A comparative techno-economic assessment of CO2 mineralization technologies: A case study from the construction sector

Abdelshafy, Ali; Strunge, Till; Stephan, Dietmar; Walther, Grit

DOI
10.1016/j.jcou.2025.103092

Publication date
2025

Document Version
Final published version

Published in
Journal of CO2 Utilization

Journal of CO2 Utilization 96 (2025) 103092

Contents lists available at ScienceDirect

Journal of CO2 Utilization

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

A comparative techno-economic assessment of CO_2 mineralization technologies: A case study from the construction sector

Ali Abdelshafy [a,b,*], Till Strunge [c,d], Dietmar Stephan [c], Grit Walther [a]

[a] Chair of Operations Management – RWTH Aachen University, Aachen, Germany
[b] Energy and Industry Group, Faculty of Technology Policy and Management, Delft University of Technology, Germany
[c] Department of Civil Engineering, Technische Universität Berlin, Berlin, Germany
[d] Research Centre for Carbon Solutions, School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, United Kingdom

A R T I C L E I N F O

Keywords:
Carbon capture and utilization
CO_2 mineralization
CO_2 concrete curing
Construction sector
Comparative assessment
Cost modelling

A B S T R A C T

CO_2 mineralization is a crucial carbon capture and utlization technique because it can sequester CO_2 emissions permanently. There are various CO_2 mineralization technological pathways, all of which are based on the reaction of CO_2 with the metal oxides present in cementitious materials and virgin minerals. However, there are techno-economic obstacles that hinder their deployment, as well as various knowledge gaps regarding the prospective supply chains. Although these pathways have several differences, such as process configuration and costs, each is usually addressed individually and comparative analysis is lacking. In this contribution, we aim to address this knowledge gap via investigating the entire supply chain of each technology and contrasting their differences by presenting a case study from the German federal state of North Rhine-Westphalia. Methodologically, several approaches and tools are used, such as cost modeling and geographic information systems. Herein, we investigate the advantages and limitations by assessing six scenarios representing the different configurations of the relevant supply chains. Most scenarios are deemed infeasible at lower carbon prices, with only three considered viable below 100 €/ton CO_2. Also, while concrete curing and concrete waste processes are constrained by material availability and logistics, CO_2 mineralization of virgin minerals offers a more abundant alternative, albeit at a higher levelized cost. Therefore, the study provides valuable insights for the design of optimal and efficient CO_2 mineralization supply chains, highlighting the need for a balanced approach that leverages the strengths of different pathways.

1. Introduction

The industrial sector is responsible for more than one fifth of the global anthropogenic CO_2 emissions, accounting for 11.6 Gt CO_2 in 2022 [1]. Besides their large share, mitigating industrial emissions can be more challenging than in other sectors. In contrast to other economic activities like transportation, many industrial emissions cannot be mitigated by electrification or using carbon-free energy sources as some processes inherently emit CO_2 or rely on carbon-based feedstocks. This is particularly true for the cement industry, the second biggest source of industrial emissions. On the one hand, the processing of $CaCO_3$--containing raw meal requires high temperatures (approximately 1400°C), making electrification difficult [2]. On the other hand, calcining the limestone feedstock also releases CO_2, which is classified as hard-to-abate emissions (Eq. 1) [3].

$$CaCO_3 \xrightarrow{heat} CaO + CO_2 \tag{1}$$

Hence, sequestering large amounts of CO_2 emissions in this industry is crucial for achieving carbon neutrality. While geological storage is often regarded as the primary method for sequestering captured CO_2, alternative techniques, such as Carbon Capture and Utilization (CCU), are also available for temporary or permanent CO_2 storage. CCU refers to using CO_2 as an input to produce other valuable products [4]. Several CCU techniques can be classified in different ways [5]. In terms of products, CCU can be used in different applications, such as chemicals, fuels, beverages, etc. While CCU technologies also have a wide range of CO_2 sequestration periods (i.e., temporary for months or years, semi-permanent for decades and permanent for millennials) [6], only those capable of permanently sequestering CO_2 will have significant impact on mitigating of industrial emissions. Primarly, two CCU methods can permanently sequester CO_2: (i) CO_2 mineralization, where

* Corresponding author at: Chair of Operations Management – RWTH Aachen University, Aachen, Germany.
E-mail address: ali.abdelshafy@om.rwth-aachen.de (A. Abdelshafy).

https://doi.org/10.1016/j.jcou.2025.103092
Received 30 October 2024; Received in revised form 16 April 2025; Accepted 17 April 2025
Available online 29 April 2025

CO_2 is reacted with oxides in virgin minerals or concrete to form stable carbonates and (ii) enhanced oil recovery, where CO_2 is used to extract oil and is stored in the oil field afterward. For hard-to-abate industries such as the cement industries, which are geographically dispersed and not typially situated near oil production fields, CO_2 mineralization presents a promising sequestration approach. Additionally, CO_2 mineralization techniques can be incorporated directly into the cement production process, as discussed below. Although CO_2 mineralization techniques rely on the same reaction (Eq. 2) [7], where alkaline-earth-metal-oxide-bearing minerals (e.g., CaO or MgO; collectively abbreviated as metal oxides (MO)) react with CO_2 to form carbonates, the process and feedstock of each pathway is different.

$$MO + CO_2 \rightarrow MCO_3 + \text{heat}\uparrow \tag{2}$$

The process of CO_2 minerlization of concrete, hereafter CO_2 concrete curing as commonly named in literature, has been investigated in multiple studies [8–10]. During the process, CO_2 reacts with CaO or Ca$(OH)_2$ during the curing of concrete [11]. This can be performed using curing chambers, where the process occurs in a controlled environment (e.g. pressure, temperature, humidity). The use of curing chambers is fairly common in the concrete industry, where precast concrete is typically cured with steam to improve its properties [12]. Despite variations in assessed CO_2 concrete curing processes and suggested setups (e.g., static curing, dynamic curing), the fundamental components of the system remain roughly consistent [8,10,13,14]. For the CO_2 mineralization of virgin minerals and concrete waste, the process involves reacting captured CO_2 with feedstocks through either direct or indirect methods. In direct aqueous carbonation, in a slurry using high pressures, elevated temperatures and additives. In multi-step indirect carbonation processes, metal-oxides are first leached from the feedstocks and then reacted with CO_2 in a separate step [15]. These processes can also yield marketable products such as cement additives (supplementary cementitious materials, SCM) [16] or synthetic aggregates that permanently sequester CO_2 and can partially replace conventional production routes [17]. Among the most promising feedstocks are calcium or magnesium-rich silicates, recycled concrete fines, and cement kiln dust [15]. During the reaction of CO_2 with certain feedstocks, silica (SiO_2) is produced as a byproduct, enhancing the utility of the carbonated material as a cement additive [18,19]. Using industrial wastes as feedstocks for mineralization also results in the diversion of materials that would otherwise be destined for landfill, converting waste into economically beneficial products for the construction sector while simultaneously reducing landfill costs [20,23].

While all pathways above are based on the same technical concept of storing CO_2 as carbonates, their supply chains differ significantly. For example, CO_2 mineralization of virgin minerals requires ultramafic rocks, such as olivine-bearing peridotites, which can be found in Europe in Norway, Italy, Spain, Greece and Turkey [21]. Hence, the feedstock, in this case, will have to be transported from mining sites to the production facility (Fig. 1A). Similarly, for the mineralization of industrial wastes like waste concrete, feedstock materials will have to be transported from construction waste recycling plants to CO_2 sources. However, concrete waste is available locally and in smaller volumes than natural minerals. Hence, the transport distances will be shorter, and the main transport mode will shift from shipping to vehicles. On the other hand, implementing CO_2 concrete curing will require transporting CO_2 to concrete plants, which will be used and sequestered during the curing process of precast concrete products (Fig. 1B).

While the different processes of CO_2 mineralization have been investigated in different studies from a life cycle or techno-economic perspective [24–27], an in-depth analysis for an industrial region comparing multiple pathways is currently lacking. Such comparisons can be crucial for decision-makers and stakeholders seeking to develop effective emission reduction strategies. Herein, a comparative and thorough assessment is needed to investigate the potentials of these technologies. Therefore, we present a harmonized framework to compare different concepts and their supply chains using a case study of an industrial region in Germany. We assess the techno-economic viability of three selected technologies, namely, CO_2 concrete curing, CO_2 mineralization of virgin minerals (i.e., olivine-bearing rocks) and CO_2 mineralization of waste concrete, while considering the demand and supply locations of feedstocks for the decarbonization of a cement plant located centrally in the case study region. In terms of structure, the paper is organized as follows. First, the different processes and relevant materials, inflows and outflows are described and compared. Second, the derived approaches, applied tools and inventory data are presented in 2. Afterwards, the derived approach is applied to the different scenarios, and the results are analyzed and discussed (3). Finally, the study is concluded by summarizing the main outcomes and illustrating the potentials of each technology at different carbon prices.

2. Methodology and data

In the following, we distinguish between two methodological approaches: (i) methodologies to assess the costs of a technology without considering CO_2 or feedstock transport, and (ii) methodologies to evaluate the costs of the entire supply chain, including determining the required plant size to fulfill the demand and estimating the transportation costs based on the plant's location.

2.1. Assessing the costs of technology

We first derived cost curves to calculate the cost for each technology based on the plant's capacity. To compare the costs of multiple novel

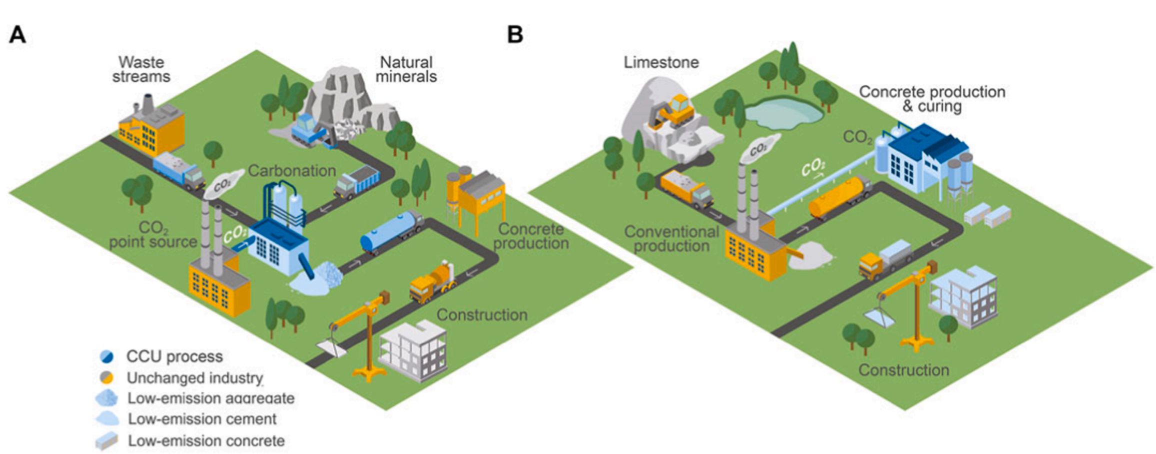

Fig. 1. Mineralization vs. carbonation supply chains taken from [22].

technologies, a harmonized assessment method is indispensable. Techno-economic assessments (TEA) for novel technologies (e.g., CO_2 mineralization pathways) involve high uncertainties due to the unknown physicochemical mechanisms (e.g., the reaction rate in a scaled-up process might be different than in lab experiments) and the need to estimate many future conditions (e.g., feedstock, energy prices, etc.). Therefore, these evaluations can vary significantly based on different underlying assumptions (e.g., electricity price) and differences in methodologies used [28–30]. To address this issue, we harmonized techno-economic estimates for the investigated technologies (i.e., CO_2 curing of concrete, CO_2 mineralization of virgin minerals and CO_2 mineralization of waste concrete). We used the same methodology as previously described in [16], which was developed according to recent guidelines for TEA in CCU [31–33].

The performance indicator selected for this assessment was the levelized cost of CO_2 sequestration (LCOS) in € per tonne of CO_2 sequestered. This indicator combines the total capital requirements (TCR) (i.e., Capital expenditures, CapEx) and operational expenditures (OpEx). We discounted the capital costs using the interest rate i and the plant's lifetime L to determine the annual costs for the proposed plants (Eqs. 3 and 4) [34]. TCR was calculated using the Total Direct Cost (TDC) and Total Overnight Costs (TOC) (Eqs. 5 – 7). Here, we used factors (i.e., $f_{indirect}$, $f_{process}$, $f_{project}$, f_{owner}) to account for indirect costs, process contingencies, project contingences and owners' costs for a first-of-a-kind plant. As first-of-a-kind plants are significantly more expensive than nth-of-a-kind (i.e., commercial) plants, we followed the hybrid approach suggested by [35] to calculate the TCR for an nth of a kind plant (Eqs. 6 and 7). Herein, N is the number of plants built, LR is the learning rate, E is the experience factor, i is the interest rate during construction and $t_{construction}$ is the construction time (i.e. 1 year).

$$LCOS_{technology} = \alpha \bullet TCR + OpEx \quad (3)$$

$$\alpha = \left(\frac{i}{1-(1+i)^{-L}}\right) \quad (4)$$

$$TOC = \sum TDC \bullet (1+f_{indirect}) \bullet \left(1+f_{process}\right) \bullet \left(1+f_{project}\right) \bullet (1+f_{owner}) \quad (5)$$

$$TCR = \left(\frac{TOC}{\dot{m}_{SCM}}\right) \bullet N^{-E} \bullet \dot{m}_{CO2avoided} \bullet (1+i)^{t_{construction}} \quad (6)$$

$$E = \frac{\ln(1-LR)}{\ln(2)} \quad (7)$$

As TCRs are derived for a specific plant size, TCR have to be scaled if used in different sizes. To do so, we apply the following scaling approach (Eq. 8), based on chemical engineering textbooks [36]. Herein, a scaling factor of s = 0.6 is used. To estimate the OpEX, we used a straightforward approach, using the mass and energy balances to determine utilities and feedstock costs while using harmonized prices (π_i) across all technologies (e.g., electricity prices) (Eq. 9). w_i denotes the amount of feedstock or energy needs, and fixed OpEx ($OpEx_{fixed}$) include insurance costs and local tax, maintenance, and labor.

$$TCR_{tech} = TCR_{tech} \bullet \left(\frac{capacity_{new}}{capacity_{old}}\right)^{s} \quad (8)$$

$$OpEx = \sum w_i \bullet \pi_i + OpEx_{fixed} \quad (9)$$

2.2. Assessing the cost of the supply chain

Based on the cost calculations in the previous step, the capital, fixed and variable costs were used to calculate the levelized costs of the CO_2 sequestered (LCOS). Afterward, a cost curve was derived for each technology to illustrate the relationship between the capacity and the LCOS. In this process, the basic model was used to compute the sequestration cost across different capacities, forming the data points that constitute the cost curve via regression. These calculations were carried out for each technology along the relevant value chains. The (regression) tables and curves are provided in the Supplementary Information (SI). Besides the technology cost, logistics and transportation costs were also considered (Eq. 10).

$$LCOS_{total} = LCOS_{technology} + LCOS_{transport} + LCOS_{logistics} \quad (10)$$

The transportation costs encompass the expenses incurred in moving the materials or captured CO_2 to the designated facilities. For the mineralization of virgin minerals, the required mineral (i.e., olivine-bearing rocks) is assumed to be sourced from the nearest location (i.e., Bergen, Norway) due to the lack of olivine sources in Germany [21]. Therefore, transportation involves overseas and inland shipping, with distances of 952 and 350 km, respectively [37,38]. To investigate the transport needs for CO_2 concrete curing and CO_2 mineralization of waste concrete, detailed data on the availability of these feedstocks are necessary. The availability of precast concrete and concrete waste in North Rhine Westphalia is depicted in Fig. 2 [26]. The inventory data is based on the official production and recycling statistics [39,40], which are filtered and analyzed using the relevant classifications [41,42]. These availabilities are then used to calculate transport needs between the material location and the CO_2 source to derive transport costs using QGIS software [43]. Herein, multiple scenarios are considered as described below. Inland and overseas transportation and transshipment costs are calculated based on [44–46]. In terms of sequestration capacity, a value of 0.35 t CO_2/t cement is considered, based on the highest value reported by [8,47]. Also, an average cement content in concrete is assumed to be 11 wt%, based on [48,49].

2.3. Assessed technologies

(1) The CO_2 mineralization process of virgin minerlas considered here uses a direct aqueous carbonation method, as described by [50,51], and further developed in [16]. In this process, ground olivine minerals react with captured CO_2 in a pressurized, stirred tank containing an aqueous slurry with additives. The modifications presented in [16] are used, including a post-processing system that (i) partially separates unreacted minerals via gravity separation and (ii) isolates magnesium carbonate ($MgCO_3$) from reaction products, yielding supplementary cementitious materials (SCMs) with variable silica (SiO_2) content. Herein, we consider previously determined cost-optimal conditions at 100-bar reaction pressure, and 190°C reaction temperature. The mineralization facility is assumed to be co-located with the cement plant. Feed minerals undergo crushing and grinding (pre-treatment) at the plant before mineralisation in continuously stirred reactors under elevated pressure and temperature, in an aqueous slurry with additives (NaCl and $NaHCO_3$). CO_2, separated from flue gas by monoethanolamine (MEA) post-combustion capture, is introduced in gaseous form into the slurry. After the reaction, the slurry and unreacted minerals are recycled, and products are purified to produce SCM suitable for the cement industry. This purification step is essential as the carbonation process generates both magnesium carbonate, which is inert and can reduce cement's compressive strength, and reactive silica, which strengthens cement.

(2) The CO_2 mineralization process of waste concrete was derived based on [52,53]. In this process, waste cement from dismantled buildings is used as a calcium source to form stable carbonates ($CaCO_3$), reacting with captured CO_2. Herein, cement particles are extracted from waste concrete, pulverized, and subjected to high-pressure CO_2 and water in a reactor. The dissolved CO_2 forms carbonic acid, facilitating the extraction of calcium ions from the cement, which then react to precipitate $CaCO_3$. Experimental studies demonstrated that key factors, including particle size, CO_2 partial pressure, and cement-to-water ratio impact calcium extraction efficiency, highlighting opportunities for

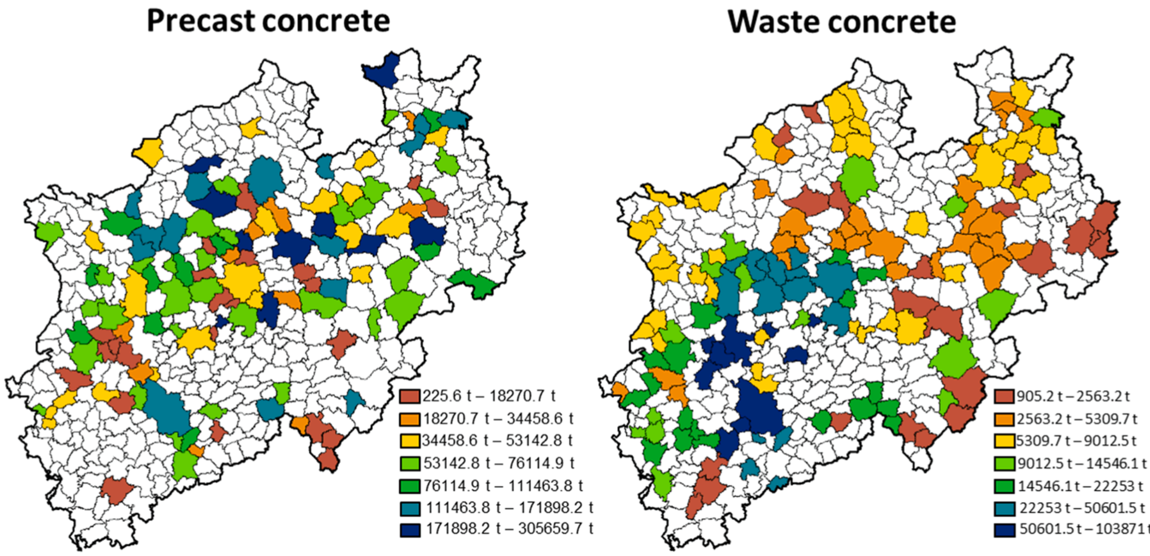

Fig. 2. The capacities/availabilities of precast concrete and waste concrete in NRW, based on [26].

process optimization [53,54]. In this study, we consider a CO_2 pressure of 3 bars and 50°C during the reaction. The products of this process are calcium carbonate and low value concrete filler, though separating them may pose techno-economic challenges [52]. (3) The process of CO_2 concrete curing considered in the assessment is based on the study of [10], which explored CO_2 curing of concrete alongside steam curing in precast concrete production. Herein, captured CO_2 (MEA post-combustion capture) is introduced at 1.5 bar together with water into the curing champer, where it reacts with calcium compounds in cement, forming stable products like calcium carbonate. Applied within 24 hours after casting, mineralisation primarily affects anhydrate phases (C_2S and C_3S) in fresh concrete, accelerating early strength gain.

2.4. Case study and region of interest

The German federal state of North Rhine-Westphalia (NRW) was selected as the case study for this analysis due to its geographical and industrial features. NRW is one of the key industrial clusters in Germany and Europe. It also has the highest population size and density in Germany, along with 11 cement plants located in the region. Therefore, there is a high availability of concrete and cementitious materials due to the extensive construction activities. The location of NRW also allows the investigation of different transportation modes and input materials. As NRW does not have sea access, the extensive minerals transported by overseas shipping will need various inland transport modes until they reach the relevant plants. The detailed data on the location-specific availabilities of concrete waste and precast concrete demand allowed us to realistically model transport needs. Fig. 3 depicts the main features and differences between the supply chains of these technologies. As abstracted in the CO_2 mineralization of virgin minerals supply chain (Fig. 3, left), the required natural feedstocks (i.e., olivine-bearing rocks) must be sourced from Northern Europe to the CO_2 sources in NRW. Herein, the transportation phase involves overseas and inland shipping as well as railway transport. Contrariwise, CO_2 concrete curing and CO_2 mineralization of waste cement (Fig. 3, right) depend on the domestic demand of precast concrete and supply of waste cement. Therefore, trucks serve as the primary mode of transport for delivering CO_2 to the relevant material sources and vice versa.

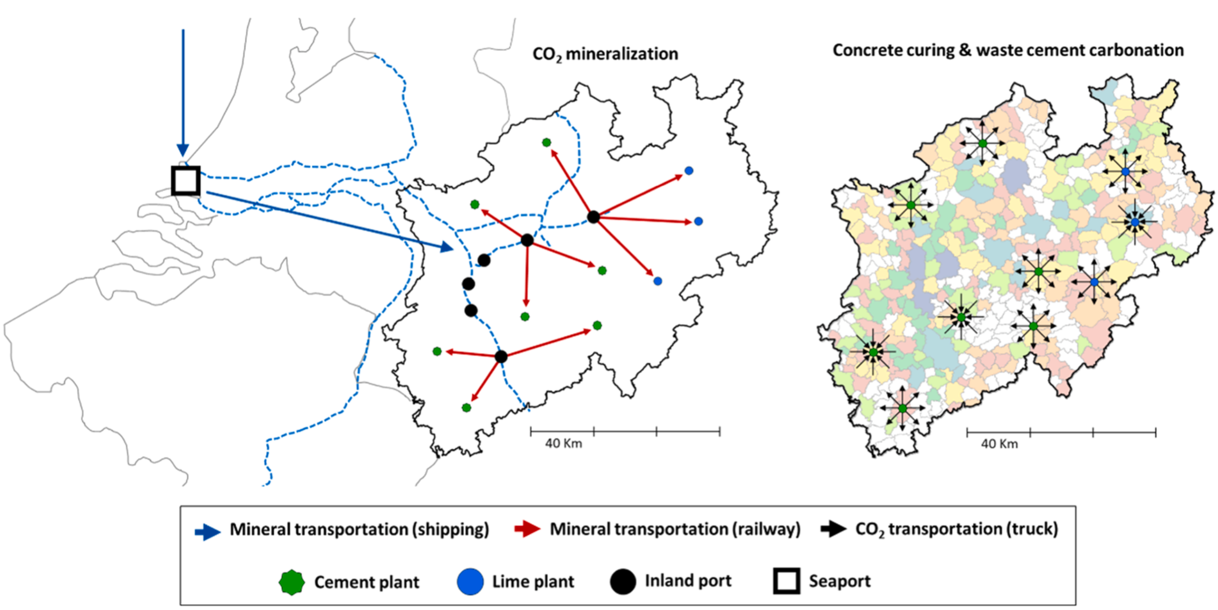

Fig. 3. Illustration of the different supply chains in NRW.

We defined six scenarios to analyze the supply chains of the investigated technologies, with two scenarios for each. Also, one cement plant was selected for the quantitative assessment due to the limited availability of domestic raw materials (concrete and mineral waste). Herein, the Beckum cement plant was selected, which has a capacity of approx. 650 kt clinker per year. As illustrated in Table 1 and Fig. 4, the first two scenarios assess two supply chain configurations for the CO_2 mineralization of virgin minerals. Both scenarios consider the olivine transportation and CO_2 curing at different capacities, but the second scenario additionally considers the usage of the process byproducts (SCMs). Scenario 2 assumes that SCM can substitute up to 30 % of the clinker production. Any additional output is going to be used as filling material. Scenarios 3 and 4 focus on the waste cement produced from the concrete waste, which is generated from processing the rubble in the construction and demolition waste (CDW) recycling plants. Both scenarios explore the same process, but they differ in the direction of the material flow. While the waste cement is transported from the recycling plant to the CO_2 source in scenario 3, scenario 4 assumes the captured CO_2 is delivered to the CDW recycling plants. Finally, the last two scenarios explore the implementation of the carbon cure technology, evaluating either the establishment of a carbon cure plant at the CO_2 emission sources, or the transportation of the captured CO_2 to existing concrete production facilities. Herein, establishing the carbon cure plant at the CO_2 emission source would involve relocating the relevant concrete production capacities adjacent to that source. The additional costs associated with transporting the precast concrete products to the initial locations are also considered in the analyses.

3. Results

3.1. CO_2 Mineralization of virgin minerals

The results of scenario 1 (CO_2 mineralization of natural minerals without product use) are shown in Fig. 4. Depending on the size of the plant, costs could lie between 150 and 200 €/t CO_2 sequestered. The results show that, although the feedstock minerals were sourced from Norway, the majority of the costs stem from the process itself rather than transport or mineral procurement. As transport relies on inexpensive offshore and onshore shipping, its economic impact remains minimal. Due to the economies of scale, the costs also decline rapidly until approximately 100 kt of CO_2 sequestered per year. Afterward, the scaling effects result in only minor cost reductions. The results for scenario 2 are shown in Fig. 5, which uses the same assumptions of scenario 1 but incorporates the use of resulting products (i.e., SCMs) and associated revenues. The results show that using the produced carbonated minerals for cement blends significantly improves the economics of this pathway. As cement blends can only take a certain amount of SCMs (assumed here to be 30 % blending rate in accordance with [18]), the economic optimum is reached at the maximum SCM blending rate. Hence, expanding the plant capacity would result in excess residual minerals that cannot be utilized in cement blends, generating no additional revenue. In our case study, the minimum costs (approximately 80 €/t CO_2 sequestered) are reached at the capacity of 100 kt CO_2 sequestered.

Table 1
Defined scenarios for the investigation.

Scenario	Description
Scenario 1	Olivine is transported to a cement plant (different capacities) without product use.
Scenario 2	Olivine is transported to a cement plant (different capacities) + selling by-products. (SCM to substitute max. 30 % of clinker production, rest: filling material)
Scenario 3	Waste cement is transported to cement plants (different capacities).
Scenario 4	CO_2 from cement plants is transported to recycling plants.
Scenario 5	CO_2 concrete curing at cement plant (different capacities).
Scenario 6	CO_2 from cement plant to precast concrete plants.

3.2. CO_2 Mineralization of waste concrete

The mineralization of recycled concrete is investigated in scenario 3 and 4, as shown in Figs. 6 and 7. Scenario 3 considers the transportation of recycled cement fines (the active ingredient of waste concrete) from the concrete recycling plants to the CO_2 source (cement plant). Herein, different capacities are considered, starting from 215 kt waste concrete (65 kt waste cement, 10 kt sequestered CO_2) to 2300 kt waste concrete (690 kt waste cement, 108 kt sequestered CO_2). As the capacity increases, the transportation distance also increases due to the limited regional resources. In other words, a plant will have to increase the sourcing radius in order to increase the CO_2 mineralization capacity. To fully utilize the capacity in NRW, waste concrete would need to be sourced up to 160 km from the cement plant. The results clearly show the trade-off between capacity and transport distance: small plants incur higher capital costs per unit due to their limited capacities, but they benefit from shorter material sourcing distances, resulting in lower transportation costs. When sourcing the waste cement from further away, a larger CO_2 mineralization plant can be built, which can result in lower capital cost per unit but higher transportation cost. Overall, the lowest cost is observed at a capacity of 94 kt CO_2 stored per year, with a cost of 150 €/t CO_2 sequestered.

Notably, these costs are higher than the costs associated with CO_2 mineralization of virgin minerals at similar capacities. Also, since the optimal (least-cost) capacity is close to the maximum available waste cement in NRW (200 kt per year), the analysis shows that it would be most cost-effective if only one of the 11 plants in NRW to adopt the technology. An alternative logistical approach has been also investigated in scenario 4. Instead of transporting waste cement to cement plants, we considered installing smaller CO_2 mineralization plants at each concrete recycling facility. This invloves transporting captured and liquified CO_2 from the cement plant to the recycling plants, where the CO_2 mineralization process takes place. As less CO_2 will be transported to each concrete recycling plant, the levelized costs are significantly higher due to a lack of economies of scale (Fig. 7). In scenario 3, 100 kt of CO_2 could be sequestered at a cost of 150 €/t of CO_2 sequestered. In comparison, scenario 4 would sequester 37 kt of CO_2 at a cost range of 322–400 €/t. Since both transport distance and plant size affect the levelized costs of each CO_2 mineralization plant, ranges have been used to illustrate the costs in Fig. 7.

3.3. CO_2 concrete curing

The results of CO_2 concrete curing scenarios are depicted in Figs. 8 and 9. Scenario 5 shows the impact of relocating the precast concrete production to be cured next to the emission source (cement plant). Fig. 8 shows the relationship between the plant capacity as a percentage of precast production in NRW and the corresponding levelized sequestration costs. Herein, the graph again shows an inverse relationship between the plant capacity and the levelized sequestration costs, which emphasizes the cost savings associated with economies of scale. As the plant capacity increases from 17 kt CO_2 to 347 kt CO_2, equivalent to 5–100 % of the precast production NRW, the levelized costs of CO_2 sequestration decline gradually from over 56 €/ton CO_2 to below 12 €/ton CO_2. Notably, this is significantly lower than the previously determined costs for CO_2 mineralization of both virgin minerals and waste concrete. While this scenario achieved the lowest costs compared with the preceding scenarios, the actual implementation is highly challenging because relocating precast concrete plants is not easily feasible in practice, which might lead to additional costs.

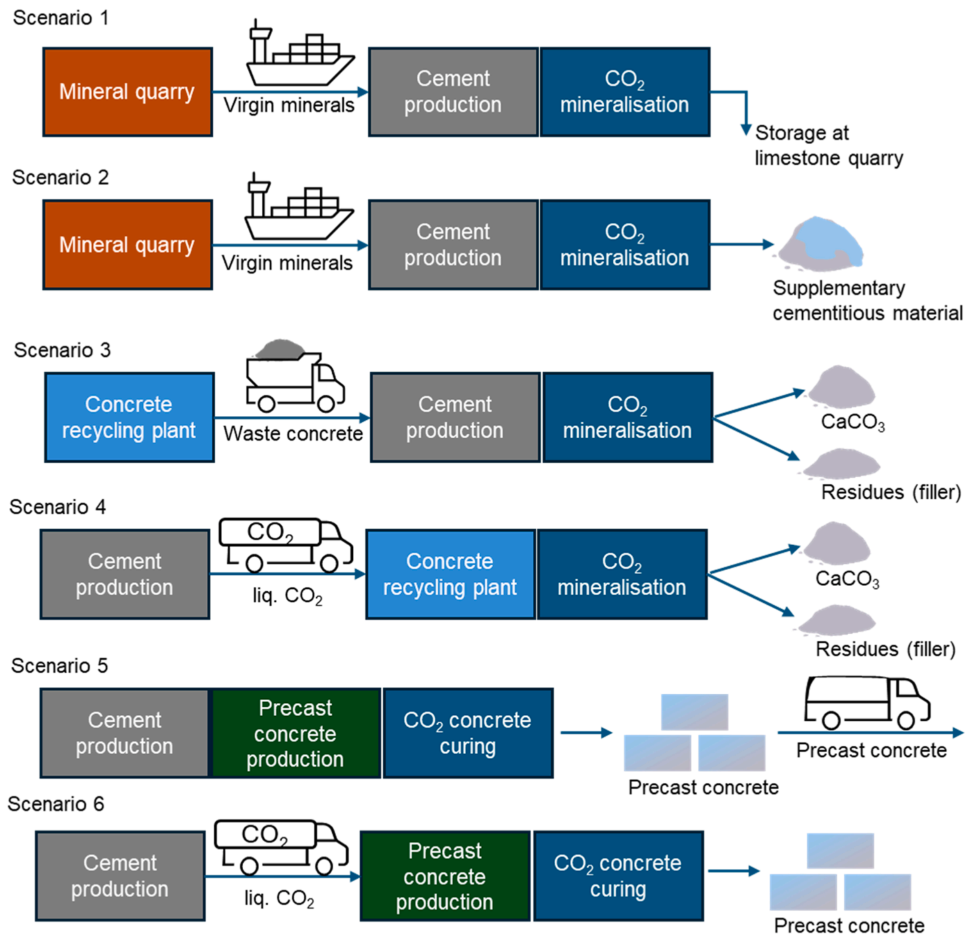

Fig. 4. Illustration of the different supply chain configurations for each scenario. Cement plants depicted in grew. Virgin mineral quarrying in orange. CO_2 mineralization or CO_2 concrete curing plants in green and blue.

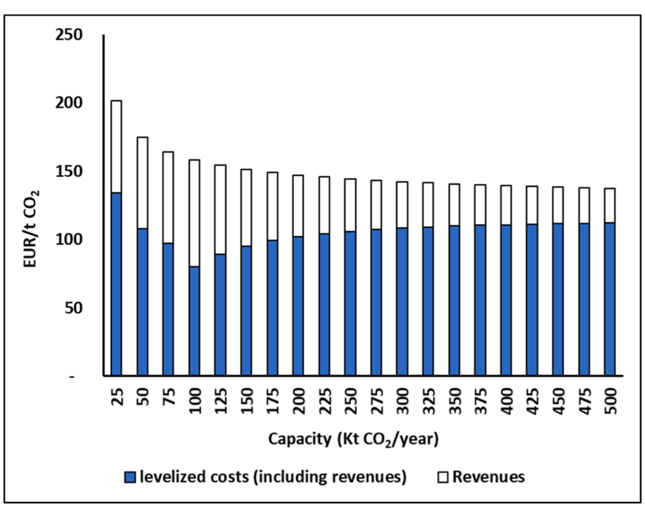

Fig. 5. Results of scenario 2, CO_2 mineralization of virgin minerals with product use.

Scenario 6 is the counterpart of scenario 5, as the transportation of CO_2 is assumed to exisiting precast concrete producers. Fig. 9 depicts the sequestration costs and the corresponding sequestration capacity. Here, the sequestration costs (€/t CO_2) are categorized again into different ranges and the corresponding sequestration capacities are provided for each cost range. In the lowest cost range (73.7 – 100 €/t CO_2), the sequestration capacity is approximately 98 kt CO_2. The cost ranges (100 – 150 €/t CO_2) and (150 – 200 €/t CO_2) also have analogous sequestration capacities. There is also a significant decrease in sequestration capacity for costs above 200 €/t CO_2.

4. Conclusions

The study investigated the complex dynamics of utilizing different materials as carbon sinks in the construction sector. Through a comprehensive array of analyses, we meticulously dissected the techno-economic intricacies inherent in various technologies and supply chains, illustrating both the shared traits and distinctive factors. Overall, the economic performance of each technology can be assessed based on the figures in the previous section. Herein, contrasting the levelized costs with the expected carbon prices can illustrate the feasibility of the relevant supply chains. Table 2 presents the feasibility of the investigated scenarios across different carbon prices (60 – 160 €/ton CO_2), based on the estimations of [55]. In general, most of the scenarios are deemed infeasible at lower carbon prices. Only three scenarios (two CO_2 concrete curing and one CO_2 mineralization of natural minerals) are considered applicable below carbon prices of 100 €/ton CO_2. As shown in scenario 1, the CO_2 mineralization of natural minerals requires higher prices, i.e., more than 140 €/ton CO_2. Nonetheless, selling the by-products can decrease the required minimum CO_2 prices to approximately 80 €/ton CO_2, as shown in scenario 2.

Similarly, the CO_2 mineralization of waste concrete is also uneconomic below 140 €/t CO_2 (scenario 3). However, this additionally requires a centralized configuration, where all the available waste

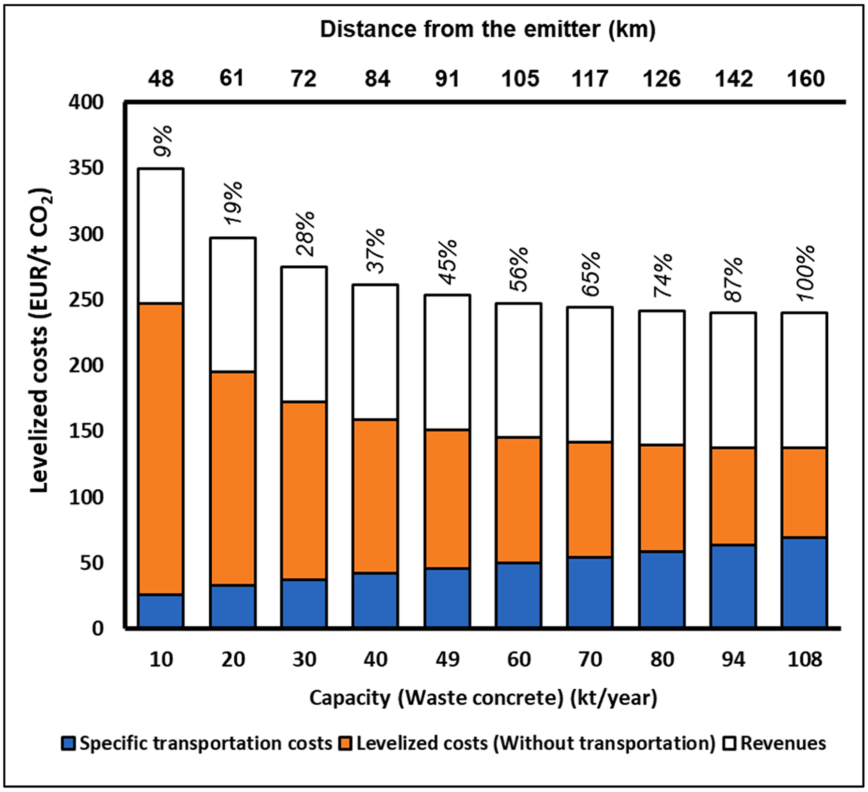

Fig. 6. Results of scenario 3, mineralization of recycled concrete. Percentages above the bars show the percentage of waste concrete supply in NRW used.

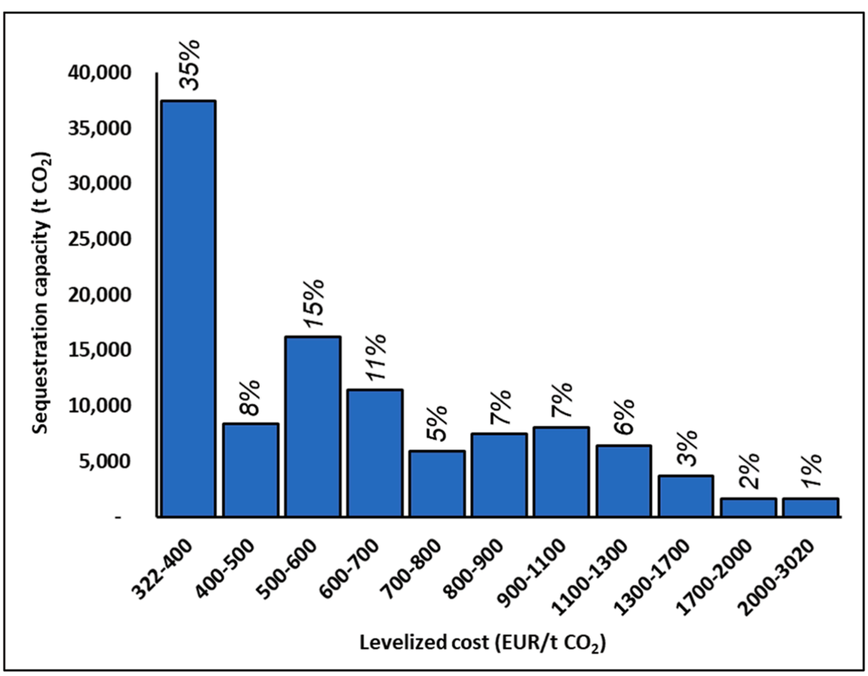

Fig. 7. Results of scenario 4. Percentages above the bars show the percentage of waste concrete supply in NRW used.

concrete in the region is collected and treated in one plant. On the other hand, scenario 4 is not feasible within this range of prices. As discussed above, at least 322 €/ton CO_2 is needed to make the supply chain profitable. Contrariwise, scenarios 5 and 6 are economically feasible at lower carbon prices (below 80 €/ton CO_2). However, both scenarios would require retrofitting the current precast production processes. Additionally, scenario 5 also necessitates relocating the precast production facilities, which can be very challenging and involve structural changes along the supply chain. Similar to scenarios 3 and 4, scenarios 5 and 6 are also limited by the regional capacities. Overall, these values could be relatively higher than the typical costs associated with sequetring CO_2 via geological storage (pipeline transport = 2.5 – 16 €/ton CO_2, railway transport = 11.5 – 29 €/ton CO_2, geological storage = 11.5 – 29 €/ton CO_2) [56–58]. Nonetheless, geological storage

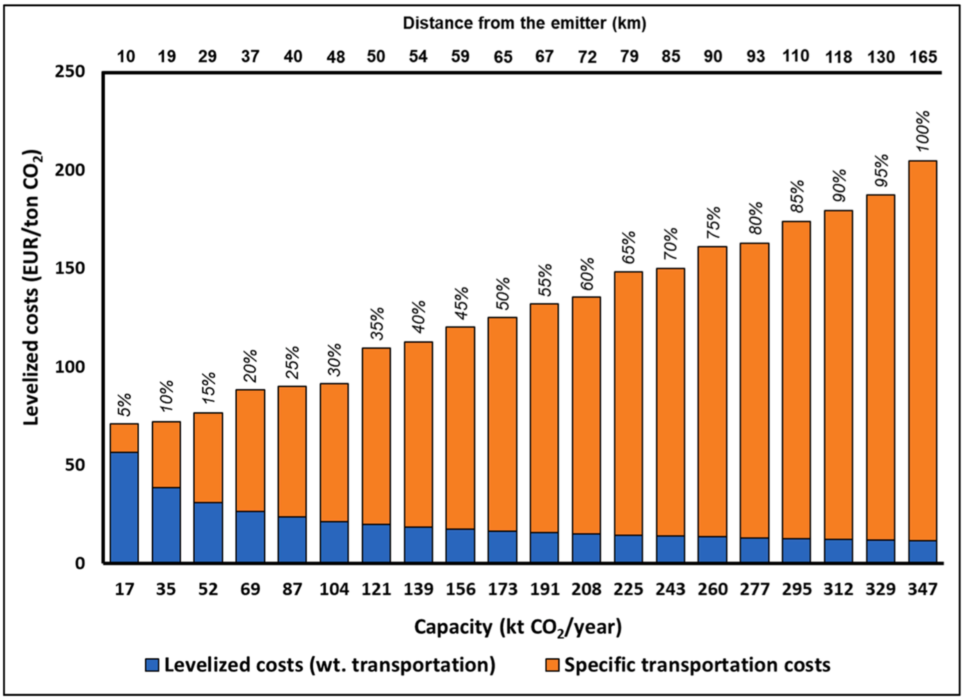

Fig. 8. Results of scenario 5, CO_2 concrete curing at cement plant. Percentages above the bars show the percentage of precast concrete production in NRW.

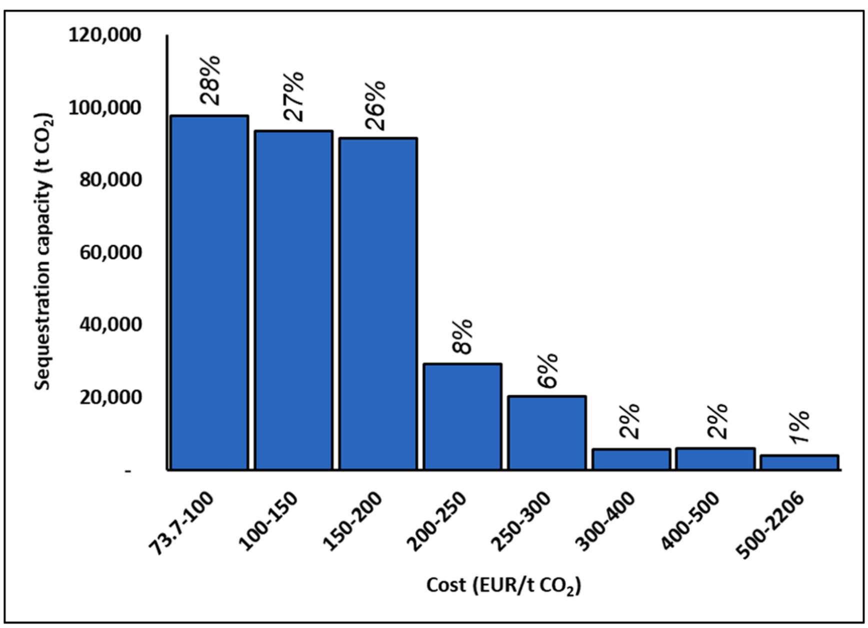

Fig. 9. Results of scenario 6. CO_2 concrete curing at precast concrete plants. Percentages above the bars show the percentage of precast concrete production in NRW.

remains subject to uncertainties regarding the actual costs, technical risks, societal opposition and legal complexities [59]. Therefore, exploring all possible CO_2 sequestration methods can be beneficial to enhance the likelihood of meeting climate goals.

In this regard, the comparative exploration presented in this study enhances the comprehension of the diverse pathways to carbon sequestration and underscores the importance of informed decision-making regarding carbon utilization pathways. Notably, while CO_2 mineralization of virgin minerals emerges as a promising avenue with its distinct advantages, such as scalability and efficiency, CO_2 concrete curing and CO_2 mineralization of waste cement are constrained by the availability of necessary materials. Hence, the boundaries imposed by domestic availability highlight the complex interplay between technological innovation and resource constraints. The results also highlight the pivotal role of economies of scale in driving down costs, with centralized scenarios demonstrating superior economic performance. While the centralized model proves feasible for the mineralization and waste cement carbonation, it presents high challenges for concrete curing, necessitating innovative solutions to overcome logistical hurdles. This may necessitate restructuring the entire cement and concrete supply chain, which is currently highly decentralized. Furthermore, the study underscores the pressing need for a deeper understanding of the properties, economics, and market demand surrounding byproducts such as SCM and filling materials. These matrials are essential for

Table 2
The feasibility of different scenarios based on the carbon prices and the economically viable CO_2 sequestration capacity.

	CO_2 mineralization of virgin minerals		CO_2 mineralization of waste concrete		CO_2 concrete curing	
Carbon price	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
60 (€/t CO_2)	✗	✗	✗	✗	✗	✗
80 (€/t CO_2)	✗	100 kt CO_2/a	✗	✗	52 kt CO_2/a	44 kt CO_2/a
100 (€/t CO_2)	✗	100 kt CO_2/a	✗	✗	104 kt CO_2/a	98 kt CO_2/a
120 (€/t CO_2)	✗	No limit	✗	✗	139 kt CO_2/a	139 kt CO_2/a
140 (€/t CO_2)	No limit	No limit	108 kt CO_2/a	✗	208 kt CO_2/a	183 kt CO_2/a
160 (€/t CO_2)	No limit	No limit	108 kt CO_2/a	✗	277 kt CO_2/a	198 kt CO_2/a

sustainable carbon utilization strategies, as CO_2 sequestration in mineral products is only possible if there is a demand for these materials. Overall, the analyses offer valuable insights into the complexities of optimizing carbon utilization pathways, laying the groundwork to find innovative solutions and derive strategies and roadmaps to pursue environmental sustainability.

CRediT authorship contribution statement

Walther Grit: Writing – review & editing, Supervision, Methodology, Conceptualization. **Stephan Dietmar:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Strunge Till:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Abdelshafy Ali:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization.

Funding

Till Strunge has been funded by the project 'Seq-kalz', which was funded by the German Federal Ministry of Education and Research (BMBF), Berlin, Germany [03VP11410].

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Till Strunge reports financial support was provided by Federal Ministry of Education and Research. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jcou.2025.103092.

Data availability

Data will be made available on request.

References

[1] M. Crippa, D. Guizzardi, F. Pagani, M. Banja, M. Muntean, E. Schaaf, W.E. Becker, F. Monforti-Ferrario, R. Quadrelli, A. Risquez Martin, P. Taghavi-Moharamli, J. Köykkä, G. Grassi, S. Rossi, J. Melo, D. Oom, A. Branco, J. San-Miguel, E. Vignati, GHG emissions of all world countries, Sci. Anal. Rev. (2023) 1831–9424, https://doi.org/10.2760/953322.

[2] S.P. Deolalkar, Designing Green Cement Plants, Elsevier, 2016.

[3] B. Lothenbach, K. Scrivener, R.D. Hooton, Supplementary cementitious materials, Cem. Concr. Res. 41 (2011) 1244–1256, https://doi.org/10.1016/j.cemconres.2010.12.001.

[4] M. Moreaux, J.-P. Amigues, G. van der Meijden, C. Withagen, Carbon capture: Storage vs. Utilization, J. Environ. Econ. Manag. 125 (2024) 102976, https://doi.org/10.1016/j.jeem.2024.102976.

[5] ZEP, CCU - Carbon Capture and Utilization, 2016, ⟨https://zeroemissionsplatform.eu/wp-content/uploads/ZEP-report-CCU-08032016.pdf⟩, accessed 14 July 2024.

[6] W. Terlouw, D. Peters, J. van Tilburg, M. Schimmel, T. Berg, J. Cihlar, G. Ur Rehman Mir, M. Spöttle, M. Staats, A. Villar Lejaretta, M. Buseman, M. Schenkel, I. van Hoorn, C. Wassmer, E. Kamensek, T. Fichter, Gas for Climate. The optimal role for gas in a net zero emissions energy system, 2019, ⟨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⟩, accessed 14 July 2024.

[7] B. Metz, O.R. Davidson, H. de Coninck, M. Loos, L. Meyer, IPCC special report on carbon dioxide capture and storage, Published for the Intergovernmental Panel on Climate Change. Canadian Electronic Library, Cambridge [England], New York, NY, Beaconsfield, Quebec, Cambridge University Press, 2013.

[8] H. El-Hassan, Y. Shao, Carbon Storage through Concrete Block Carbonation, JOCET (2014) 287–291, https://doi.org/10.7763/JOCET.2014.V2.141.

[9] Z. He, Z. Li, Y. Shao, Effect of carbonation mixing on CO2 uptake and strength gain in concrete, J. Mater. Civ. Eng. 29 (2017), https://doi.org/10.1061/(ASCE)MT.1943-5533.0002031.

[10] V. Rostami, Y. Shao, A.J. Boyd, Carbonation curing versus steam curing for precast concrete production, J. Mater. Civ. Eng. 24 (2012) 1221–1229, https://doi.org/10.1061/(ASCE)MT.1943-5533.0000462.

[11] D. Zhang, Z. Ghouleh, Y. Shao, Review on carbonation curing of cement-based materials, J. CO2 Util. 21 (2017) 119–131, https://doi.org/10.1016/j.jcou.2017.07.003.

[12] J. Wang, G. Long, Y. Xiang, R. Dong, Z. Tang, Q. Xiao, Z. Yang, K. Ma, Influence of rapid curing methods on concrete microstructure and properties: A review, Case Stud. Constr. Mater. 17 (2022) e01600, https://doi.org/10.1016/j.cscm.2022.e01600.

[13] Y. Shao, Beneficial Use of Carbon Dioxide in Precast Concrete Production, 2014.

[14] Y. Shao, S. Monkman, S. Wang (Eds.), Market analysis of CO2 sequestration in concrete building products, 2010.

[15] A. Sanna, M. Uibu, G. Caramanna, R. Kuusik, M.M. Maroto-Valer, A review of mineral carbonation technologies to sequester CO2, Chem. Soc. Rev. 43 (2014) 8049–8080, https://doi.org/10.1039/C4CS00035H.

[16] T. Strunge, P. Renforth, M. van der Spek, Towards a business case for CO2 mineralisation in the cement industry, Commun. Earth Environ. 3 (2022), https://doi.org/10.1038/s43247-022-00390-0.

[17] C.M. Woodall, N. McQueen, H. Pilorgé, J. Wilcox, Utilization of mineral carbonation products: current state and potential, Greenh. Gases 9 (2019) 1096–1113, https://doi.org/10.1002/ghg.1940.

[18] D. Kremer, T. Strunge, J. Skocek, S. Schabel, M. Kostka, C. Hopmann, H. Wotruba, Separation of reaction products from ex-situ mineral carbonation and utilization as a substitute in cement, paper, and rubber applications, J. CO2 Util. 62 (2022) 102067, https://doi.org/10.1016/j.jcou.2022.102067.

[19] H. Ostovari, A. Sternberg, A. Bardow, Rock 'n' use of CO 2 carbon footprint of carbon capture and utilization by mineralization, Sustain. Energy Fuels 4 (2020) 4482–4496, https://doi.org/10.1039/D0SE00190B.

[20] D. Sandalow, R. Aines, J. Friedmann, C. McCormick, S. McCoy, Carbon Dioxide Utilization (CO2U) ICEF Roadmap 2.0. Draft October 2017, 2017.

[21] D. Kremer, S. Etzold, J. Boldt, P. Blaum, K.M. Hahn, H. Wotruba, R. Telle, Geological mapping and characterization of possible primary input materials for the mineral sequestration of carbon dioxide in Europe, Minerals 9 (2019) 485, https://doi.org/10.3390/min9080485.

[22] B. Olfe-Kräutlein, T. Strunge, A. Chanin, Push or pull? Policy barriers and incentives to the development and deployment of CO2 utilization, in particular CO2 mineralization, Front. Energy Res. 9 (2021), https://doi.org/10.3389/fenrg.2021.742709.

[23] IEA, Putting CO2 to Use - Creating value from emissions, 2019, ⟨https://iea.blob.core.windows.net/assets/50652405-26db-4c41-82dc-c23657893059/Putting_CO2_to_Use.pdf⟩, accessed 11 July 2024.

[24] H. Ostovari, L. Müller, F. Mayer, A. Bardow, A climate-optimal supply chain for CO2 capture, utilization, and storage by mineralization, J. Clean. Prod. 360 (2022) 131750, https://doi.org/10.1016/j.jclepro.2022.131750.
[25] T. Strunge, L. Küng, P. Renforth, M. van der Spek, Marginal cost curves for decarbonizing the European cement industry, SSRN J. (2022), https://doi.org/10.2139/ssrn.4286149.
[26] A. Abdelshafy, G. Walther, Coupling carbon capture and utilization with the construction industry: Opportunities in Western Germany, J. CO2 Util. 57 (2022) 101866, https://doi.org/10.1016/j.jcou.2021.101866.
[27] T.M. Strunge, L. Kung, N. Sunny, N. Shah, P. Renforth, M. van der Spek, Marginal Cost Curves Show Least-Cost, Full Decarbonisation of European Cement Includes CO2 Capture and Storage, Alternative Clinkers, and Carbon Dioxide Removal, 2024.
[28] V. Sick, K. Armstrong, G. Cooney, L. Cremonese, A. Eggleston, G. Faber, G. Hackett, A. Kätelhön, G. Keoleian, J. Marano, J. Marriott, S. McCord, S.A. Miller, M. Mutchek, B. Olfe-Kräutlein, D. Ravikumar, L.K. Roper, J. Schaidle, T. Skone, L. Smith, T. Strunge, P. Styring, L. Tao, S. Völker, A. Zimmermann, The Need for and Path to Harmonized life cycle assessment and techno-economic assessment for carbon dioxide capture and utilization, Energy Tech. 8 (2020), https://doi.org/10.1002/ente.201901034.
[29] A.J.K. Newman, P. Styring, The pursuit of methodological harmonization within the holistic sustainability assessment of CCU projects: a history and critical review, Front. Sustain 3 (2023), https://doi.org/10.3389/frsus.2022.1057476.
[30] V. Sick, K. Armstrong, S. Moni, Editorial: Harmonizing life cycle analysis (LCA) and techno-economic analysis (TEA) guidelines: a common framework for consistent conduct and transparent reporting of carbon dioxide removal and CCU technology appraisal, Front. Clim. 5 (2023), https://doi.org/10.3389/fclim.2023.1204840.
[31] IEAGHG, IEAGHG Technical Review: Towards improved guidelines for cost evaluation of carbon capture and storage, 2021, ⟨https://www.cmu.edu/epp/iecm/rubin/PDF%20files/2021/IEAGHG_2021-TR05%20Towards%20improved%20guidelines%20for%20cost%20evaluation%20of%20CCS.pdf⟩, accessed 11 July 2024.
[32] T. Langhorst, S. McCord, A. Zimmermann, L. Müller, L. Cremonese, T. Strunge, Y. Wang, A.V. Zaragoza, J. Wunderlich, A. Marxen, K. Armstrong, G. Buchner, A. Kätelhön, M. Bachmann, A. Sternberg, S. Michailos, H. Naims, B. Winter, D. Roskosch, G. Faber, C. Mangin, B. Olfe-Kräutlein, P. Styring, R. Schomäcker, A. Bardow, V. Sick, Techno-economic assessment & life cycle assessment guidelines for CO2 Utilization (Version 2.0), Glob. CO2 Initiat. (2022).
[33] E.S. Rubin, N. Berghout, G. Booras, T. Fout, M. Garcia, S.M. Nazir, A. Ramirez Ramirez, S. Roussanaly, M. van der Spek, Toward IMproved Cost Guidelines for Advanced Low-carbon Technologies, SSRN J. (2021), https://doi.org/10.2139/ssrn.3818896.
[34] R. Smith, Chemical process design and integration, John Wiley & Sons, Chichester, [Angleterre, 2016.
[35] E.S. Rubin, C. Short, G. Booras, J. Davison, C. Ekstrom, M. Matuszewski, S. McCoy, A proposed methodology for CO2 capture and storage cost estimates, Int. J. Greenh. Gas. Control 17 (2013) 488–503, https://doi.org/10.1016/j.ijggc.2013.06.004.
[36] Chemical Engineering Design, Elsevier, 2022.
[37] Ports, Sea route & distance: Port of Bergen, Norway to Port of Wilhelmshaven, Germany, 2024, ⟨http://ports.com/sea-route/port-of-bergen,norway/port-of-wilhelmshaven,germany/⟩, accessed 15 July 2024.
[38] WSV, Die Wasserstraßen- und Schifffahrtsverwaltung des Bundes (WSV), 2024, ⟨https://via.bund.de/wsv/elwis/map/#⟩, accessed 15 July 2024.
[39] DESTATIS, Qualitätsbericht - Erhebung über die Aufbereitung und Verwertung von Bau- und Abbruchabfällen (Statistisches Bundesamt) (2020).
[40] DESTATIS, Qualitätsbericht - Produktionserhebungen (Statistisches Bundesamt) (2021).
[41] DESTATIS, Güterverzeichnis für Produktionsstatistiken, Ausgabe 2019 (GP 2019). Statistisches Bundesamt (2018).
[42] BMJV, Verordnung über das Europäische Abfallverzeichnis (Abfallverzeichnis-Verordnung - AVV) (Bundesministeriums der Justiz und für Verbraucherschutz) (2001).
[43] QGIS, QGIS software, 2024, ⟨https://www.qgis.org/⟩, accessed 15 July 2024.
[44] D. Bernacki, Assessing the Link between Vessel Size and Maritime Supply Chain Sustainable Performance, Energies 14 (2021) 2979, https://doi.org/10.3390/en14112979.
[45] B. Wiegmans, R. Konings, Intermodal inland waterway transport: modelling conditions influencing its cost competitiveness, Asian J. Shipp. Logist. 31 (2015) 273–294, https://doi.org/10.1016/j.ajsl.2015.06.006.
[46] S. Van der Meulen, T. Grijspaardt, W. Mars, W. Van der Geest, A. Roest-Crollius, J. Kiel, Cost figures for freight transport - final report (2020).
[47] Y. Shao, H. El Hassan (Eds.), CO2 utilization in concrete, 2013.
[48] PCA, Applications of Cement, 2025, ⟨https://www.cement.org/cement-concrete/applications-of-cement/⟩, accessed 4 March 2025.
[49] M.W. Tait, W.M. Cheung, A comparative cradle-to-gate life cycle assessment of three concrete mix designs, Int J. Life Cycle Assess. 21 (2016) 847–860, https://doi.org/10.1007/s11367-016-1045-5.
[50] E. Eikeland, A.B. Blichfeld, C. Tyrsted, A. Jensen, B.B. Iversen, Optimized carbonation of magnesium silicate mineral for CO2 storage, ACS Appl. Mater. Interfaces 7 (2015) 5258–5264, https://doi.org/10.1021/am508432w.
[51] S.J. Gerdemann, W.K. O'Connor, D.C. Dahlin, L.R. Penner, H. Rush, Ex situ aqueous mineral carbonation, Environ. Sci. Technol. 41 (2007) 2587–2593, https://doi.org/10.1021/es0619253.
[52] A. Iizuka, A. Yamasaki, Y. Yanagisawa, Cost evaluation for a carbon dioxide sequestration process by aqueous mineral carbonation of waste concrete, J. Chem. Eng. Jpn. / JCEJ 46 (2013) 326–334, https://doi.org/10.1252/jcej.12we237.
[53] A. Iizuka, M. Fujii, A. Yamasaki, Y. Yanagisawa, Development of a new CO2 sequestration process utilizing the carbonation of waste cement, Ind. Eng. Chem. Res. 43 (2004) 7880–7887, https://doi.org/10.1021/ie0496176.
[54] Y. Katsuyama, A. Yamasaki, A. Iizuka, M. Fujii, K. Kumagai, Y. Yanagisawa, Development of a process for producing high-purity calcium carbonate (CaCO3) from waste cement using pressurized CO 2, Environ. Prog. 24 (2005) 162–170, https://doi.org/10.1002/ep.10080.
[55] M. Pahle, J. Sitarz, S. Osorio, B. Görlach, The EU-ETS price through 2030 and beyond: A closer look at drivers, models and assumptions - Input material and takeaways from a workshop in Brussels, 2022, ⟨https://ariadneprojekt.de/media/2023/01/Ariadne-Documentation_ETSWorkshopBruessel_December2022.pdf⟩, accessed 12 July 2024.
[56] ZEP, Business models for commercial CO2 transport and storage - Delivering large-scale CCS in Europe by 2030, 2014, ⟨https://zeroemissionsplatform.eu/wp-content/uploads/ZEP-report-on-Business-Models-for-Commercial-CO2-Transport-and-Storage.pdf⟩, accessed 10 March 2025.
[57] M. Al-Juaied, A. Whitmore, Prospects for Direct Air Carbon Capture and Storage: Costs, Scale, and Funding, 2023, ⟨https://www.belfercenter.org/publication/prospects-direct-air-carbon-capture-and-storage-costs-scale-and-funding⟩, accessed 10 March 2025.
[58] J.-F. Gruson, S. Serbutoviez, F. Delprat-Jannaud, M. Akhurst, C. Nielsen, F. Dalhoff, P. Bergmo, C. Bos, V. Volpi, S. Iacobellis, Techno-economic assessment of four CO 2 storage sites, Oil Gas. Sci. Technol. – Rev. IFP Energ. Nouv. 70 (2015) 753–766, https://doi.org/10.2516/ogst/2014057.
[59] A. Abdelshafy, M. Lambert, G. Walther, The role of CCUS in decarbonizing the cement industry: a German case study, Energy Insight (2022).