cement Industry'. International Energy Agency.
Xu, D., Cui, Y., Li, H., Yang, K., Xu, W., and Chen, Y. (2015). 'On the future of Chinese cement industry'. *Cement and Concrete Research*, *78*, 2–13. https://doi.org/10.1016/j.cemconres.2015.06.012
[9] USGS (2017). 'Historical Statistics for Mineral and Material Commodities in the United States. US Geological Survey
[10] IEA. (2021). *Cement - Tracking report*. https://www.iea.org/reports/cement

production technologies, fuel consumption, cement types, emissions and so on. Despite all the environmental techniques adopted by the cement industry, clinker production is, and will be, associated with significant amounts of CO_2 emissions. In contrast to other energy-intensive industries, emissions caused by fuel consumption do not constitute the major part in total emissions. Clinker production is associated with significant amounts of process emissions due to the calcination process (which is also employed in the lime industry). Calcination refers to the chemical process of transforming calcium carbonates ($CaCO_3$) to calcium oxides (CaO), which results in significant amounts of CO_2 as shown in the following equations:

Production equation: $CaCO_3$ + Heat → CaO + CO_2 (Fraction CaO = 0.646)

Emission Factor Clinker = Fraction CaO x 0.785 = 0.5071 tonne CO2/tonne clinker (process emissions)

Limestone calcination is responsible for approximately two-thirds of clinker production's carbon footprint (i.e. process emissions), while fuels are responsible for the rest of emissions. The process emissions can be classified as 'hard-to-abate', as they cannot be simply avoided even if carbon-neutral fuels are used (e.g. biomass, renewable electricity, green hydrogen, etc.). Such challenges can only be tackled by sequestering the generated CO_2 via carbon capture, utilization and storage (CCUS). Nonetheless, CCUS value chains are complicated and associated with various uncertainties. From a technical perspective, there are various alternatives with different features in terms of technology readiness level (TRL), requirements, and so on. Economically, using CCUS technologies implies additional costs regardless of the option adopted. Additionally, there is a lack of public support regarding developing the required infrastructure (e.g. pipeline networks and geological storage), especially in Europe.

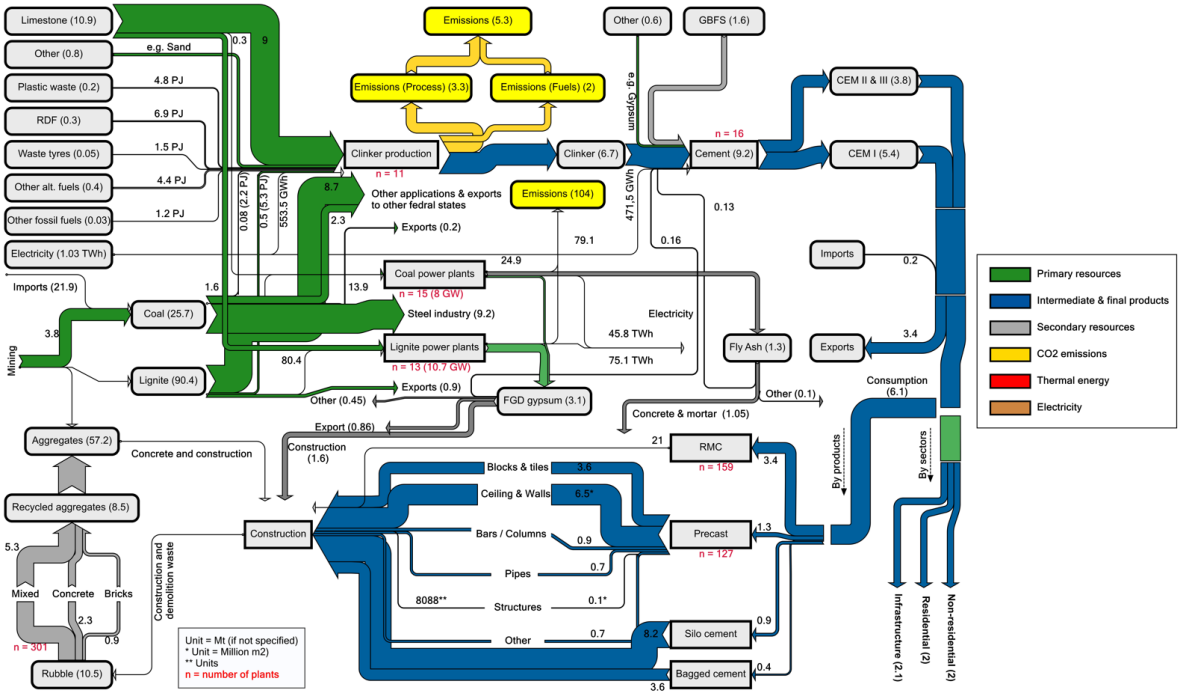
2.3 Cement and construction industries in NRW

2.3.1 Material and energy flows

The value chains of the cement and construction industries in NRW are depicted in Figure 2. The main input of cement production (clinker) is produced in eleven plants (including one plant with two registries/stacks). In total, 5.3 Mt CO_2 are emitted annually which can be split into process emissions (3.3 Mt CO_2) and fuel-related emissions (2 Mt CO_2). The majority of NRW plants have relatively average capacities and there is no high variance between the plants in terms of production and emissions, as shown in Figure 3. The total plant emissions range between 250 kt CO_2 and 700 kt CO_2 and the process emissions range between 160 kt CO_2 and 430 kt CO_2. The clinker yield (6.7 Mt) is ground with other components to a certain size to produce cement. Cement production (9.2 Mt) takes place in 16 plants and consumes roughly half of the total electricity required throughout the production process. In terms of type and composition, the market is mainly dominated by three cements (Portland cement/CEM I, CEM II and CEM III). Due to the proximity of NRW to other countries (e.g. Belgium and the Netherlands), a big portion of the domestic yield (3.4 Mt) is exported. The rest is used to produce various products (e.g. ready-mix concrete (RMC), precast concrete, etc.) for the construction sector (i.e. residential, non-residential and infrastructure).

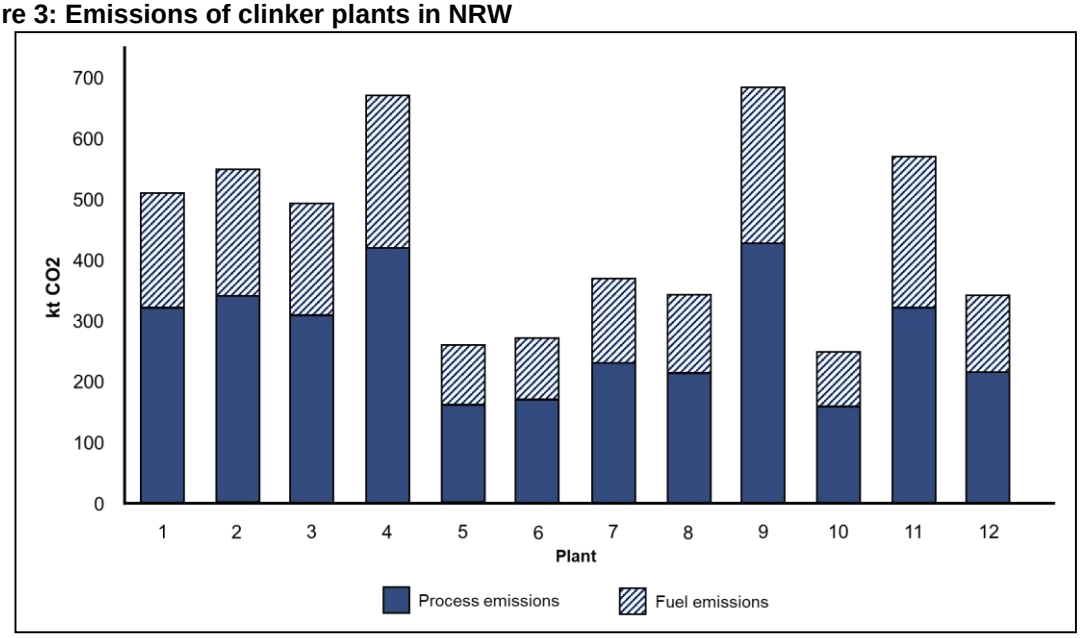
OWD. (2020). 'CO2 and greenhouse gas emissions'. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

Figure 2: MFA model of cement and construction industries in NRW



Source: Abdelshafy, A., and Walther G. (2022b)[11]

Figure 3: Emissions of clinker plants in NRW



Source: Author's intepretation based on EC (2020)[12]

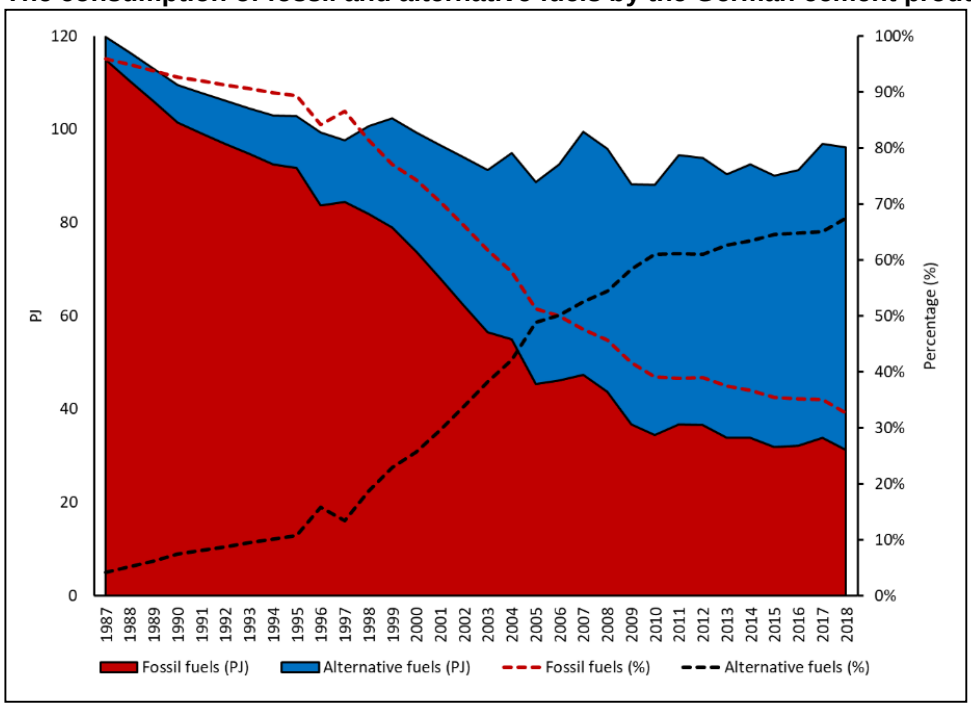
[11] Abdelshafy, A., & Walther, G. (2022b). 'Exploring the effects of energy transition on the industrial value chains and alternative resources: A case study from the German federal state of North Rhine-Westphalia (NRW)'. *Resources, Conservation and Recycling*, *177*, 105992. https://doi.org/10.1016/j.resconrec.2021.105992

[12] EC (2020). European Union Transaction Log. European Commission

2.3.2 Existing efficiency measures

In addition to the general energy efficient technologies discussed above, the cement producers in Germany (including NRW) have succeeded in adopting other measures in terms of alternative fuels and materials. As shown in Figure 4, the usage of alternative fuels has developed significantly in Germany in the last 30 years (4% in 1987 to 67% in 2018), of which RDF and plastic waste constitute roughly two thirds. This substitution rate is the highest in the EU and significantly higher than the world average (world average = 5-10%. EU average = 41%).[13] In terms of alternative materials, Germany has reduced its market share of Portland cement from 77 per cent in 1993 to 28 per cent in 2018 as shown Figure 5. In terms of production technologies, the majority of cement plants in NRW and Germany already have energy-efficient appliances (i.e. preheater and precalciner). Adopting these measures has helped the cement industry to decrease its emissions by more than one fifth in the last three decades in absolute and relative terms (26.5 Mt and 0.75 ton CO_2/ton cement in 1990 to 20 Mt and 0.59 ton CO_2/ton cement in 2019)[14]. However, achieving the same level of emission reduction rates in the coming three decades using the same methods is not expected as they have already been exhausted. Hence, other techniques (e.g. CCUS) have to be adopted to reach carbon neutrality as long as there is no other production technology or alternative binding material.

Figure 4: The consumption of fossil and alternative fuels by the German cement producers



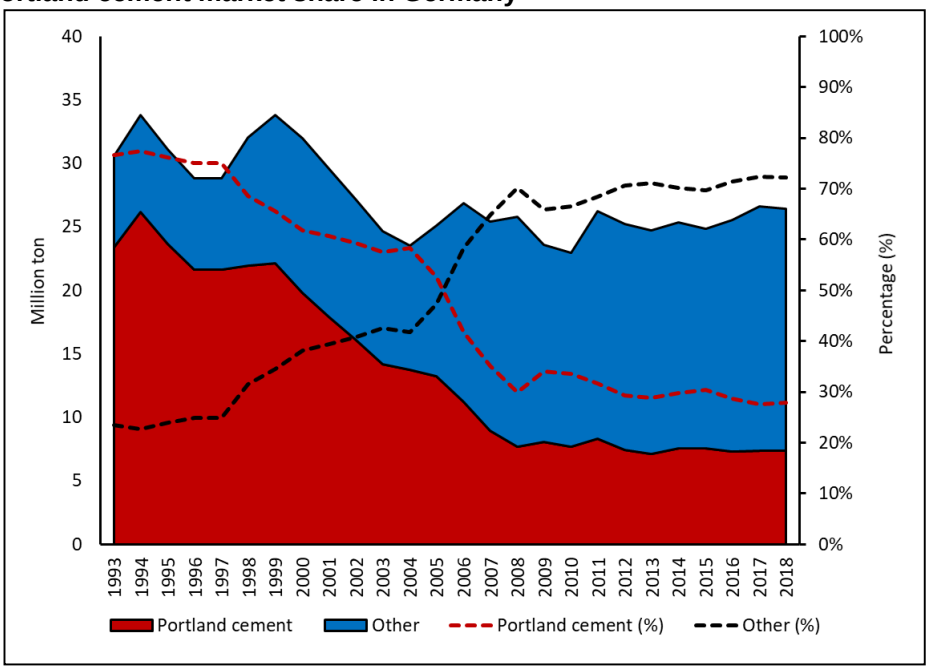
Source: Author's interpretation based on Löckener and Timmer (2002); VDZ (2005) and (2019)[15]

[13] de Beer, J., Cihlar, J., Hensing, I., and Zabeti, M. (2017). 'Status and prospects of co-processing of waste in EU cement plants'
IEA (2018b). Technology Roadmap - Low-carbon Transition in the Cement Industry. International Energy Agency
Sarc, R., Pomberger, R., and Lorber, K. E. (2013). 'Perspektiven der Verwertung von Ersatzbrennstoffen in Zementwerken'
Sarc, R., Lorber, K. E., Pomberger, R., Rogetzer, M., and Sipple, E. M. (2014). 'Design, quality and quality assurance of solid recovered fuels for the substitution of fossil feedstock in the cement industry'

[14] VDZ (2020). Dekarbonisierung von Zement und Beton - Minderungspfade und Handlungsstrategien

[15] Löckener, R., and Timmer, B. (2002). Nachhaltigkeit und Zementindustrie: Dokumentation von Beiträgen und Handlungsoptionen
VDZ (2005). Umweltdaten der deutschen Zementindustrie. Der Verein Deutscher Zementwerke e.V.
VDZ. (2019). Zementindustrie im Überblick 2019/2020. Verein Deutscher Zementwerke e.V.

Figure 5: Portland cement market share in Germany



Source: Author's intepretation based on Löckener and Timmer (2002); VDZ (2005) and (2019)

3. CCUS technologies

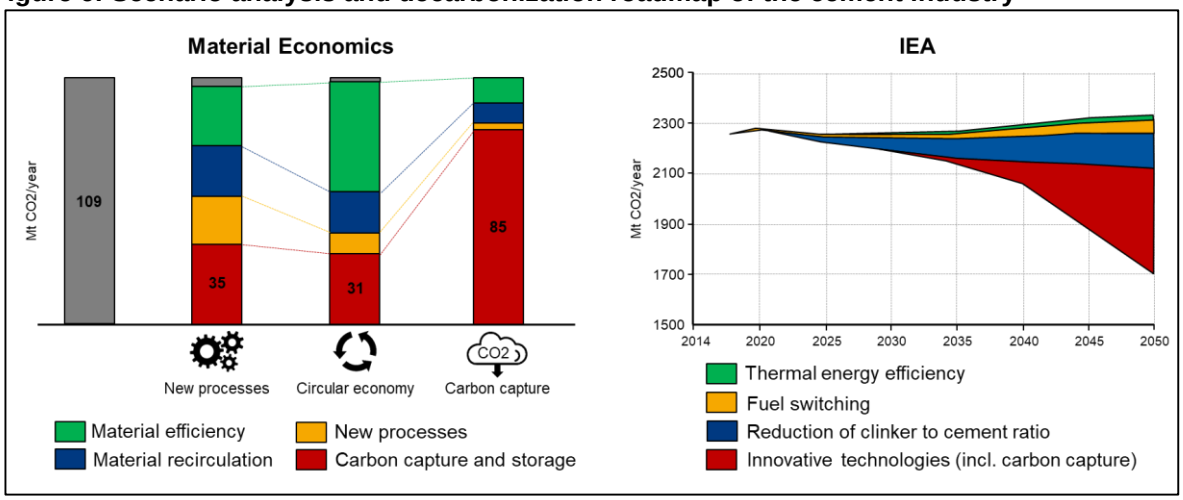
3.1 Decarbonization roadmaps and strategies

Although there are European and national strategic goals to reach net-zero emissions by 2045/2050 (e.g. EU Green deal and German Energiewende/energy transition policy), there is no consensus either on the decarbonization pathways or on the types of potential technologies. The lack of consensus is not only due to the uncertainties related to the future technologies in terms of costs, economies of scale, reliability and available resources, but also the geographical aspects of each region which directly influence the availability and costs of resources (e.g. renewable energies, water ways, geological storage, etc.). Therefore, the location of each region shall shape its preferences and priorities in terms of decarbonization pathways.

A clear example of this variance is depicted in Figure 6 which shows a roadmap and scenario analysis adopted by International Energy Agency (IEA) and Materials Economics[16]. Although the mitigation techniques are analogous, the contribution of each is different. The roadmap of IEA addresses the global cement industry and expects that the total emissions will decrease from approximately 2.3 Gt CO_2 to 1.7 Gt despite the increase in the production. The roadmap envisages that innovative technologies (e.g. CCS) shall cumulatively mitigate 48 per cent of CO_2 emissions, nonetheless the technology deployment will be gradual and should be more obvious by 2035. Other CO_2-mitigation techniques will have lower shares and more stable contributions in the coming years. Reducing the clinker content should be the second technique with a cumulative contribution of 37 per cent, followed by substituting fossil fuels with fuels having a lower carbon-footprint (e.g. biomass) (12%), and finally adopting energy-efficiency measures (3%).

[16] IEA (2018a). Technology roadmap - Low-carbon transition in the cement industry (summary)
IEA (2018b). Technology Roadmap - Low-carbon Transition in the Cement Industry. International Energy Agency
Material Economics (2019). Industrial Transformation 2050 – Pathways to net-zero emissions from EU Heavy Industry

Figure 6: Scenario analysis and decarbonization roadmap of the cement industry



Source: Author's interpretation based on IEA (2018a) (2018b) and Material Economics (2019)

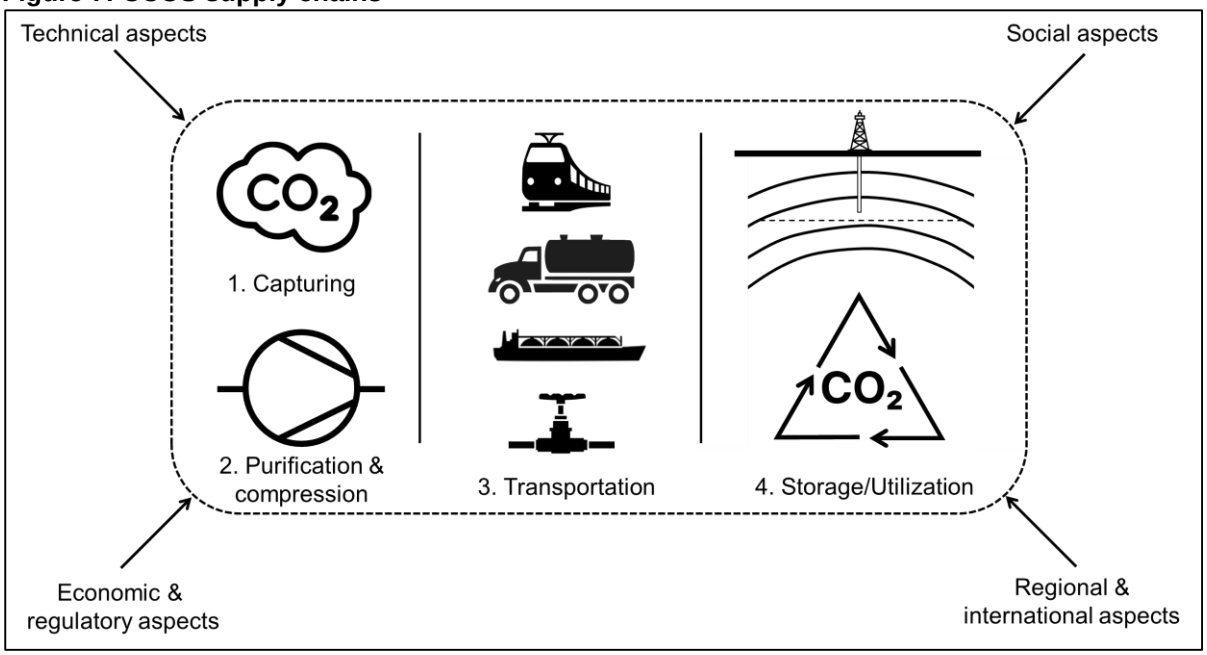
Contrariwise, the analyses by Material Economics focuses only on Europe and investigates the possibility of reaching carbon neutrality via three scenarios. The first pathway (new processes) assumes the possibility of electrifying the production process driven by the availability of electrical energy. The second pathway (circular economy) envisions high emissions reductions due to lower cement production and more efficient consumption. Finally, the last pathway (carbon capture) envisages a higher dependency on CCUS. Although the role of CCUS is endorsed by the three scenarios, the contribution is different in each case. While the first two scenarios assume that approximately one-third of the emissions will be sequestered by CCUS, the third one envisages a significantly higher contribution (more than three quarters). Recently, the association of German cement producers (VDZ) has published its CO_2 roadmap for the cement industry in Germany.[17] This study introduced two scenarios (ambitious reference scenario and climate neutrality scenario) and estimated that more than half of the emissions will be mitigated via CCUS by 2050 in the second scenario. Therefore, the main conclusion of these roadmaps and scenario analyses can be stated as 'While the magnitude of the CCUS role in the decarbonization dossier is controversial, there is a consensus that the technology will be needed.'

3.2 A techno-economic overview of CCUS technologies

As discussed, the production of clinker results in significant amounts of process emissions. Therefore, regardless of the fuel used, the generated process CO_2 emissions need to be sequestered via carbon capture and utilization or storage (CCUS) in order to reach carbon neutrality. As shown in Figure 7, the supply chain of CCUS can be split into four main phases; (1) CO_2 capture/separation from the flue gas, (2) CO_2 purification and compression, (3) transportation, and finally (4) CO_2 geological storage or utilization.[18] As CCUS is a multidisciplinary theme, all mentioned phases can be influenced by various aspects (e.g. technical, economy, regional, social, etc.). The effects of some factors are comparable, regardless of the region (e.g. technical aspects), while others are highly influenced by the geographical location (e.g. social and regulatory aspects). This section briefly presents the key techno-economic aspects and the different technological options available at each stage.

[17] VDZ (2020). Dekarbonisierung von Zement und Beton - Minderungspfade und Handlungsstrategien
[18] Folger, P. (2018). Carbon Capture and Sequestration (CCS) in the United States

Figure 7: CCUS supply chains



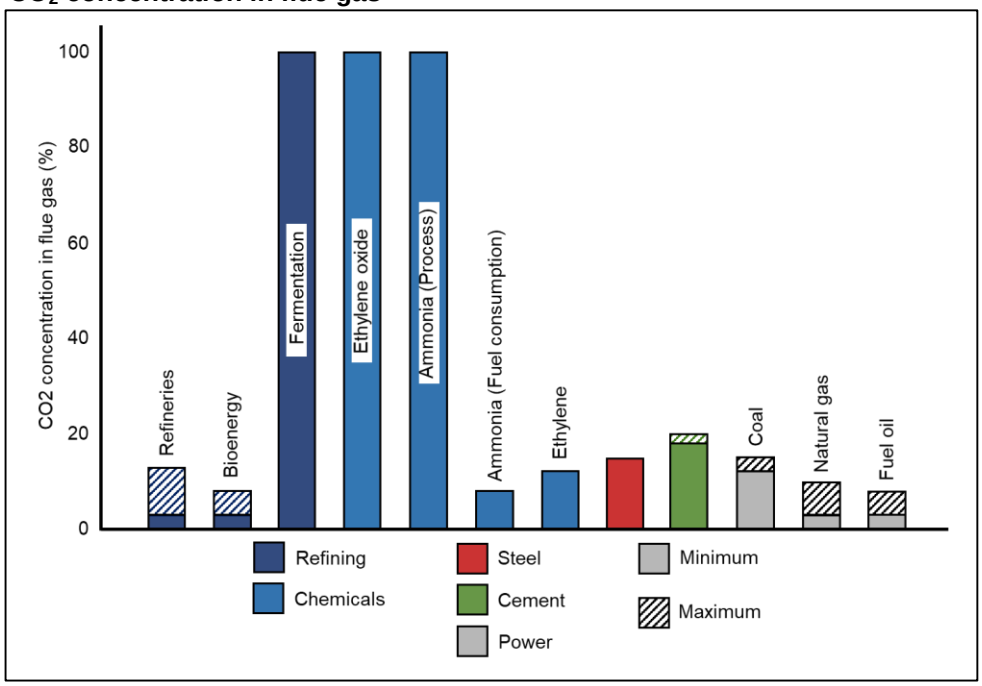
Source: Author's own illustration

3.2.1 CO_2 capture

CO_2 from chimneys is not pure, it is normally mixed with other constituents. The flue gas composition directly affects the capturing costs which have a major impact on the whole CCUS supply chain as it has the highest contribution to the total costs. As shown in Figure 8, only few industrial processes in the chemical and refining sectors have roughly pure CO_2 streams (e.g. ammonia production and fermentation), while the CO_2 concentration in the rest of major industries is less than 20 per cent.[19] If the high purity streams in the chemical and refining sectors are omitted, the CO_2 concentration in the flue gas of clinker production is relatively high and ranges between 18 and 20 per cent[20]. The number of flue-gas stacks in the plant is also important as it can significantly affect the economics of the operations.[21] For example, the emissions of an integrated steel plant normally come out of multiple points (e.g. blast furnace, coke oven, power plant, etc.) which mean that a carbon capture plant is needed at each point, or a method to merge all the flue gases in one place before the capturing process needs to be found. In this regard, the cement industry also has a comparative advantage as the flue gases can be retrieved at one point.

[19] Gale, J., Bradshaw, J., Chen, Z., Garg, A., Gomez, D., Rogner, H. H., Simbeck, D., Williams, R., Toth, F., and Van Vuuren, D. (2005). IPCC special report on Carbon dioxide capture and storage. Chapter 2: Sources of CO2. Intergovernmental Panel on Climate Change (IPCC)
Markewitz, P., Zhao, L., Ryssel, M., Moumin, G., Wang, Y., Sattler, C., Robinius, M. and Stolten, D. (2019). 'Carbon Capture for CO2 Emission Reduction in the Cement Industry in Germany'. *Energies*, *12*(12), 2432. https://doi.org/10.3390/en12122432
[20] Markewitz, P et al. *Energies*, *12*(12), 2432. https://doi.org/10.3390/en12122432
[21] Terlouw, W., Peters, D., Van Tilburg, J., Schimmel, M., Berg, T., Cihlar, J., Rehman Mir, G. U., Spöttle, M., Staats, M., Lejaretta, A. V., Buseman, M., Schenkel, M., Van Hoorn, I., Wassmer, C., Kamensek, E., and Fichter, T. (2019). Gas for Climate. The optimal role for gas in a net zero emissions energy system. https://www.europeanbiogas.eu/wp-content/uploads/2019/11/GfC-study-The-optimal-role-for-gas-in-a-net-zero-emissions-energy-system.pdf

Figure 8: CO_2 concentration in flue gas



Source: Author's interpretation based on Gale et al. (2005) and Markewitz et al. (2019)[22]

CO_2 capture is a sophisticated technology and its processes are quite complex. Many technologies have been developed with different technical concepts, energy requirements (penalties), efficiencies, costs and TRLs (Figures 9 and 10) which can be classified in several ways. Firstly, the mechanism which refers to the scientific or technical principle applied in the technology (e.g. absorption, adsorption, membranes, etc.). Regardless of the science field of the concept (e.g. chemistry, physics, etc.), the main aim is to find a method to trap CO_2 molecules and let the other constitutes of the flue gas pass through. For example, the concept of chemical absorption is to use a solvent (e.g. amine) to absorb CO_2 while the flue gas flows and then recover the CO_2 from the solvent. Therefore, there is always an energy penalty, which depends on the mechanism adopted. Other studies use another related classification which is the main substance used in the capturing process (e.g. liquid solvent, solid adsorbent, etc.).

The third classification is the technical approach, which is comparable to the first one but broader and refers to when and how the capturing process takes place. In this regard, CO_2 capture technologies can be split into five types; (1) pre-combustion technologies which are based on removing the CO_2 before the combustion process (e.g. coal gasification), (2) post-combustion technologies which capture the CO_2 afterwards (i.e. from the flue gas), (3) direct air capture, (4) oxy-fuel technology uses oxygen during combustion in order to generate a flue-gas with a high CO_2-concentration, and finally (5) direct separation (Calix Advanced Calciner) which isolates the calcination process from the thermal energy source and can yield a pure CO_2 stream from the process emissions.[23] This last technology is mainly

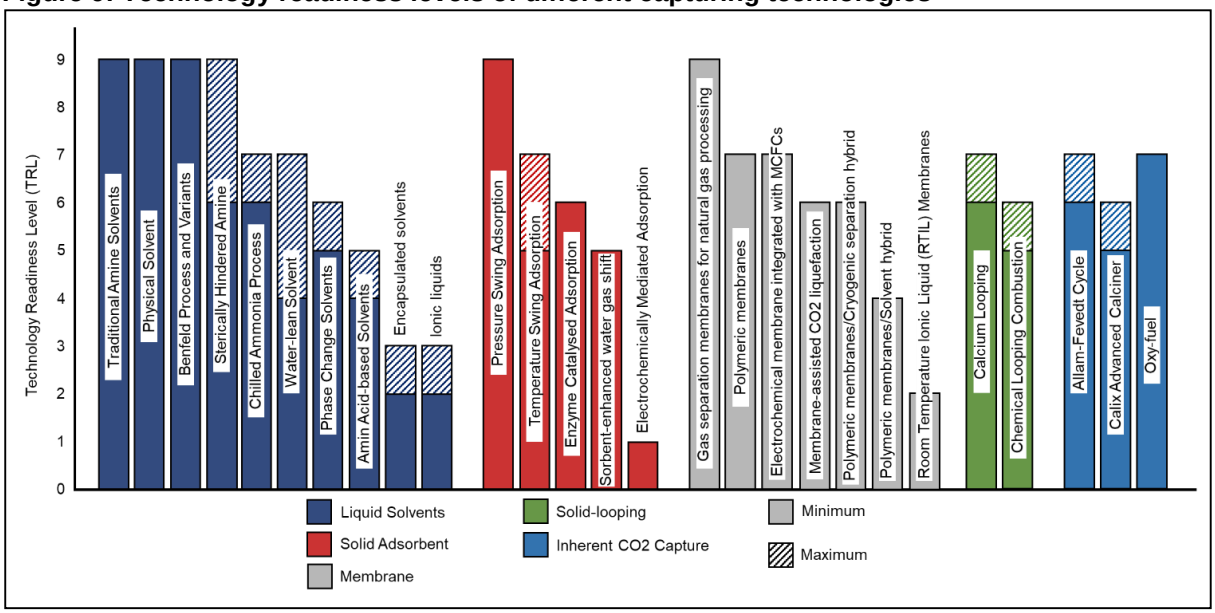
[22] Gale, J., Bradshaw, J., Chen, Z., Garg, A., Gomez, D., Rogner, H. H., Simbeck, D., Williams, R., Toth, F., and Van Vuuren, D. (2005). IPCC special report on Carbon dioxide capture and storage. Chapter 2: Sources of CO2. Intergovernmental Panel on Climate Change (IPCC)
Markewitz, Zhao, Ryssel, Moumin, Wang, Sattler, Robinius, and Stolten (2019). 'Carbon Capture for CO2 Emission Reduction in the Cement Industry in Germany'. *Energies*, *12*(12), 2432. https://doi.org/10.3390/en12122432

[23] Concawe (2021). Technology scouting - Carbon capture: from today's to novel technologies
GCCSI (2020). Global status of CCS 2020. Global CCS Institute (GCCSI)
Hills, T. P., Sceats, M., Rennie, D., and Fennell, P. (2017). LEILAC: 'Low Cost CO2 Capture for the Cement and Lime Industries'. *Energy Procedia*, *114*, 6166–6170. https://doi.org/10.1016/j.egypro.2017.03.1753

related to the cement and lime industries and has not been mentioned or classified by various studies as it was recently scaled-up and applied in the LEILAC project.[24]

These technologies can be also classified based on the **configuration** (i.e. tail-end vs. integrated) and some of them are actually available in both (e.g. calcium looping).[25] 'Tail-end' means that the capture unit is an additional separate module at the end of the production process, while an 'integrated' configuration implies that the technology becomes a part of the production process, and consequently retrofitting a cement kiln would be mandatory. In terms of the maturity or the technology readiness level (TRL), there is also an additional classification which is the **generation**. Herein the capturing technologies can be classified into three generations based on the TRL (first generation = 7-9, second generation = 3-6 and third generation = 1-3).[26]

Figure 9: Technology readiness levels of different capturing technologies



Source : Author's interpretation based on Concawe (2021), Haines et al. (2014), Hills et al. (2016) and Kearns et al. (2021)[27]

[24] LEILAC. (2021). *Low Emissions Intensity Lime and Cement (LEILAC)*. https://www.project-leilac.eu/

[25] Anantharaman, R., Berstad, D., De Lena, E., Fu, C., Osk Gardarsdottir, S., Jamali, A., Pérez-Calvo, J. F., Romano, M., Roussanaly, S., Ruppert, J., Stallmann, O., Sutter, D., and Voldsund, M. (2018). CEMCAP comparative tech-economic analysis of CO2 capture in cement plants

[26] ZEP (2017). Future CCS technologies. Zero Emissions Platform (ZEP)

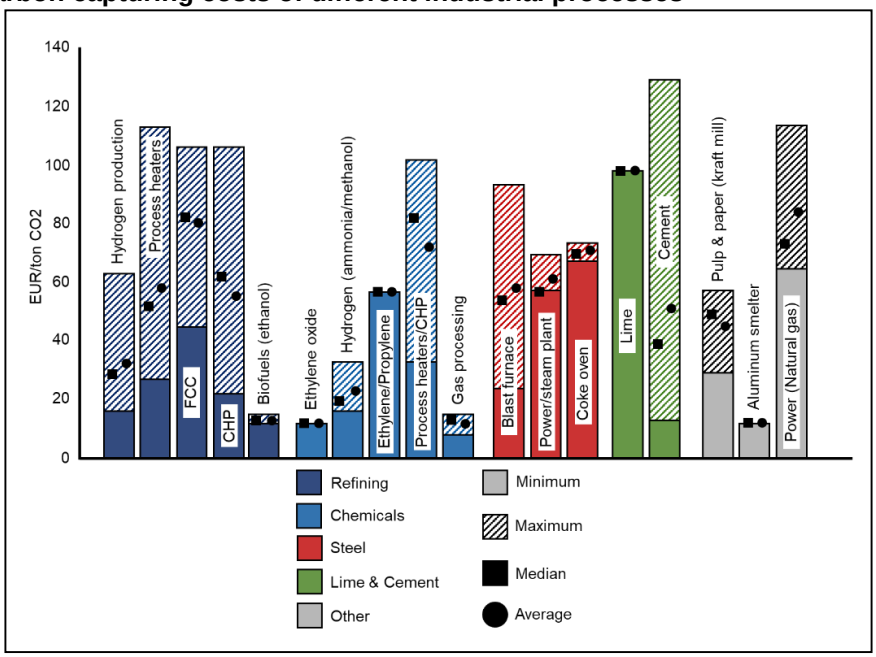
[27] Concawe (2021). Technology scouting - Carbon capture: from today's to novel technologies

Haines, M., Kemper, J., Davison, J., Gale, J., Singh, P., and Santos, S. (2014). 'Assessment of emerging CO2 capture technologies and their potentials to reduce costs'

Hills, T., Leeson, D., Florin, N., & Fennell, P. (2016). 'Carbon Capture in the Cement Industry: Technologies, Progress, and Retrofitting'. *Environmental Science & Technology*, *50*(1), 368–377. https://doi.org/10.1021/acs.est.5b03508

Kearns, D., Liu, H., & Consoli, C. (2021). Technology readiness and costs of CCS. Global CCS Institute

Figure 10: Carbon capturing costs of different industrial processes



Source: Author's interpretation based on Leeson et al. (2017) and Terlouw et al. (2019)[28]

As depicted, there is a wide range of CO_2 capture costs reported in the literature (≈ 20-140 EUR/ton CO_2). It is worth highlighting that the cheapest technology should not be interpreted as the best alternative. First of all, there is a discrepancy in terms of the specific cost as can be seen in the different studies.[29] Such lack of agreement can be linked to the assumptions taken into consideration as well as the OPEX which can highly influence the costs (for example, electricity prices). Secondly, the figures of some technologies are not based on industrial-scale plants (e.g. desk analysis, process simulation, pilot projects, etc.) which means there are various uncertainties regarding the performance and costs of large-scale operations. Moreover, other factors and costs should be taken into account such as reliability, maintenance, flexibility, retrofitting possibilities, and so on. Finally, emerging technologies with low TRLs need months, if not years, of operation to be tested and verified.

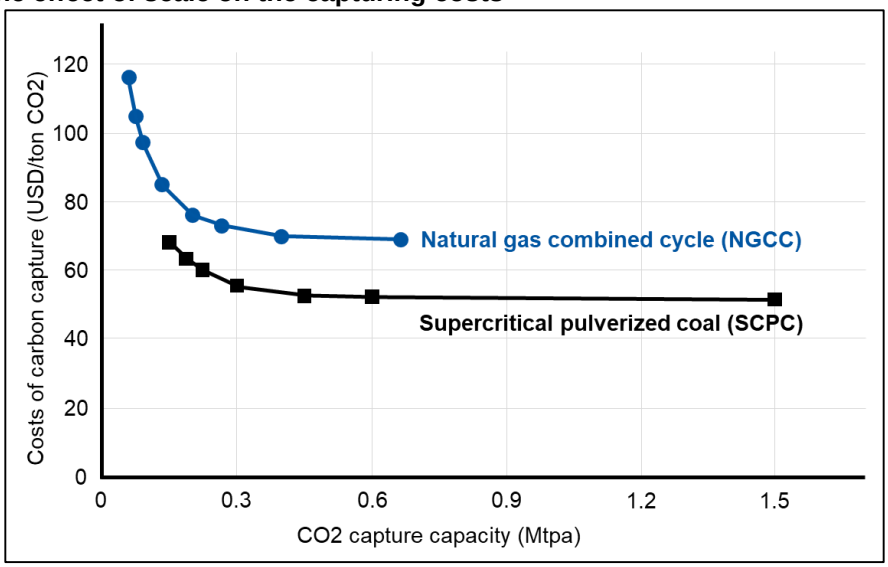
Therefore, the decision regarding the technology to be adopted is not easy and incurs various risks due to the many aspects to be considered. For the cement industry, some research projects have already been conducted in order to define suitable technologies. The CEMCAP project[30] identified five potential capturing technologies for the cement industry (amine scrubbing, chilled ammonia, oxyfuel, membrane-assisted CO_2 liquefaction and calcium looping). Amine scrubbing and chilled ammonia are based on the same mechanism (absorption) but they use different materials (monoethanolamine (MEA) and chilled ammonia respectively). The membrane-assisted CO_2 liquefaction is a tail-end technology and captures CO_2 via polymeric membranes and then liquefies and purifies the captured stream. The technology of calcium looping is available in two different configurations (tail-end and integrated) and captures CO_2 via the carbonation and calcination reactions ($CaCO_3 \leftarrow\rightarrow CaO + CO_2$).

[28] Leeson, D., Mac Dowell, N., Shah, N., Petit, C., and Fennell, P. S. (2017). A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources. *International Journal of Greenhouse Gas Control*, *61*, 71–84. https://doi.org/10.1016/j.ijggc.2017.03.020
Terlouw, W. et al. (2019). Gas for Climate. The optimal role for gas in a net zero emissions energy system
[29] Anantharaman, R., et al. (2018). CEMCAP comparative tech-economic analysis of CO2 capture in cement plants
Leeson, D. et al. (2017). https://doi.org/10.1016/j.ijggc.2017.03.020
Terlouw, W. et al. (2019). Gas for Climate. The optimal role for gas in a net zero emissions energy system
[30] Anantharaman, R. et al. (2018). CEMCAP comparative tech-economic analysis of CO2 capture in cement plants

As can be seen, these technologies belong to different mechanisms and generations. Hence, the operator will have enough flexibility to select the technology suitable for the plant conditions. The cement industry has been testing various technologies in different regions. For example: the Brevik CCS project - absorption; CO2MENT - adsorbtion; ACCSESS - enzyme-based CO_2 capture; and Cleanker - calcium looping.[31] The current research and pilot projects will increase the efficiency and decrease the associated costs, especially of emerging technologies. Having a limited number of technologies and higher demand for CO_2-capture technologies can open the door for modularization and consequently lower CAPEX.[32]

Similar to any industrial facility, scale also has a major impact on the costs, regardless of the technology adopted. As shown in Figure 11, the economies of scale significantly influence the capturing costs of the small capacities (i.e. lower than 300 kt CO_2 pa).[33] For medium and large capacities (i.e. higher than 300 kt CO_2 pa) the costs are roughly constant and scale has no major effect. As shown in Figure 3, all clinker producers in NRW roughly exceed this number if total emissions are considered. If only the process emissions are considered, then half of the producers would exceed this threshold.

Figure 11: The effect of scale on the capturing costs



Source: Author's interpretation based on James et al. (2019) and Kearns et al. (2021)[34]

3.2.2 Electrification

Instead of carbon capture, electrification or plasma burners offer the possibility of eliminating CO_2 emissions of fuels as well as generating a pure CO_2 stream. In this regards, an important study was started in 2019 in Sweden (CemZero project) and carried out by Cementa and Vattenfall.[35] One of the key conclusions of this feasibility study was that moving from conventional production methods to

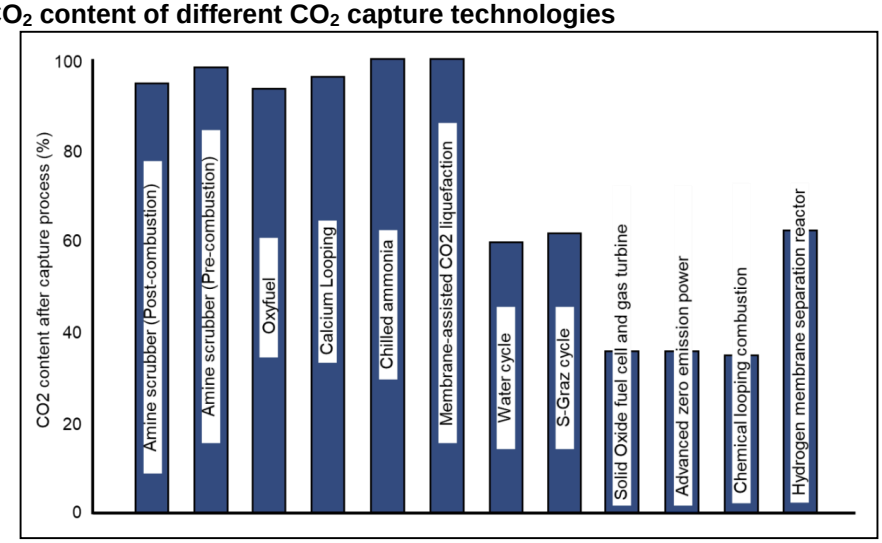
[31] Perilii, D. (2021). *CCS: CO2 capture & storage in cement*. https://www.globalcement.com/magazine/articles/1232-ccs-co2-capture-storage-in-cement
Plaza, M. G., Martínez, S., and Rubiera, F. (2020). CO2 Capture, Use, and Storage in the Cement Industry: State of the Art and Expectations. *Energies*, *13*(21), 5692. https://doi.org/10.3390/en13215692
[32] Kearns, D. et al. (2021). Technology readiness and costs of CCS. Global CCS Institute
[33] James, R., Zoelle, A., Keaims, D., Turner, M., Woods, M., and Koehn, N. (2019). Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity
Kearns, D. et al. (2021). Technology readiness and costs of CCS. Global CCS Institute
[34] James, R. et al. (2019) and Kearns, D. et al. (2021)
[35] Cementa (2019). Cementa and Vattenfall take the next step towards a climate neutral cement
Klugman, S., Stripple, H., Lönnqvist, T., Sandberg, E., and Krook-Riekkola, A. (2019). A climate neutral Swedish industry – An inventory of technologies
Nurdiawati, A., and Urban, F. (2021). Towards Deep Decarbonisation of Energy-Intensive Industries: A Review of Current Status, Technologies and Policies. *Energies*, *14*(9), 2408. https://doi.org/10.3390/en14092408

electrification would double production costs. Nonetheless, avoiding the capturing costs suggests that the technology can achieve cost savings in the future when CO_2 capture becomes an indispensable part of any clinker plant. Similarly, some projects have started to investigate the potential for incorporating green hydrogen in the fuel-mix.[36] The availability and price of these renewable resources (i.e. renewable electricity or green hydrogen) will be decisive for the development of each route. For example, the power system in Sweden (or generally the Scandinavian countries) and the availability of renewable energy can make electrification a suitable technology.

3.2.3 Purification and compression

Capturing CO_2 from flue gas doesn't directly imply that it is ready for the next phases (i.e. transportation and storage). Normally it has to meet certain specifications (e.g. minimum purity, composition, etc.).[37] Higher levels of impurities can cause corrosion in the pipeline system, which implies that the operators have to either get CO_2 with higher purity or establish a network with better steel specifications.[38] Moreover, impurities can trigger several risks during the storage phase (e.g. leakage, mineral dissolution, erosion, etc.).[39] As depicted in Figure 12, capture technologies do not have the same performance in terms of the final CO_2 purity. Therefore, depending on the technology adopted, the producers may need an additional purification phase before compression and transportation. The selection of capture and purification technologies will not only depend on the costs but also on the required specifications.

Figure 12: CO_2 content of different CO_2 capture technologies



Source: Author's work based on Augustsson et al. (2017), Berstad et al. (2017), Cormos and Petrescu (2014), Lombardo et al. (2014), Murugan et al (2020), Terlouw et al (2019)[40]

[36] Frangoul, A. (2021). *Cement giants turn to green hydrogen and carbon capture in efforts to curb emissions*. https://www.cnbc.com/2021/02/15/cement-giants-turn-to-green-hydrogen-carbon-capture-to-curb-emissions.html
HeidelbergCement. (2020). *HeidelbergCement researches use of climate-neutral fuels in the United Kingdom*. https://www.heidelbergcement.com/en/pr-26-02-2020

[37] Murugan, A., Brown, R. J. C., Wilmot, R., Hussain, D., Bartlett, S., Brewer, P. J., Worton, D. R., Bacquart, T., Gardiner, T., Robinson, R. A., and Finlayson, A. J. (2020). Performing Quality Assurance of Carbon Dioxide for Carbon Capture and Storage. *C*, *6*(4), 76. https://doi.org/10.3390/c6040076

[38] Hafez, A., and Fateen, S. E. K. (2016). CO2 transport and storage technologies
ZEP (2011). The Costs of CO2 Transport - Post-demonstration CCS in the EU. Zero Emissions Platform (ZEP)

[39] Brownsort, P. A. (2019). Briefing on carbon dioxide specifications for transport. 1st report of the thematic working group on: CO2 transport, storage and networks
IEAGHG (2011). Effects of impurities on geological storage of CO2

[40] Augustsson, O., Baburao, B., Dube, S., Bedell, S., Strunz, P., Balfe, M., and Stallmann, O. (2017). Chilled Ammonia Process Scale-up and Lessons Learned. *Energy Procedia*, *114*, 5593–5615. https://doi.org/10.1016/j.egypro.2017.03.1699
Berstad, D., Anantharaman, R., Van Os, P., and Vercauteren, F. (2017). Membrane-assisted CO2 liquefaction. 2nd ECRA/CEMCAP workshop - Carbon capture technologies in the cement industry

Despite the significant influence of CO_2 on the whole supply chain, there is neither consensus on the required specifications nor official standards. As shown in Table 2, while the purity of the CO_2 used for Enhamced Oil Recovery (EOR) operations in USA is not very high (≈96%) and contains considerable proportions of inerts, recent CCS studies[41] favour very high purity (food-grade CO_2) with low amounts of impurities. Although the CO_2 purity of capture technologies in cement industry (e.g. amine scrubbing, calcium looping, etc.) is high (≈98%, Figure 12), it is not high enough to meet such elevated standards without an additional purification phase.

Lack of official standards in terms of the specifications required for geological storage can increase the uncertainties for cement producers, as, with a wide range of available options, they lack guidance for making investment decisions. Moreover, imposing stricter specifications than required as a precautionary action could also negatively affect technology deployment as producers may not be motivated to invest due to the higher costs. For example, according to research by Kolster et al.[42] , the costs of purifying the CO_2 stream (≈100%) and compressing it (≈100 bar) could cost up to €20/ton CO_2.

Table 2: Different CO2 specifications/requirements for CCS

Component	Murugan et al., 2020			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					

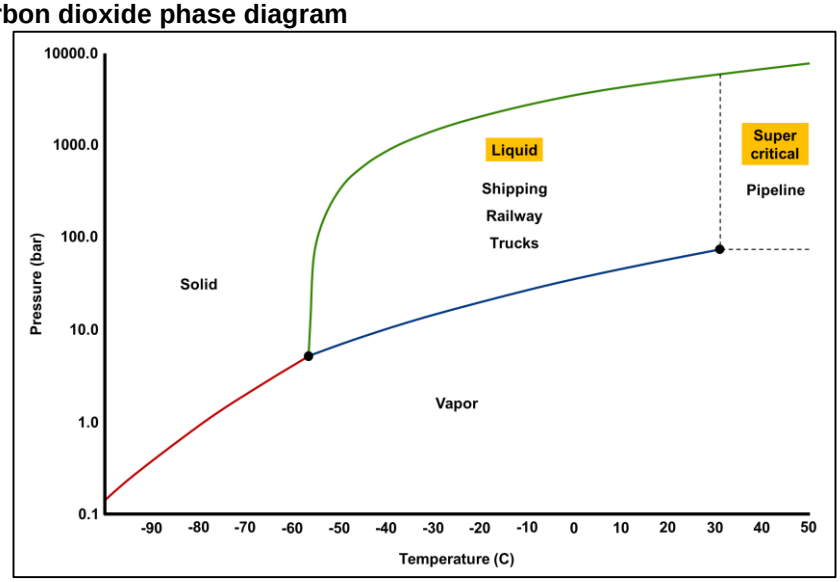
Source: Author's work based on Murugan (2020), Posch and Haider (2012) and Visser (2008)[43]

Cormos, C.-C. and Petrescu, L. (2014). Evaluation of Calcium Looping as Carbon Capture Option for Combustion and Gasification Power Plants. *Energy Procedia*, *51*, 154–160. https://doi.org/10.1016/j.egypro.2014.07.017
Lombardo, G., Agarwal, R., and Askander, J. (2014). Chilled Ammonia Process at Technology Center Mongstad – First Results. *Energy Procedia*, *51*, 31–39. https://doi.org/10.1016/j.egypro.2014.07.004
Murugan, A., Brown, R. J. C., Wilmot, R., Hussain, D., Bartlett, S., Brewer, P. J., Worton, D. R., Bacquart, T., Gardiner, T., Robinson, R. A., and Finlayson, A. J. (2020). Performing Quality Assurance of Carbon Dioxide for Carbon Capture and Storage. *C*, *6*(4), 76. https://doi.org/10.3390/c6040076
Terlouw, W., Peters, D., Van Tilburg, J., Schimmel, M., Berg, T., Cihlar, J., Rehman Mir, G. U., Spöttle, M., Staats, M., Lejaretta, A. V., Buseman, M., Schenkel, M., Van Hoorn, I., Wassmer, C., Kamensek, E., and Fichter, T. (2019). Gas for Climate. The optimal role for gas in a net zero emissions energy system
[41] Murugan, A. et al. (2020) https://doi.org/10.3390/c6040076
[42] Kolster, C., Mechleri, E., Krevor, S., and Mac Dowell, N. (2017). 'The role of CO 2 purification and transport networks in carbon capture and storage cost reduction'. *International Journal of Greenhouse Gas Control*, *58*, 127–141. https://doi.org/10.1016/j.ijggc.2017.01.014
[43] Murugan, A. et al. (2020) https://doi.org/10.3390/c6040076

3.2.4 CO_2 transportation

In order to transport captured CO_2 from source to sink, various modes can be used (e.g. pipelines, shipping, railway and trucks). As well as purity, the phase of CO_2 is also a crucial factor in the transportation process. As the gaseous phase is associated with very high transportation costs due to the low flow rate, CO_2 is normally transported in a liquid or super-critical phase. As shown in Figure 13, the CO_2 phase is a function of pressure and temperature. The liquid phase (shipping, railway and trucks) requires a low temperature and low pressure. For the super-critical phase (pipeline) high temperature and high pressure are needed. Maintaining the same phase while transporting CO_2 is also essential, otherwise it can lead to various technical problems. Therefore, there are usually booster stations along the pipeline network in order to keep the pressure higher than the threshold.[44]

Figure 13: Carbon dioxide phase diagram



Source: Author's interpretation based on ChemicaLogic (2021)[45]

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 flow rates respectively. Establishing a pipeline network is normally associated with high investments, therefore, having high flow rates is essential in order to lower the unit cost (€/ton) as shown in Figure 14 (A). For extremely long distances (e.g. > 1500 km), pipelines can be more expensive than shipping even with high flow rates as shown in Figure 14 (B). On the other hand, road and railway are more expensive and are only efficient for transporting low amounts of CO2 (for shorter distances).[46] A truck can load up to 25 tons at a cost of €9.2/ton per 100 km and a train can tow up to 18 wagons (each wagon can load up to 60 tons) at a cost of €5.5/ton per 100 km.[47] Unlike pipelines and shipping, trucks and railways are more flexible and can easily change their endpoints and reach more destinations. It is worth mentioning that the transportation

Posch, S., and Haider, M. (2012). 'Optimization of CO2 compression and purification units (CO2CPU) for CCS power plants'. *Fuel*, *101*, 254–263. https://doi.org/10.1016/j.fuel.2011.07.039

Visser, E. de, Hendriks, C., Barrio, M., Mølnvik, M. J., Koeijer, G. de, Liljemark, S., and Le Gallo, Y. (2008). 'Dynamis CO2 quality recommendations'. *International Journal of Greenhouse Gas Control*, *2*(4), 478–484. https://doi.org/10.1016/j.ijggc.2008.04.006

[44] Mohammadi, M., Hourfar, F., Elkamel, A., and Leonenko, Y. (2019). 'Economic Optimization Design of CO 2 Pipeline Transportation with Booster Stations'. *Industrial & Engineering Chemistry Research*, *58*(36), 16730–16742. https://doi.org/10.1021/acs.iecr.9b02348

[45] ChemicaLogic (2021). Carbon dixoide phase diagram

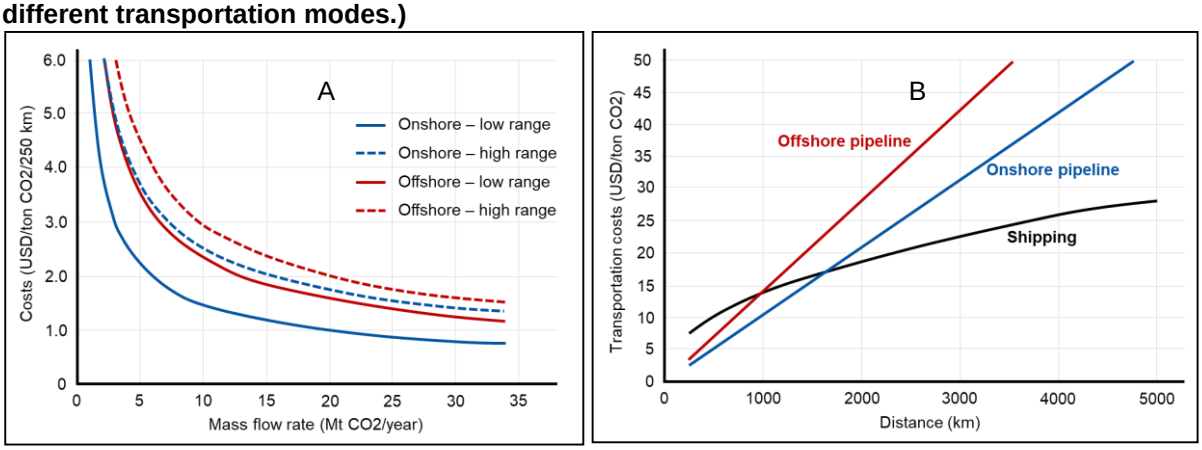
[46] Coal21 (2021). Carbon capture and storage: Transporting CO2 https://coal21.com/wp-content/uploads/2018/05/Coal21Fund_Fact_Sheet_-_Carbon_Capture_and_storage_-_Transporting.pdf

GCCSI (2021a). Fact sheet: Transporting CO2. Global CCS Institute (GCCSI)

[47] Eckle, P. (2019). CO2-Transport

mode is not the only system component; other supportive facilities are needed in order to ensure an efficient system (e.g. buffer storage, loading & unloading, etc.).

Figure 14: CO2 transportation costs (A: flow rate of pipeline vs. costs. B: distance vs. costs of different transportation modes.)

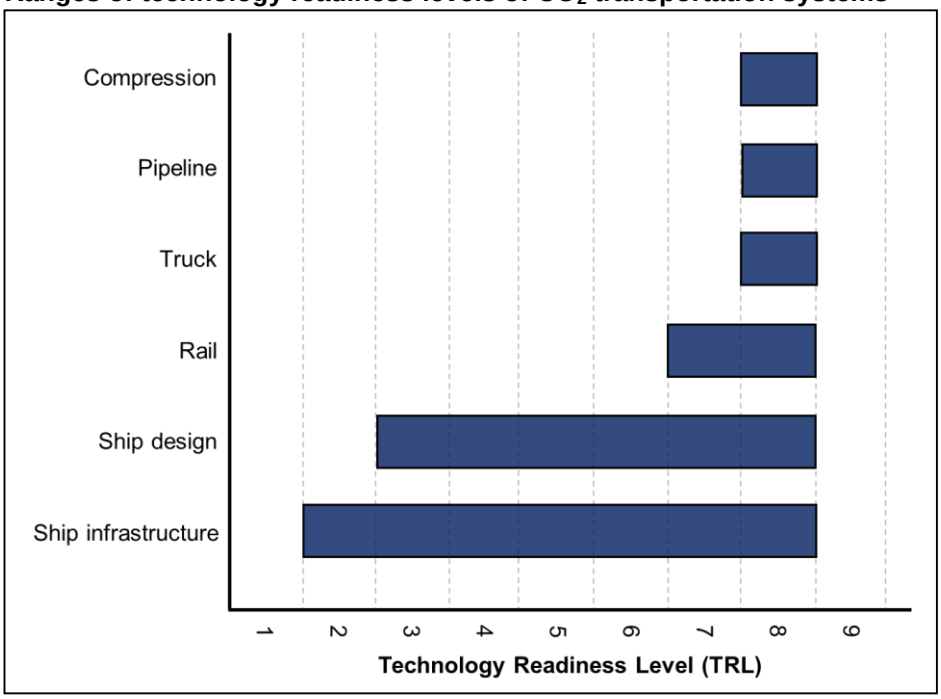


Source: Author's interpretation based on Brownsort (2015) and Richard (2005)[48]

Unlike CO_2 capture, transportation technologies have high TRLs (Figure 15) due to decades of experience in different sectors. CO_2 compression and pipelines have been extensively used by the US EOR industry and transporting CO_2 by trucks is also common in the food industry. Regarding CO_2 shipping, there is already experience in this due to LNG and LPG shipping. However, although the main elements should be analogous, retrofitting the current LNG and LPG carriers is not always possible as the required conditions are not identical (e.g. temperature and pressure).[49] Transporting CO_2 via ship is currently not very common, there are around six tankers in Europe with capacities between 900 and 1800 tons.[50] Such capacities will definitely be too small for future CO_2 volumes and bigger vessels will be needed. Some studies[51] have introduced designs for CO_2 vessels with capacities up to 105 kt.

[48] Brownsort, P. (2015). Ship transport of CO2 for enhanced oil recovery - Literature survey
Richard, D., Palmer, A., Coleman, D., Davison, J., Hendriks, C., Kaarstad, O., Ozaki, M., Austell, M., Pichs-Madruga, R., and Timashev, S. (2005). Transport of CO2 -Carbon dioxide capture and storage. Intergovernmental Panel on Climate Change (IPCC)
https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf
[49] ZEP (2017). Future CCS technologies. Zero Emissions Platform (ZEP)
[50] Brownsort, P. (2015). Ship transport of CO2 for enhanced oil recovery - Literature survey
[51] Durusut, E., & Joos, M. (2018). Shipping CO2 - UK cost estimation study
Yoo, B.-Y., Choi, D.-K., Kim, H.-J., Moon, Y.-S., Na, H.-S., and Lee, S.-G. (2013). 'Development of CO2 terminal and CO2 carrier for future commercialized CCS market'. *International Journal of Greenhouse Gas Control*, *12*, 323–332. https://doi.org/10.1016/j.ijggc.2012.11.008

Figure 15: Ranges of technology readiness levels of CO_2 transportation systems



Source: Author's interpretation based on Kearns (2021)[52]

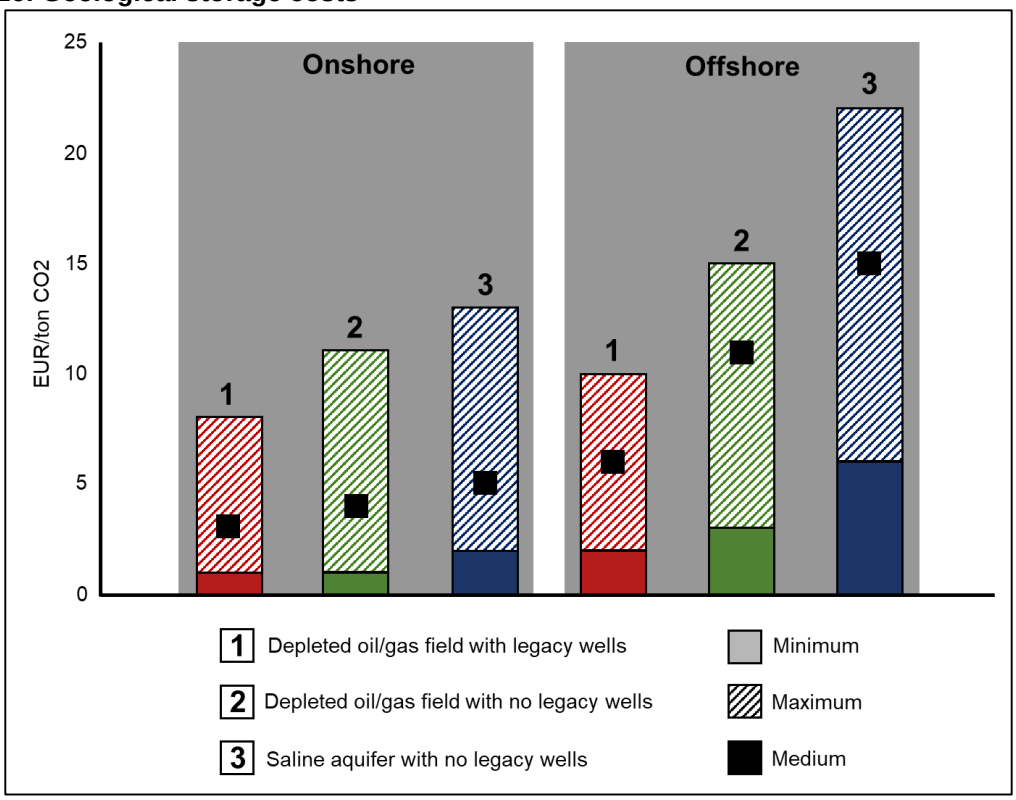
3.2.5 CO_2 geological storage

CO_2 geological storage refers to storing captured CO_2 permanently underground and ensure that it will not get back into the atmosphere. Carbon dioxide can be geologically stored in various formations, nonetheless, two mediums have caught the attention of CCS studies due to their available capacities (i.e. depleted oil and gas fields and saline aquifers). In terms of the mechanism, CO_2 is geologically trapped via three mechanisms, namely physical (relevant for depleted oil and gas fields), residual and solubility trapping (associated with saline aquifers).[53]

Each storage site has its own characteristics which need to be studied and handled differently. Hence, although CO_2 injection and storage has a high TRL due to the EOR operations, exploring and securing a storage site is a time-consuming process and takes years.[54] Therefore, due to the characterization, infrastructure and monitoring costs, the economies of scale also influence geological storage (i.e. the bigger the reservoir capacity, the lower the specific storage costs).[55] The uniqueness of each storage site can also explain the lack of agreement on the costs of CO_2 storage. Figure 16 shows the range of CO_2 storage costs reported by Terlouw in 2019.

[52] Kearns, D., Liu, H., and Consoli, C. (2021). Technology readiness and costs of CCS. Global CCS Institute
[53] Anderson, S. T. (2017). 'Risk, Liability, and Economic Issues with Long-Term CO2 Storage—A Review'. *Natural Resources Research*, *26*(1), 89–112. https://doi.org/10.1007/s11053-016-9303-6
Hafez, A., and Fateen, S. E. K. (2016). CO2 transport and storage technologies
https://www.researchgate.net/publication/304251602_CO2_Transport_and_Storage_Technologies
[54] IEA (2013). Technology Roadmap Carbon Capture and Storage
[55] Terlouw, W. et al. (2019). Gas for Climate. The optimal role for gas in a net zero emissions energy system.
https://gasforclimate2050.eu/wp-content/uploads/2020/03/Navigant-Gas-for-Climate-The-optimal-role-for-gas-in-a-net-zero-emissions-energy-system-March-2019.pdf

Figure 16: Geological storage costs



Source: Author's work based on Terlouw (2019)[56]

As depicted, the expected costs range between €1/ton CO_2 and €22 EUR/ton CO_2. In general, offshore storage is more expensive than onshore storage which can be attributed to the challenges of the environment and the additional investment needed.[57] Nonetheless, offshore storage has lower social resistance being far from populated areas, than onshore storage. Also, using saline aquifers is more expensive than depleted oil and gas fields due to the extensive additional exploration and characterization costs. Moreover, the risks associated with saline aquifers are higher due to the lack of knowledge and experience whereas using depleted oil and gas fields benefits from decades of experience of CO_2 EOR operations. However, saline aquifers have a comparative advantage in terms of availability (i.e. total capacity) and the high individual capacity of each storage site.

In contrast to many conventional projects, the time horizon for CCS projects (especially CO_2 storage) is long. While CO_2 capture and transportation can take hours or days, CO_2 geological storage requires hundreds of years. It is important to highlight that 'CO_2 storage' is not a synonym for 'CO_2 injection'. The term geological storage implies that the injected CO_2 will be stored and remain there (forever). According to Farret et al.,[58] the lifetime of a CCS project can be split into three phases: (1) 0 – 50 years: this phase includes all the activities related to designing, construction of wells and CO_2 injection. (2) 50 – 250 years: this phase focuses on CO_2 and site monitoring. (3) 250 – 1250 years: during this phase, the storage well will be too old to be remembered. Nevertheless, geological events can still occur and the storage effectiveness should be observed and ensured.

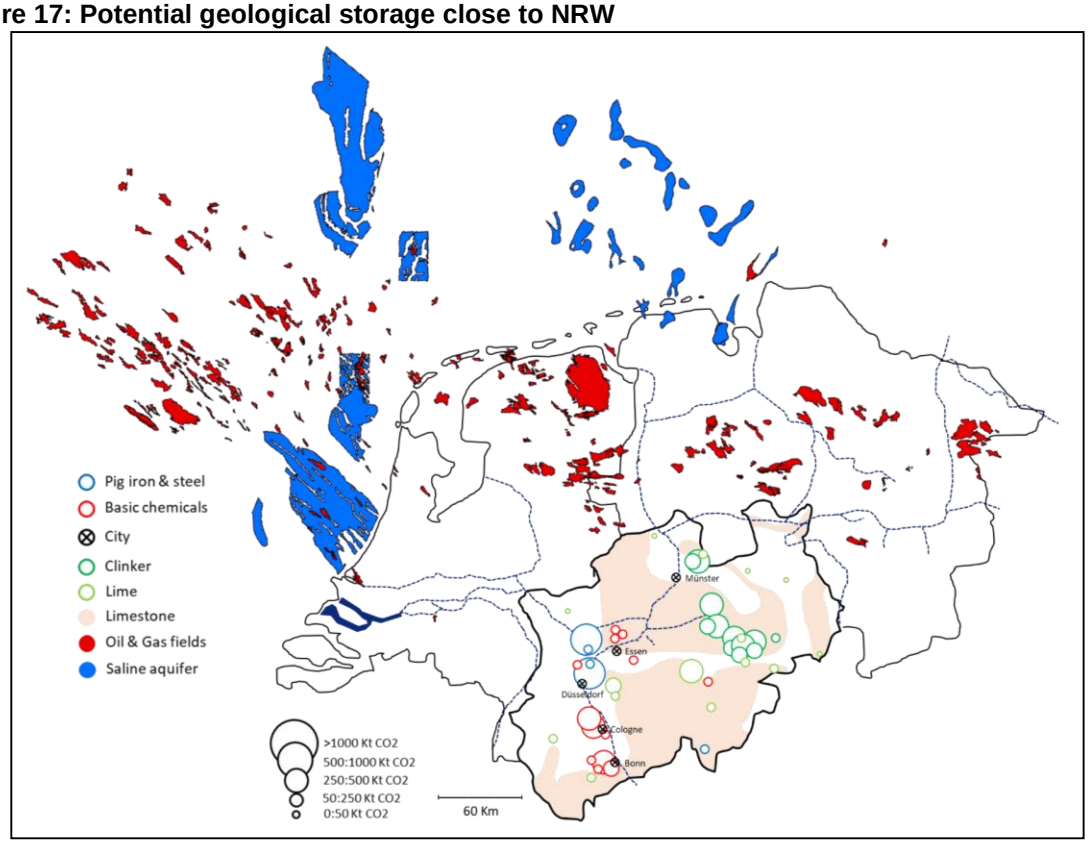
[56] Terlouw, W. et al. (2019). Gas for Climate. The optimal role for gas in a net zero emissions energy system
[57] Welkenhuysen, K. (2012). The cost of CO2 geological storage is more than a number
[58] Farret, R., Gombert, P., Lahaie, F., Cherkaoui, A., Lafortune, S., and Roux, P. (2011). 'Design of fault trees as a practical method for risk analysis of CCS: Application to the different life stages of deep aquifer storage, combining long-term and short-term issues'. *Energy Procedia*, *4*, 4193–4198. https://doi.org/10.1016/j.egypro.2011.02.366

In addition to the time scale, the storage stage is associated with more techno-economic risks and higher uncertainties than the first operational phases (i.e. capture and transportation). CO_2 storage does not only refer to CO_2 injection into the geological formation, but also to make sure that CO_2 will stay in the formation and will neither contaminate the underground water nor get back into the atmosphere. Despite the advancements in reservoir engineering, the possibility of such events is not zero and could take place either naturally or due to operational mistakes (e.g. exceeding the fracture pressure of the cap rock). Therefore, geological storage has always been a controversial theme due to the concerns related to leakage.

3.2.6 CO_2 geological storage in NRW

The main geological assessment regarding storage capacity in Germany has been implemented by the Federal Institute for Geoscience and Natural Resources (BGR).[59] In terms of onshore capacity, BGR only considered oil and gas fields with capacities higher than 5 Mt CO_2. For the saline aquifers, only those with capacities higher than 25 Mt CO_2 were counted. Based on this assessment, the German geological storage capacity is mainly concentrated in the North-West. As depicted in Figure 17, oil and gas fields are mainly located in Lower Saxony (total capacity ≈ 2.3 Gt CO_2) and saline aquifers in the North Sea (total capacity ≈ 2.8 Gt CO_2)[60] and there is no recorded geological storage capacity in NRW.

Figure 17: Potential geological storage close to NRW



Source: Author's work based on Poulsen (2014)[61]

[59] BGR. (2021). *CO2 Storage. Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)*. https://www.bgr.bund.de/EN/Themen/Nutzung_tieferer_Untergrund_CO2Speicherung/CO2Speicherung/co2speicherung_node_en.html
Knopf, S., and May, F. (2017). 'Comparing Methods for the Estimation of CO2 Storage Capacity in Saline Aquifers in Germany: Regional Aquifer Based vs. Structural Trap Based Assessments'. *Energy Procedia*, *114*, 4710–4721. https://doi.org/10.1016/j.egypro.2017.03.1605

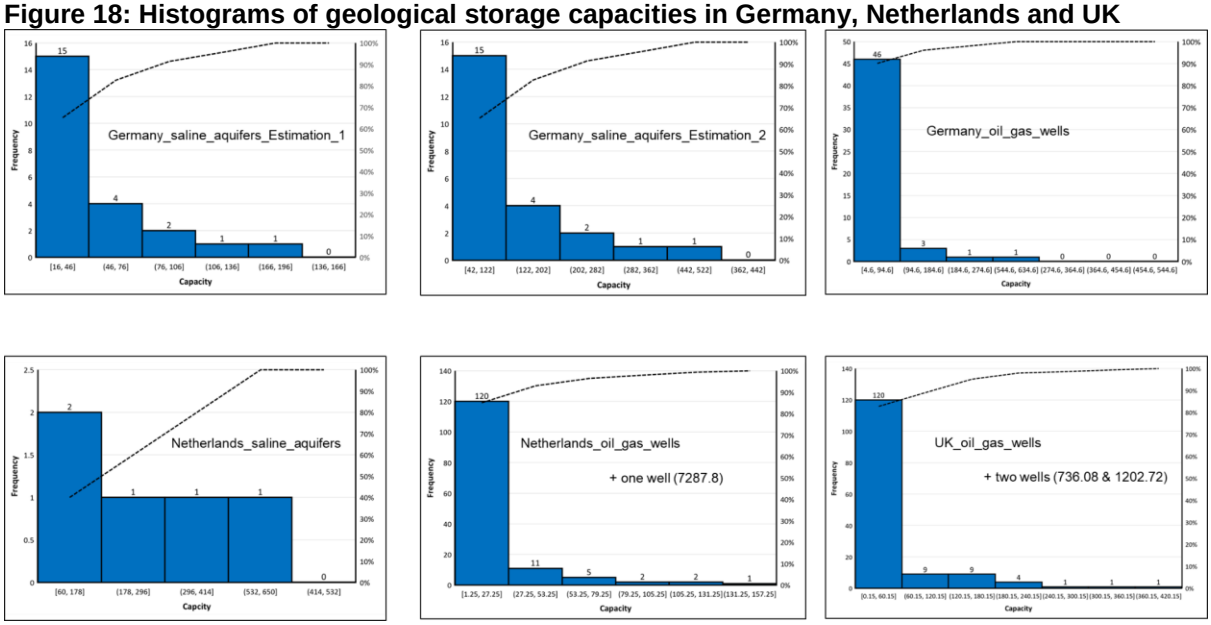
[60] Poulsen, N., Holloway, S., Neele, F., Smith, N. A., and Kirk, K. (2014). CO2StoP final report - Assessment of CO2 storage potential in Europe

[61] Poulsen, N. et al (2014). CO2StoP final report - Assessment of CO2 storage potential in Europe

Due to the lack of regional storage capacity, NRW has to depend on capacity in other regions. The location can also enable the cement industry to consider suitable storage capacity in neighbouring countries (e.g. the Netherlands and UK), especially if CO_2 shipping is considered as an interim transportation mode in the coming few years. There are ≈ 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.[62] Nonetheless, it should be noted that each country has its own methodology in quantifying available capacity. Moreover, such estimations are liable to modification in future assessments.

In terms of the individual capacities, these vary significantly between storage sites in the three countries. As depicted in Figure 18, 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). The number of identified oil and gas wells is significantly higher than saline aquifers but the capacity of the majority is very small. A storage site needs to be large enough to be economically efficient.[63] Hence, much seemingly available storage capacity may be economically inefficient, especially the small oil and gas fields in UK.

Figure 18: Histograms of geological storage capacities in Germany, Netherlands and UK



Source: Author's work based on Poulsen (2014)[64]

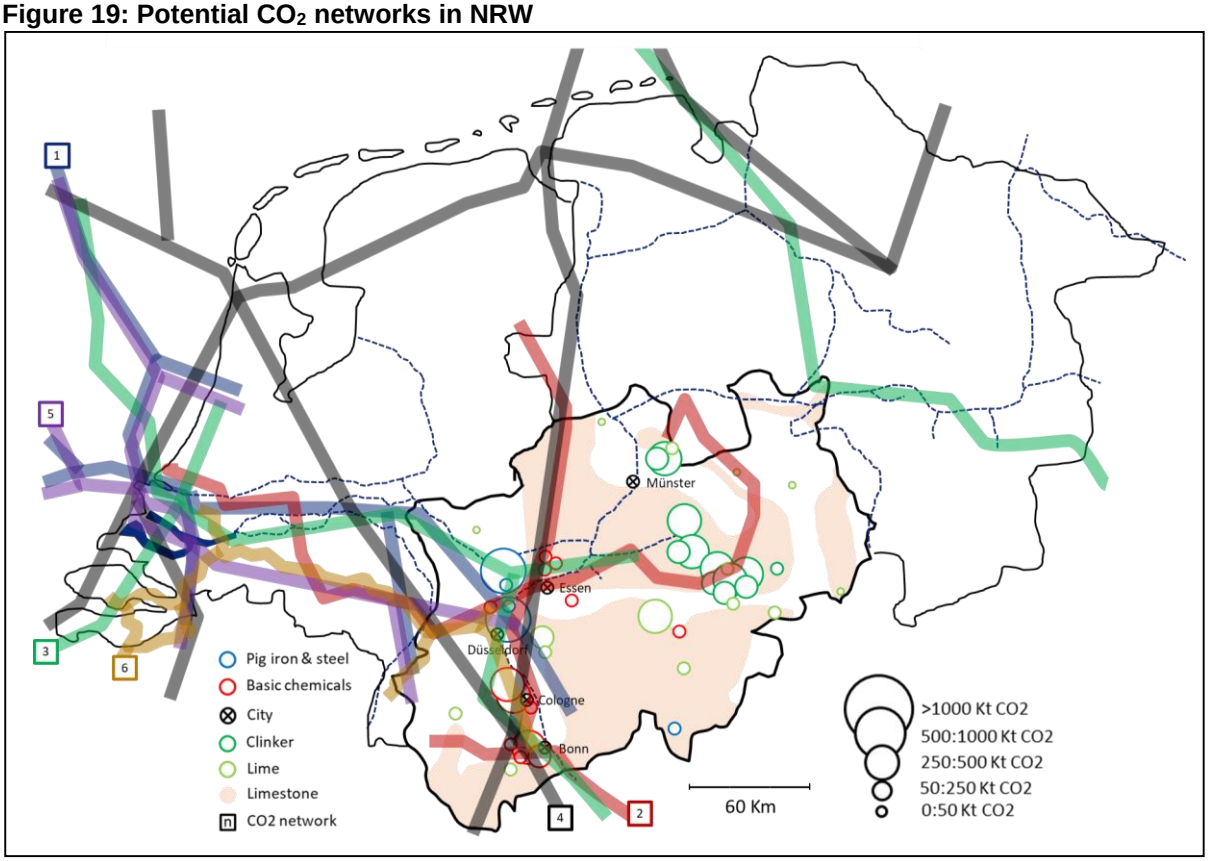
Linking CO_2 sources in NRW with geological CO_2 sinks in Netherlands, UK and Northwestern Germany could be achieved via a pipeline or shipping due to quantity and distance. The existence of industrial hubs is very important for establishing a common infrastructure as it can significantly reduce the costs due to economies of scale.[65] As Figure 17 shows, there are two obvious industrial clusters in NRW; (1) the steel and chemical industries which are close to the Ruhr area and Rhine river and (2) the cement industry which is clustered in the Northwestern part of the state.

As an important industrial hub, NRW has been already added to several studies related to building a European CO_2 backbone as shown in Figure 19. Such analyses normally have different assumptions and priorities (e.g. to cover all the emitters or to consider only the major ones, future emissions, storage sites, etc.). Nonetheless, there is consensus on the importance of having a CO_2 corridor between NRW and Rotterdam. All these concepts have focused on the industrial cluster close to the Ruhr area and only one has given any attention to the cement cluster. The cement producers are spatially disadvantaged as they are far from the main industrial cluster in the Ruhr. Moreover, they are also not

[62] Poulsen, N. et al (2014). CO2StoP final report - Assessment of CO2 storage potential in Europe
[63] Hafez, A., & Fateen, S. E. K. (2016). CO2 transport and storage technologies
[64] Poulsen, N. et al (2014). CO2StoP final report - Assessment of CO2 storage potential in Europe
[65] ZEP (2016). Identifying and developing European CCS hubs. Zero Emissions Platform (ZEP

close to the waterways in NRW which implies that the producers will have to develop a link to either the Ruhr (and then to Rotterdam/Netherlands) or to Northwestern Germany (e.g. Wilhelmshaven).

Figure 19: Potential CO_2 networks in NRW



Source: Author's work based on Benrath (2020), Binn (2021), Binnenschifffahrt Online (2021), EC (2021), Haszeldine (2009), Morbee (2010), PoR (2021), VDZ (2019), WV Stahl (2017) and ZEP (2013, 2016)[66]

3.2.6 CO_2 utilization

Instead of mitigating CO_2 emissions via geological storage, utilizing the CO_2 in producing other products is also a feasible alternative. Figure 20 shows that CO_2 utilization techniques can be classified in several ways (i.e. field of application, maturity and duration). In terms of applications, CO_2 can be used as an input in several industries (e.g. food, fuels, chemicals, etc.). These technologies have different levels of maturity (i.e. TRL) and also various CO_2 sequestration time spans (i.e. temporary, permanent and semi-

[66] Benrath, D., Flamme, S., Glanz, S., and Hoffart, F. M. (2020). CO2 and H2 infrastructure in Germany - Final report of the German case study
Binn, J. (2021). Hafen Rotterdam prüft Pipeline nach NRW. https://aha24x7.com/hafen-rotterdam-prueft-pipeline-nach-nrw/
Binnenschifffahrt Online (2021). Rotterdam prüft Pipeline bis NRW - Binnenschifffahrt Online. https://binnenschifffahrt-online.de/2021/07/seehaefen/21061/rotterdam-prueft-pipeline-bis-nrw
EC (2020). European Union Transaction Log. The European Comission
Haszeldine, R. S. (2009). Carbon capture and storage: How green can black be? *Science (New York, N.Y.)*, *325*(5948), 1647–1652. https://doi.org/10.1126/science.1172246
Morbee, J., Serpa, J., and Tzimas, E. (2010). The evolution of the extent and the investment requirements of trans-European CO2 transport network
PoR (2021). Wasserstoffwirtschaft in Rotterdam beginnt mit Backbone. Port of Rotterdam (PoR)
VDZ (2019). Zementindustrie im Überblick 2019/2020. Verein Deutscher Zementwerke e.V
WV Stahl (2017). Fakten zur Stahlindustrie in Deutschland. Wirtschaftsvereinigung Stahl
ZEP (2013). Building a CO2 transport infrastructure for Europe. Zero Emissions Platform (ZEP).
ZEP (2016). Identifying and developing European CCS hubs. Zero Emissions Platform (ZEP)

permanent). Reaching carbon neutrality necessitates using permanent carbon sinks. Relying on temporary or semi-permanent sinks implies delaying the challenges associated with process emissions. Hence, mineralization and carbonation may be more relevant for the cement industry. Both technologies are based on fixing captured CO_2 into certain minerals and cementitious materials by means of reacting with the oxides present in them. Minerals (e.g. olivine, serpentine) and cementitious materials (e.g. concrete and construction waste) contain various oxides that can react with CO_2 under certain conditions (e.g. pressure, temperature, humidity, etc.) and form stable compounds (i.e. carbonates) as illustrated in eq. 1 – eq. 4.

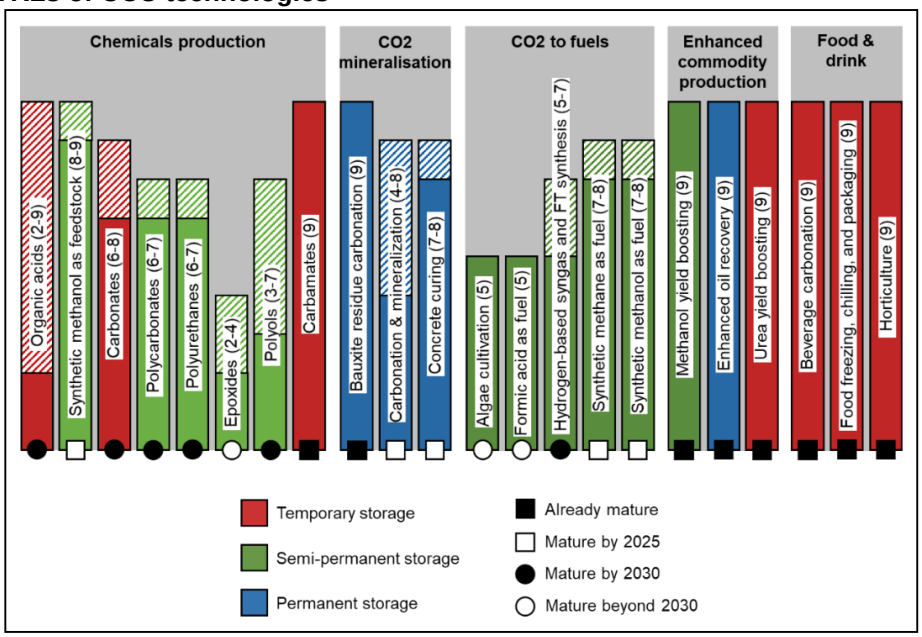
$$MgSiO_4 + CO_2 \rightarrow 2MgCO_3 + SiO_2 \quad (1)$$

$$Mg_3Si_2O_5(OH)_4 + 3CO_2 \rightarrow 2MgCO_3 + 2SiO_2 + H_2O \quad (2)$$

$$3CaO.2SiO_2.H_2O + 3CO_2 \rightarrow 3CaCO_3 + 2SiO_2 + 3H_2O \quad (3)$$

$$4CaO.Al2O_3.13H_2O + 4CO_2 \rightarrow 4CaCO_3 + 2Al(OH)_3 + 10H_2O \quad (4)$$

Figure 20: TRLs of CCU technologies



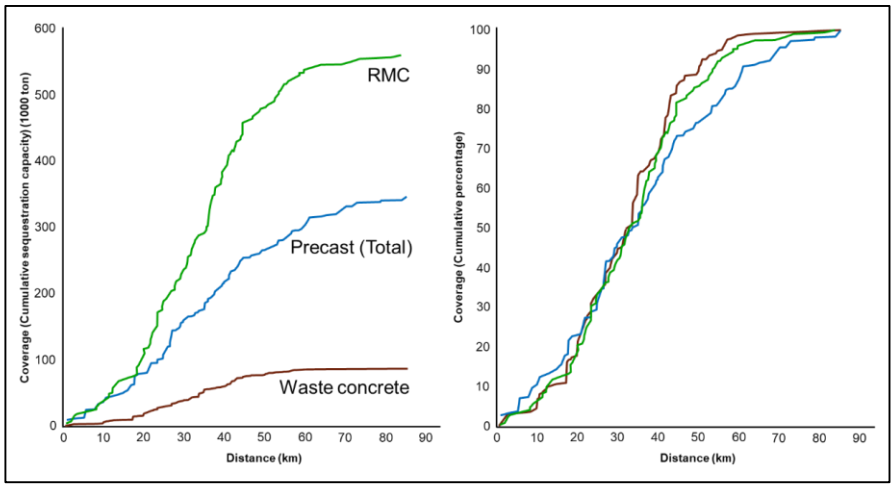
Source: Author's interpretation based on Alberici (2017), Bassanella (2017), Terlouw (2019)[67]

The value chains of mineralization and carbonation are different from CCS; firstly, the scale of CCS projects should be very large and centralized due to the reasons already mentioned. By contrast, the scale of carbonation projects is relatively small due to the size of concrete and recycling plants. In general, the minerals suitable for CO_2 sequestration are not available in NRW and Germany which implies that they will have to be imported and transported close to the emission sources. In terms of carbonation, relying on domestic resources (i.e. cementitious products and waste concrete) would be more reasonable. As precast concrete producers and recyclers cannot easily change their locations, the emitters have to transport their captured CO_2 to their facilities. Also, as the production and recycling plants are spatially distributed, the CO_2 will have to be transported via small-scale transportation means (e.g. trucks) which are associated with high costs. Therefore, unlike transporting CO_2 for geological

[67] Alberici, S., Noothout, P., Rehman Mir, G. U., Stork, M., Wiersma, F., Mac Dowell, N., Shah, N., and Fennell, P. (2017). Assessing the potential of CO2 utilisation in the UK
Bazzanella, A. M., Ausfelder, F., and DECHEMA (2017). Low carbon energy and feedstock for the European chemical industry
Terlouw, W. et al. (2019). Gas for Climate. The optimal role for gas in a net zero emissions energy system

storage via pipeline or shipping, the location of emitters and concrete and recycling plants can significantly influence the supply chain. As shown in Figure 21, there is up to one million tons sequestration capacity via carbonation in NRW but captured CO_2 has to be transported up to 90 km.[68]

Figure 21: The relationship between distance and sequestration capacities of cementitious materials in NRW



Source: Abdelshafy & Walther, (2022a)

4. Economic, regulatory and social challenges

The challenges associated with CCUS are not limited to the technical aspects discussed earlier. Other social, economic and regulatory challenges exist and need to be tackled. Although the concept of technology readiness level has been widely used to assess the maturity of various technologies and applications, other indices have been introduced in order to address the other aspects (e.g. economic, social, etc.).[69] While the technology readiness level focuses on the technical aspects, commercial readiness level (CRL) evaluates the commercial maturity via a scale of six levels. Similarly, social readiness level (SRL) assesses how much society is willing to accept or adopt the new technology. Table 3 compares technology, commercial and social readiness levels for different CCUS technologies.[70] Although commercial and social readiness levels may not be the same in all regions, this comparison highlights the lag between technological advancement and commercial and social preparedness. In the following sections the main reasons behind this gap and how it can be addressed are discussed.

[68] Abdelshafy, A., and Walther, G. (2022a). Coupling carbon capture and utilization with the construction industry: Opportunities in Western Germany. *Journal of CO2 Utilization*, *57*, 101866. https://doi.org/10.1016/j.jcou.2021.101866

[69] ARENA (2014). Commercial Readiness Index for Renewable Energy Sectors. Australian Renewable Energy Agency (ARENA)

IEA RETD TCP (2017), Commercial Readiness Index Assessment – Using the method as a tool in renewable energy policy design (RE-CRI), IEA Renewable Energy Technology Deployment Technology Collaboration Programme (IEA RETD TCP), Utrecht, 2017
http://iea-retd.org/wp-content/uploads/2017/06/IEA-RETD-RE-CRI-Report.pdf

Bruno, I., Lobo, G., Covino, B. V., Donarelli, A., Marchetti, V., Panni, A. S., and Molinari, F. (2020). Technology readiness revisited: a proposal for extending the scope of impact assessment of European public services. https://doi.org/10.1145/3428502.3428552

REEEM (2017). Innovation readiness level report - Energy storage technologies

[70] NPC (2019). Meeting the dual challenge - A roadmap to at-scale deployement of carbon capture, use, and storage - Volume I - Report summary (A report of the National Petroleum Council)

UNECE (2021). Technology brief - Carbon capture, use and storage (CCUS)

Table 3: Comparison between technology, commercial and social readiness levels of CCUS technologies[71]

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

Source: Author's intepretation based on NPC (2019), UNECE (2021)[72]

4.1 Economic, commercial and legislative challenges

Several aspects of CCUS technologies are innovative, therefore there are various uncertainties and risks. The uncertainties associated with CCUS can be classified in several ways (e.g. **location:** surface or underground, **time:** short-term or long-term and **severity:** low and high).[73] The following sections focus on the high-severity risks (i.e. hard-to-mitigate or control).

4.1.1 Long-term liability (CO_2 leakage)

As discussed in 3.2.5, there are several reasons for CO_2 leakage (e.g. through the caprock, injection well or other connected wells.[74] Each geological storage site is unique and the risk of fracture due to pressure build-up will exist in each site which can behave differently. Although the risk decreases after

[71] The TRL of some technologies reported by UNECE (2021) can be lower than the actual values. For example, the oxy-fuel technology is now used in some projects, which implies that its TRL should be higher than 4. However, this doesn't influence the main conclusion of the table

[72] NPC (2019). Meeting the dual challenge - A roadmap to at-scale deployement of carbon capture, use, and storage - Volume I - Report summary (A report of the National Petroleum Council)
UNECE (2021). Technology brief - Carbon capture, use and storage (CCUS)

[73] Farret, R. et al (2011). https://doi.org/10.1016/j.egypro.2011.02.366
GCCSI (2021b). Unlocking private finance to support CCS investments. Global CCS Institute (GCCSI)
Oraee-Mirzamani, B., Cockerill, T., and Makuch, Z. (2013). Risk Assessment and Management Associated with CCS. *Energy Procedia*, *37*, 4757–4764. https://doi.org/10.1016/j.egypro.2013.06.385
Zapantis, A., Townsend, A., and Rassool, D. (2019). Policy prorities to incentivise the large scale deployment of CCS. Global CCS Institute

[74] Farret, R. et al (2011). https://doi.org/10.1016/j.egypro.2011.02.366
Oraee-Mirzamani, B. et al (2013). https://doi.org/10.1016/j.egypro.2013.06.385

the injection phase ceases, it does not disappear and will always exist.[75] Despite the know-how of reservoir engineering gathered in the last decades and high simulation capabilities, the certainty of no fracture/leakage cannot be guaranteed. From a state or policymaker perspective, imposing a clear accountability on the operators is important for minimizing public opposition and making sure the highest levels of safety and quality are applied. According to the EU directive (2009/31/EC), liability transfer should not occur before 20 years, with high requirements in terms of characterization and monitoring. [76]

Unlike most existing industries, the time horizons of CSS projects (more specifically the storage phase) are extremely long. Fulfilling such strict requirements implies that future generations of a company will have to burden huge responsibilities. Such enormous and undefined liability will certainly restrain private entities (e.g. investors, insurers, etc.) from entering the CCS business. Although science can give some assurances regarding the effectiveness of technologies, some uncertainties will always remain. Hence, the main question is: who should bear the risks? And for how long? Indefinite liability will inhibit the industrial sector, investors and insurers from developing CCS projects.[77] The state needs to find a good balance by taking a share in the responsibility, especially in the long term, while allocating as much liability as possible to the private sector (which could make the CCS business still attractive and profitable).

4.1.2 Cross-chain interdependency and monopolies

The CCS supply chain is composed of successive phases (capture, transportation, storage) which are operated by various stakeholders. Dealing with enormous amounts of CO_2 with different specifications and sourced from various emitters needs a high level of coordination and harmony.[78] The CO_2 infrastructure should be designed with optimal parameters in order to minimize the costs as any disorder at any point can significantly influence the whole supply chain. For example, any failure at any CO_2 capturing point will make the transportation system run with lower capacities. Or if any problem takes place at any point along the transportation system, the captured CO_2 may end up in the atmosphere instead of the geological sink.

Focusing on industrial clusters could be a suitable approach to address this challenge.[79] Industrial clusters not only offer efficiency in terms of transportation costs due to the existence of many emitters in the same vicinity, but also flexibility due to the availability of different categories of emitters, as well as the ability to coordinate them. Additionally, having a good number of stakeholders in the same area can help in applying risk mitigation strategies (e.g. intermediate storage facilities). Nonetheless, this cross-chain risk would still exist and additional logistical and financial tools should be developed in order to minimize such risks. In this, NRW has a comparative advantage as an industrial hub; the regional producers have the opportunity to collaborate, realise synergies and minimize the risks.

Another issue related to the supply chain is the monopolistic nature of some phases.[80] For example, transportation and storage are normally administrated by one operator. Due to high investment costs, it would be risky for any competitor to enter the market as the initial operator will be more powerful and can provide cheaper services.[81] Therefore, free market principles cannot be applied and the role of

[75] Coninck, H. de, and Benson, S. M. (2014). Carbon Dioxide Capture and Storage: Issues and Prospects. *Annual Review of Environment and Resources*, *39*(1), 243–270. https://doi.org/10.1146/annurev-environ-032112-095222
[76] European Parliament (2009). Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/200
[77] Oraee-Mirzamani, B. et al (2013). https://doi.org/10.1016/j.egypro.2013.06.385
[78] GCCSI (2021b). Unlocking private finance to support CCS investments. Global CCS Institute (GCCSI)
[79] Zapantis, A., Townsend, A., & Rassool, D. (2019). Policy prorities to incentivise the large scale deployment of CCS. Global CCS Institute
[80] Zapantis, A., Townsend, A., & Rassool, D. (2019). Policy prorities to incentivise the large scale deployment of CCS. Global CCS Institute
[81] Whitmore, A., and Andreas, J. (2021). Models for transport and storage of captured CO2 - A review of some options. https://network.bellona.org/content/uploads/sites/3/2021/06/2021-Models-for-Transport-and-Storage-of-Captured-CO2.pdf

state as a regulator or investor will be vital to tackle such market failures and ensure fair and sustainable operations. The project Longship in Norway can be seen as a clear example (25 billion Norwegian Krone (NOK)). The Norwegian government funds approximately two thirds of first-phase expenditures.[82]

4.1.3 CO2 prices and policies

From an economic perspective, the main revenue from mitigating CO_2 via CCS is the savings in costs incurred by releasing CO_2 into the atmosphere. Such costs can be**,** for example, carbon price (e.g. EU ETS), carbon taxes, and obligations. Therefore, CCS will be unprofitable as long as the CO_2 price is lower than the CCS costs. The industrial sector is aware that the current CO_2 price doesn't reflect the future and there is a general conception that prices are going to increase. However, there is no agreement on how much and when. For example, various studies[83] refer to CO_2 price ranges between €40 and €360/ton by 2050. Such economic uncertainties can be a major barrier for producers to design CO_2 mitigation strategies, especially if the sector (e.g. cement) achieves low profits and cannot burden additional costs without being able to retrieve them via higher prices. Although there is an evident goal to reach carbon neutrality by 2045, there is no official roadmap regarding carbon prices until then. Therefore, the policymakers should provide a clear statement on carbon monetary value in the coming two decades or at least a potential range of prices. In this regard, instruments such as Carbon Contracts for Difference (CCfD) can be effective in reducing investment risks and stimulating CCS projects.[84]

4.1.4 Legislation

As can be deduced, 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). In NRW, CO_2 transportation and establishing the required pipeline infrastructure shows the associated legal complexities. 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, which are presented in the 2020 study by Benrath et al.**[85]** As Table 4 shows, there are numerous relevant laws that can increase the legal complexity. Additionally, there are few precedents in Germany, which increases various legal uncertainties.

[82] Knudsen, J. C., Phillips, D., Aasen, E. Y., and Valen, H. (2022). Carbon capture and storage (CCS) in Norway: Experiences and challenges from within. *OIES Forum*, *Issue 130*

[83] Fischedick, M., Marzinkowski, J., Winzer, P., and Weigel, M. (2014). Techno-economic evaluation of innovative steel production technologies. *Journal of Cleaner Production*, *84*, 563–580. https://doi.org/10.1016/j.jclepro.2014.05.063
Pietzcker, R. C., Osorio, S., and Rodrigues, R. (2021). 'Tightening EU ETS targets in line with the European Green Deal: Impacts on the decarbonization of the EU power sector'. *Applied Energy*, *293*, 116914. https://doi.org/10.1016/j.apenergy.2021.116914
UBA (2020). Jährliche Treibhausgas-Emissionen in Deutschland/Annual greenhouse gas emissions in Germany. Umweltbundesamt (UBA)

[84]Richstein, J. C., Kröger, M., Neuhoff, K., Chiappinelli, O., and Lettow, F. (2021). Carbon Contracts for Difference: An assessment of selected socio-economic impacts for Germany
Sartor, O., and Bataille, C. (2019). Decarbonzing basic materials in Europe: How Carbon Contracts-for-Difference could help bring breakthrough technologies to market (Institute for Sustainable Development and International Relations IDDRI)

[85] Benrath, D. et al. (2020). CO2 and H2 infrastructure in Germany - Final report of the German case study

Table 4: 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)[86]	German implementation of directive 2009/31/EC (European Parliament, 2009). The act addresses major aspects related to CO_2 pipelines (e.g. construction, liability, etc.) and refers to other respective laws.
2) Verwaltungsverfahrensgesetz (VwVfG) (administrative procedures law) (BMJ, 1976)[87]	Pipeline planning and permitting procedures of the CO_2 pipelines.
3) Gesetz über die Umweltverträglichkeitsprüfung (UVPG) (environmental impact assessment law) (BMJ, 1990)[88]	Environmental impact assessment during pipeline planning and permitting procedures.
4) Gesetz über die Elektrizitäts- und Gasversorgung (Energiewirtschaftsgesetz – EnWG) (energy industry law) (BMJ, 2005)[89]	As indicated by KSpG, 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)[90]	Regional planning of CO_2 pipelines and project compatibility.
6) Verordnung zur Durchführung des Landesplanungsgesetzes (LandesplanungsgesetzDVO – LPlG DVO) (Ordinance on the implementation of the state planning act) (MI NRW, 2010)[91]	Regional planning procedures of CO_2 pipelines (>30cm) in North Rhine-Westphalia.
7) London protocol (IMO, 2006)[92]	Offshore CO_2 storage and CO_2 exports for offshore storage.
8) Verordnung über Rohrfernleitungsanlagen (Rohrfernleitungsverordnung – RohrFLtgV) (log-distance pipeline ordinance) (BMJ, 2002)[93]	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)[94]	

Source: Author's work based on Benrath (2020)[95]

[86] BMJ (2012). Gesetz zur Demonstration der dauerhaften Speicherung von Kohlendioxid (Kohlendioxid-Speicherungsgesetz - KSpG) (Bundesministerium der Justiz)
[87] BMJ (1976). Verwaltungsverfahrensgesetz (VwVfG) (Bundesministerium der Justiz)
[88] BMJ (1990). Gesetz über die Umweltverträglichkeitsprüfung (UVPG) (Bundesministerium der Justiz)
[89] BMJ (2005). Gesetz über die Elektrizitäts- und Gasversorgung (Energiewirtschaftsgesetz - EnWG) (Bundesministeriums der Justiz)
[90] BMJ (2008). Raumordnungsgesetz (ROG) (Bundesministerium der Justiz)
[91] MI NRW (2010). Verordnung zur Durchführung des Landesplanungsgesetzes (LandesplanungsgesetzDVO LPlG DVO)
[92] IMO (2006). 1996 protocol to the convention on the prevention of marine pollution by dumping of wastes and other matter (as amended in 2006) (International Maritime Organization)
[93] BMJ (2002). Verordnung über Rohrfernleitungsanlagen (Rohrfernleitungsverordnung - RohrFLtgV)
[94] BMJ (2011). Verordnung über Gashochdruckleitungen (Gashochdruckleitungsverordnung - GasHDrLtgV) (Bundesministerium der Justiz)
[95] Benrath, D. et al. (2020). CO2 and H2 infrastructure in Germany - Final report of the German case study

4.2 Social challenges

Besides the economic challenges, the societal aspects are also crucial. CCUS is very controversial and can be generally classified as 'unpopular', especially in Europe, for various reasons. Public opinion, fear and perception needs to be seriously taken into account regardless of whether they are based on scientific facts. The public inclusion is vital since certain communities are going to be close to potential CO_2 infrastructure, including pipelines and storage sites. Any opposition, currently or in the future, is going to deter investors. Therefore, several studies in different countries have already been implemented to investigate the reasons behind public perception and define the regulatory instruments that will be needed to promote acceptance of the technology.

Many factors can influence the public standpoint such as **(1) terminology** used while conveying the information, **(2) information and public awareness** (e.g. CCUS benefits vs. risks and the climate change severity), **(3) public trust** (e.g. if the society tends to rely on the opinions of environmental non-governmental organizations (NGOs) and governmental officials more than the industrial sector and academia[96]) and **(4) economic background** (e.g. if the affected communities have some fears regarding the value of their properties such as real estate or incurring additional costs related to establishing such new infrastructure).

(5) Incentives can also lead to different results. Although there is a general belief that there is public opposition to having CO_2 infrastructure nearby (i.e. Not In My Backyard NIMBYism), one study[97] states that this is not always the case and sometimes YIMBYism (Yes In My Backyard) can be the case if communities are familiar with the industrial infrastructure and grasp the economic opportunities of CCUS, as in some regions in the UK. This can also explain the acceptance of EOR and CO_2 infrastructure in the USA and Norway which can be compared to NRW as a hub for heavy industry. Public awareness regarding the economic structure and the dependency of the job market on existing industries can be a good introduction to CCUS advantages. Moreover, other obsolete value chains (e.g. coal and lignite in NRW) can influence public perception and acceptance of CCS not only as a tool to protect their industry from moving to other regions, but also as a new business that can provide job opportunities.

(6) Culture also plays a vital role in this process. Concepts such as trust, risk, benefit, and ethics are highly influenced by culture. Therefore, considering a country's culture when developing a whole project is vital. It can actually impact on the success of a CCS project.[98] Some studies[99] focused on public perception in Germany and concluded low levels of support for CCS technologies. Other studies[100] linked these results with cultural attributes (e.g. long-term orientation (LTO), risk aversion, etc.).

In general, several studies have addressed public perception and acceptance in Germany, which also reflect the situation in NRW. However, these studies focused on various groups and used different approaches, which may explain the discrepancies in their results. While some studies[101] show positive results others[102] provide negative ones. Overall, these studies can only illustrate some fragments of reality. Firstly, the surveyed groups may not be from the communities affected by pipelines or from regions that have low connection to the industrial system. Secondly, and most importantly, these studies

[96] Karayannis, V., Charalampides, G., and Lakioti, E. (2014). Socio-economic Aspects of CCS Technologies. *Procedia Economics and Finance*, *14*, 295–302. https://doi.org/10.1016/S2212-5671(14)00716-3

[97] Whitmarsh, L., Xenias, D., and Jones, C. R. (2019). Framing effects on public support for carbon capture and storage. *Palgrave Communications*, *5*(1). https://doi.org/10.1057/s41599-019-0217-x

[98] Karimi, F., and Toikka, A. (2018). 'General public reactions to carbon capture and storage: Does culture matter?' *International Journal of Greenhouse Gas Control*, *70*, 193–201. https://doi.org/10.1016/j.ijggc.2018.01.012

[99] Braun, C., Merk, C., Pönitzsch, G., Rehdanz, K., and Schmidt, U. (2018). Public perception of climate engineering and carbon capture and storage in Germany: survey evidence. *Climate Policy*, *18*(4), 471–484. https://doi.org/10.1080/14693062.2017.1304888

[100] Karimi, F. et al (2018). https://doi.org/10.1016/j.ijggc.2018.01.012

[101] Benrath, D., Flamme, S., Glanz, S., and Hoffart, F. M. (2020). CO2 and H2 infrastructure in Germany - Final report of the German case study

[102] Schumann, D., Duetschke, E., and Pietzner, K. (2014). Public Perception of CO2 Offshore Storage in Germany: Regional Differences and Determinants

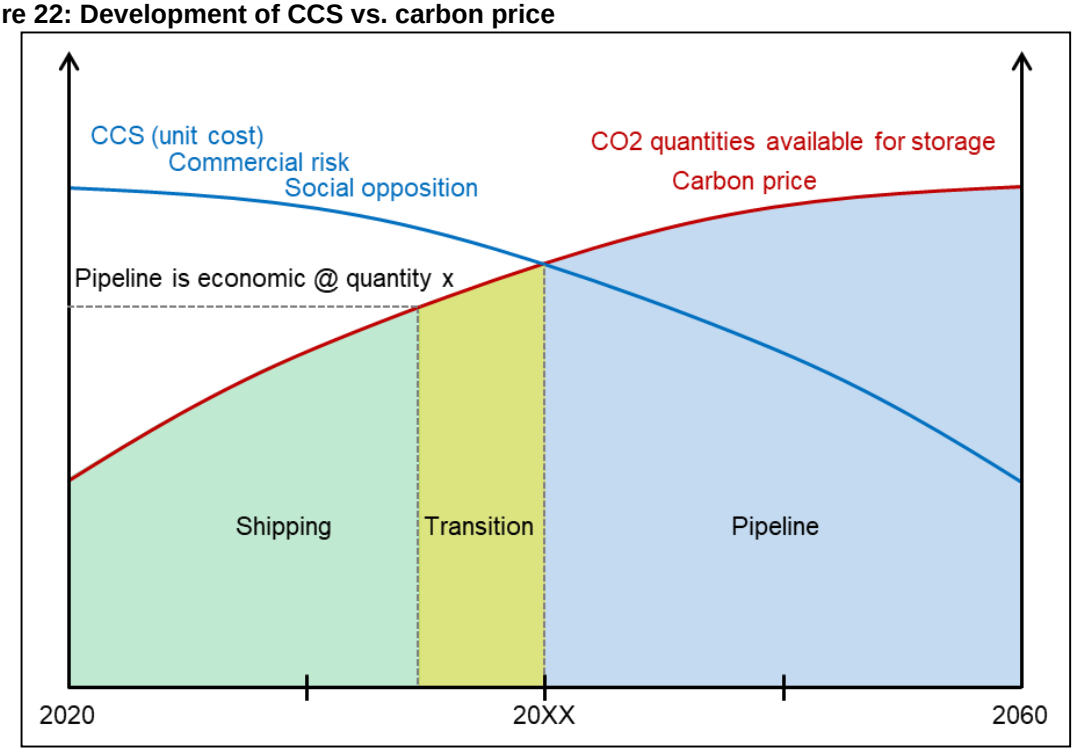
address the topic from a universal or general perspective. The participants of these studies have not been surveyed regarding an actual case study or pipeline route.

However, the main importance of these studies is defining and clarifying the factors that influence social acceptance. These factors should be taken into account when implementing an active discussion with communities concerned with pipeline construction in NRW. Or at an even earlier stage (i.e. planning the pipelines thus enabling areas expected to demonstrate very high resistance or refusal to be avoided). However, these studies cannot replace carrying out a dedicated regional study in the early planning stages once a route is defined. Hence, defining the pipeline route as early as possible is of importance in order to ensure public participation and acceptance, which is a time-consuming process.

5. Conclusions and outlook

Due to the significant amount of process emissions generated in NRW, CCUS will be a necessity in order to reach carbon neutrality by 2045. However, as discussed, there are several obstacles along the CCUS supply chain. From a techno-economic perspective, the TRL of several CCS technologies is still low and the costs are relatively high. Therefore, more research and pilot projects are needed. Although some studies in the last decades expected that CCS would be commercialized by 2020[103] the technologies are still in their pilot project phase. It is clear that the CCS industry is stagnating and obviously behind with the ambitious goals to reach the climate goals. Establishing CCS supply chain implies that various components have to develop simultaneously until a fully-functioning system is gradually realized. As shown in Figure 22, the current carbon prices are lower than the carbon sequestration costs via CCUS. However, the free-market dynamics are supposed to be dominant in the future. This can only be achievable if the carbon prices are higher than the sequestration costs. Therefore, having high carbon prices cannot solely achieve that and lowering the CCUS costs is also mandatory.

Figure 22: Development of CCS vs. carbon price



Source: Author's own illustration

[103] Karayannis, V. et al. (2014). https://doi.org/10.1016/S2212-5671(14)00716-3

As discussed, there is a big variance in terms of the costs of CO_2 capture, transportation and storage. According to Leeson et al.,[104] the avoidance cost of CO_2 emissions from the cement industry ranges between (≈ €50-170/ton CO_2). Regardless of the techno-economic reasons behind this significant variance, the uncertainties related to the technologies, costs and carbon prices (Carbon price – EU ETS ≈ €25/ton CO_2 in 2019 and ≈ €80/ton CO_2 in 2022[105]) impose various investment risks. Therefore, due to the unconventionality of CCUS business models, the state should also play an untypical role. This role should not be limited to supporting research activities and pilot projects. Despite the importance of existing industrial roadmaps, policymakers have not yet formulated a concrete opinion regarding the role of CCUS. Economically, the state should decrease the investment risks and take part in developing the required infrastructure. From a legal perspective, designing a balanced liability concept would be important to ensure that operators apply the highest standards in terms of human and environmental protection and simultaneously motivate investors and insurers to put CCUS projects on their portfolios.

In terms of location, there are various opportunities as well as challenges. The clinker plants form a cluster in the north-eastern part of the state, which can help in establishing a common CO_2-infrastructure. The closeness of NRW to Rotterdam (as a potential CO_2-hub) is also advantageous. However, the remoteness of the clinker plants from the main industrial hub in the Ruhr implies that the industry must invest in additional infrastructure. Legally, realizing an efficient CO_2 transportation system within a federal system may incur various challenges and even contradictions. This is actually not limited to connecting the pipeline from NRW to an adjacent country (e.g. the Netherlands), but also with other federal states as the legislative systems and authorizing bodies are different. Therefore, legal and social challenges could make shorter and individual pipelines more favourable. However, it is economically more efficient to establish a longer and interconnected pipeline network due to the economies of scale.

As presented, there are several stakeholders along the CCUS value chains. Therefore, realizing future projects necessitates communication, mutual understanding and trust. Collaboration between different emitters (i.e. inter and intra-industrial partners) is mandatory in order to decrease the risks and costs. Integration of transportation companies, pipeline and storage operators is also vital in order to ensure system efficiency. On the international level, cooperation is also required due to lack of regional storage capacity and the potential for establishing international geological storage hubs. Furthermore, public engagement and endorsement is vital. It is evident that the social studies are relatively few compared with the techno-economic studies. More social investigations, especially on a regional level, are needed to assess actual public opinion in a scientific way and define the factors that influence public perception and how the affected communities can be compensated or incentivized.

[104] Leeson, D. et al. (2017). https://doi.org/10.1016/j.ijggc.2017.03.020

[105] ICAP (2022). ICAP Allowance Price Explorer (International Carbon Action Partnership). https://icapcarbonaction.com/en/ets-prices