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Towards a European supply chain for CO_2 capture, utilization, and storage by mineralization: Insights from cost-optimal design

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ABSTRACT

Carbon dioxide (CO_2) capture, utilization, and storage (CCUS) by mineralization has been shown to reduce greenhouse gas (GHG) emissions not only in stand-alone plants but also in large-scale climate-optimal supply chains. Yet, implementing the large-scale supply chain for CCUS by mineralization requires a substantial financial investment and, thus, a deep understanding of its economics. The current literature estimates the economics of CO_2 mineralization for stand-alone plants. While CO_2 mineralization plants have their specific a) CO_2 supply, b) solid feedstock supply, c) energy supply, and d) product market, the plant-level cost estimation does not account for a large and potentially shared supply chain. In our study, we assess the economics of mineralization by designing and analyzing cost-optimal supply chains for CCUS by mineralization in Europe. Our results show that the CO_{2e} abatement costs of individual mineralization plants in a supply chain range from 110 to 312 €/ton CO_{2e} avoided. The proposed supply chains for CCUS by mineralization can avoid 60 Mt CO_{2e}/year in Europe at CO_{2e} abatement costs comparable to CO_2 capture and geological storage. Furthermore, we identify five locations that could offer a robust business case for CO_2 mineralization. The analysis thus shows pathways on how to add CO_2 mineralization to the GHG mitigation portfolio of Europe.

1. Introduction

Reducing the eight gigatons (Gt) of greenhouse gas (GHG) emitted annually by industry requires not only a transition toward renewable energy supply but also the implementation of carbon dioxide (CO_2) capture, utilization, and storage (CCUS) [1]. A promising CCUS technology is CO_2 mineralization. To permanently store CO_2 by mineralization, CO_2 reacts with calcium oxide-bearing (CaO) or magnesium oxide-bearing (MgO) materials and produces stable carbonates [2]. The CaO-/MgO-bearing materials can be industrial byproducts such as steel slag, or natural minerals such as olivine and serpentine. Reaction (1) shows CO_2 mineralization of forsterite (Mg_2SiO_4).

$$Mg_2SiO_4 + 2\ CO_2 \rightarrow 2\ MgCO_3 + SiO_2 + \text{heat}\cdot \tag{1}$$

Forsterite is the main component of olivine and is an example of MgO-bearing materials [3].

CO_2 mineralization can avoid GHG emissions not only by capturing and permanently storing CO_2 but also by yielding value-added products utilized in, e.g., the cement industry [4,5]. Silicates (SiO_2), the byproduct of CO_2 mineralization, can act as a pozzolanic material and partially substitute clinker in the cement industry [6,7]. Also, the main product of CO_2 mineralization, carbonates, can be utilized in the industry [8].

Several studies showed that CO_2 mineralization could avoid GHG emissions by converting CO_2 and utilizing its products [4,8–10]. In Europe, CO_2 mineralization could avoid up to 160 Mt CO_{2e}/year, yet, this saving requires a large-scale and climate-optimal supply chain that captures, utilizes, and stores CO_2 [11]. The proposed climate-optimal supply chain for CCUS by mineralization optimally matches mineralization plants with the four key elements: a) CO_2 sources, b) solid feedstock sources, c) energy supply system, and d) product market. Although the climate benefits of CCUS by mineralization have been quantified [11], scaling up the mineralization technology and the supply chain infrastructure requires a substantial investment. Thus, implementing CO_2 mineralization at a large scale requires a deep understanding of its economics, e.g., capital and operational expenditures.

Several studies estimated the economics of mineralization by calculating the cost of mineralizing CO_2 at a stand-alone mineralization plant, with fixed assumptions for the layout of the four key

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elements [9,12–19]:

a) CO_2 supply: type of CO_2 source, CO_2 transportation distance and method,

b) Solid feedstock supply: type of solid feedstock, solid feedstock transportation distance and method,

c) Energy supply: availability, cost, and GHG emissions of energy supply,

d) Product market: availability, size, price, and distance of the market for mineralization products.

The plant-level cost assessments of mineralizing CO_2 have given insights into its economics. The reported costs range from 50 to 425 € per ton of stored CO_2 [9,12–19]. This large variation by almost an order of magnitude in reported costs is due to the broad spectrum of possible assumptions.

In a large-scale supply chain for CCUS by mineralization, however, mineralization does not occur in stand-alone plants that are all located at the same site with identical parameters for their key elements [11]. In contrast, individual mineralization plants compete with each other for limited resources, such as low-emission energy and the product market. Thus, the performance of each mineralization plant depends strongly on the supply chain. Consequently, assessing the large-scale economics of mineralization requires considering the entire supply chain and optimizing its cost. Literature on CO_2 capture and geological storage (CCGS) confirms that understanding the large-scale economics of CO_2 capture and storage technologies requires designing the whole supply chain to reveal the system's cost [20–23].

Since the motivation for CO_2 mineralization is climate change mitigation, the cost of the supply chain must be related to the avoided GHG emissions. CO_2 mineralization is energy-intensive and causes GHG emissions that can partially offset the CO_2 stored by mineralization. Therefore, the amount of avoided GHG emissions differs from the amount of stored CO_2 in a mineralization plant. The avoided GHG emissions vary substantially for individual mineralization plants in a supply chain and can only be estimated via designing the entire supply chain [11]. From this design, the avoided CO_{2e} per ton of captured CO_2 can derive the GHG-emission-reduction indicator. However, such an economic assessment of implementing CO_2 mineralization on a large scale is missing.

Here, we, therefore, design cost-optimal supply chains to capture, utilize, and store CO_2 by mineralization in Europe, considering both supply-chain-related and uncertain parameters. Our results show that the CO_{2e} abatement costs of individual mineralization plants in a supply chain range from 110 to 312 €/ton CO_{2e} avoided. This emphasizes that the economics of CO_2 mineralization can only be determined by designing the entire supply chain and not by individual plant-level cost assessments. Our scenario analysis illustrates the strong dependence of CO_2 mineralization economics on uncertain parameters. Yet, for all scenarios, supply chains for CCUS by mineralization can avoid 60 Mt CO_{2e}/year in Europe at CO_{2e} abatement costs comparable to CO_2 capture and geological storage. From the scenario analysis, we derive five locations that could offer a robust business case for CO_2 mineralization. Hence, CO_2 mineralization appears to be a promising option for the GHG mitigation portfolio of Europe.

Section ↱2 presents the layout of the CCUS supply chains regarding the solid feedstock, CO_2, and energy supply as well as the background data used for our model. Sections ↱3.1 and ↱3.2 introduce our approach to designing cost-optimal supply chains. Section ↱3.3 describes the considered scenarios. In Section ↱4.1, we analyze the cost-optimal supply chain of CCUS by mineralization for a base-case scenario. Section ↱4.2 investigates the effects of uncertain parameters on the economics of CO_2 mineralization using scenario analysis. Based on the scenario analysis, we identify five promising locations for CO_2 mineralization plants (Section ↱4.3). Section ↱5 summarizes the results of our study and provides a vision for the large-scale economics of CCUS by mineralization.

2. Materials: technologies, options, data, and scope for supply chains

The considered supply chain for CCUS by mineralization (Fig. 1) cost-optimally connects mineralization plants to their four key elements: a) CO_2 source, b) solid feedstock source, c) energy supply system, and d) product market while considering the entire supply chain.

The solid feedstock ($(MO)SiO_2$) is obtained by mining in the case of natural minerals or directly collected from a production site in the case of industrial byproducts. The obtained solid feedstock is transported to the mineralization plant, where it is activated using energy. CO_2 is captured from industrial sources or directly from the atmosphere using direct air capture and transported to the mineralization plant. The supplied CO_2 reacts with the activated solid feedstock to produce carbonates (MCO_3) and silicates (SiO_2, Fig. 1). The main product of mineralization, MCO_3, is sent back to the location of the solid feedstock supply to be stored safely and permanently. The byproduct of mineralization, SiO_2, is transported to cement plants to be used as a pozzolanic material and partially substitute cement (Fig. 1). The partial substitution of cement avoids GHG emissions related to conventional cement production and improves the economic potential of CO_2 mineralization. At several points in the supply chain of CCUS by mineralization, energy is required which is supplied via regional energy systems. To design supply chains for CCUS by mineralization, all stages of CCUS by mineralization need to be analyzed based on a sound database.

In this section, we explain the considered technologies, options, and data along the entire supply chain for CCUS by mineralization. Section ↱2.1 introduces the options for solid feedstock, $CO_{2,}$ and energy supply. In Section ↱2.2, we present the considered data for the entire supply chain, followed by defining the scope of our study in Section ↱2.3.

2.1. Options for solid feedstock, CO_2, and energy supply

Mineralization is still in the development phase; therefore, real-world data is unavailable for a large-scale mineralization supply chain. Yet, several options are available to supply CO_2, solid feedstock, and energy. Here, we introduce the options considered for our CCUS supply chain.

CO_2 feedstock supply

The required CO_2 for a CCUS supply chain can be captured from CO_2 point sources or directly from the atmosphere. As CO_2 point sources, we select difficult-to-eliminate CO_2 emissions from the industry sector: steel, cement, chemical, and paper industries (cf. ESI Section S15 and Fig. S24). To capture CO_2 from the atmosphere, we use direct air capture (DAC) technology. Although the energy demand of DAC is currently higher than for CO_2 capture from point sources, DAC could enable negative emissions [24,25]. Furthermore, DAC is independent of location and can theoretically be installed everywhere. Thus, both options of CO_2 sources are considered.

The captured CO_2 can be transported to the mineralization plant either by pipeline or by truck. Transporting CO_2 via pipeline causes less GHG emissions than truck transportation [11]. Yet, the social acceptance and implementation of a CO_2 pipeline network could be critical [26,27]. Thus, we consider both CO_2 pipeline and truck transport.

Solid feedstock supply

The required solid feedstock for CO_2 mineralization could be obtained from natural minerals (olivine, serpentine) or from industrial byproducts (steel slag). For steel slag, the current production locations and capacities are known and thus used for our study (cf. ESI Section S15). For the natural solid feedstock, only five mines are currently active in Europe [28]. To explore the future potential, we consider potentially available mining sites as further natural solid feedstock options (cf. ESI Section S15).

Besides the location, the CCUS supply chain is affected by the extraction capacities of the natural solid feedstock [11]. The extraction

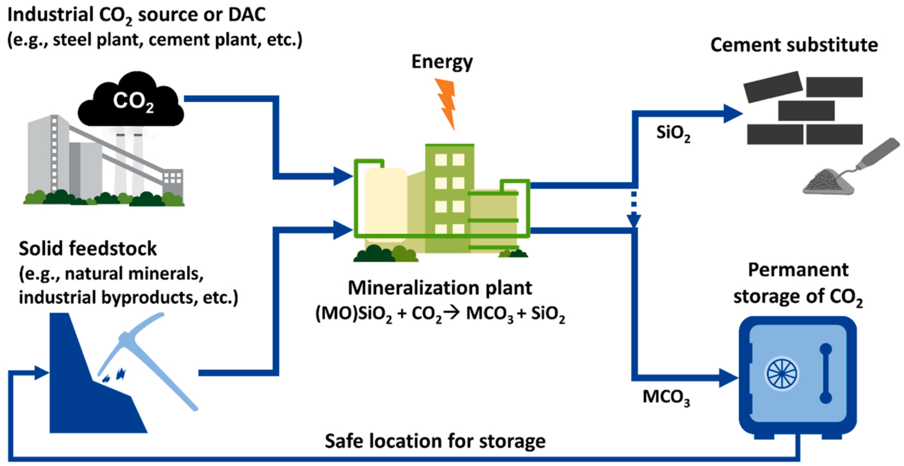

Fig. 1. The considered CO_2 capture, utilization, and storage by mineralization in our study. DAC is direct air capture. Silicates (SiO_2) are assumed to partially substitute cement. We assumed that carbonates (MCO_3) are sent back to the location of solid feedstock to be safely stored.

capacity of a natural solid feedstock site is determined by its mineral deposit. However, limited data on mineral deposits are available. To cover the potential extraction capacity of natural solid feedstock sites, we propose three options:

1- Present extraction capacity of the five active mines [28],

2- Extraction capacity of an average limestone mine (2.5 Mt minerals/year),

3- Extraction capacity of a large-scale copper mine (10 Mt minerals/year).

Energy supply

As CCUS by mineralization is energy-intensive, the energy supply affects the supply chain considerably. To analyze the role of energy supply, we consider two options: the current energy system, and a low-emission energy system. For the current energy system, the electricity supply in each country is based on its current national electricity mix (cf. ESI Section S16). Our study assumes that electric heating supplies the thermal heat demand in locations where the GHG emissions of natural gas combustion are higher than national electricity; elsewhere, natural gas combustion provides the required thermal heat demand. For the low-emission energy system, the electricity supply of all countries is based on the predicted European grid mix of 2040 (114 g CO_{2e}/kWh) [29]. In this case, electric heating is assumed to supply the required thermal heat demand entirely.

We consider all options described above for the supply of CO_2, solid feedstock, and energy. Yet, the specification of these options relies on future predictions that are uncertain. To reflect the effect of uncertain parameters on the economics of CO_2 mineralization, we define several scenarios in Section ↱3.3.

2.2. Life cycle inventories and expenditure

To design cost-optimal supply chains for CCUS by mineralization, we collect life cycle inventory (LCI) and expenditure data along the entire supply chain. The considered data are presented in the following.

*CO_2 mineralization*For each solid feedstock (olivine, serpentine, and steel slag), we consider a specific CO_2 mineralization technology. Our previous study used laboratory results by Eikeland et al. [30], Gerdemann et al. [14], and Huijgen et al. [31] to develop and analyze the entire CO_2 mineralization pathway for each solid feedstock [4]. From the specific CO_2 mineralization pathways, we derived LCIs that are presented in ESI Section S16 [11]. Following the work of Strunge et al. [19], we use cost estimation methods from the literature and the Aspen Capital Cost Estimator to calculate the costs of the main pieces of equipment [32–37]. The costs of the main pieces of equipment for the three mineralization technologies are presented in ESI Section S12, Table S1. From the total cost of the main pieces of equipment, we calculate other types of capital costs, such as piping and building costs using the approach of Peters et al. [38]. The capital expenditure (CapEx) is calculated by adding all types of capital costs (ESI Section S12, Table S2). The operational expenditure (OpEx) is divided into fixed OpEx and variable OpEx. The fixed OpEx, such as labor cost, is calculated from the total cost of the main pieces of equipment using the approach of Turton [39]. The variable OpEx, such as utility cost, is calculated from the mass and energy balances of LCIs using pricing data [40–43] (ESI Section S12, Table S3).

*CO_2 capture*LCIs, capital, and operational expenditure (CapEx, OpEx) of direct air capture are based on literature [24,44]. For CO_2 capture from CO_2 point sources, we consider amine scrubbing technology. We calculate the required energy demand for capturing CO_2 according to the CO_2 source type [45,46]. LCIs, capital, and operational expenditure (CapEx, OpEx) of CO_2 capture from point sources are based on literature (ESI Section S12 and S16). The amount and location of available CO_2 from point sources are taken from the report of the European Environment Agency [47] and completed using von der Assen et al. [45] (ESI Section S15).

*CO_2 transport*LCIs, capital, and operational expenditure (CapEx, OpEx) of CO_2 transport by pipeline or truck are based on literature and presented in ESI Sections S12 and S16.

*Energy supply*We consider data from LCA databases for the environmental impacts of each country's current thermal energy supply and electricity supply (ESI Section S16). The current cost of electricity and thermal energy are based on Eurostat databases [40,41]. For low-emission energy, the environmental impacts and costs are taken from LCA databases and literature [29,48].

*Product market*We assume that the main product of mineralization, carbonate (MCO_3), is transported back to the site of the solid feedstock source to be permanently stored. Carbonates are very stable and can store CO_2 for several hundred years. However, high temperatures (above 350 °C) and strong acids could still release the CO_2 from MCO_3. Furthermore, the carbonates from the mineralization have a particle size in the range of micrometers and could contain a trace amount of solvents. Thus, to ensure the permanent storage of the captured CO_2, we assume that the carbonates are landfilled in a protected area at the mining site. Silicate (SiO_2), the byproduct of mineralization, however, is utilized in the cement industry to partially substitute cement (Fig. 1). The silicate (SiO_2) is a pozzolan, yet, not a self-cementing material. Thus, SiO_2 cannot completely substitute cement. We assume 20 wt% substitution fraction since at this fraction, the effect of pozzolanic material on the performance of the cement is still limited such that the performance standards for CEMII can be fulfilled [49–53]. The location and production capacity of cement plants are based on the European Environment Agency report [47]. LCIs, capital, and operational expenditure (CapEx, OpEx) of cement production are calculated using LCA databases and literature (ESI Section S16, [42]).

2.3. Goal and scope of our assessment

Our study aims to analyze the large-scale economics of CO_2 mineralization. The economics of CO_2 mineralization is expressed by the CO_{2e} abatement cost, i.e., the cost of avoiding CO_{2e} emission. To determine the avoided GHG emissions due to CCUS by mineralization, we apply the standardized life cycle assessment method (LCA, 54–57). Following the recommendation for LCA of the European Commission, we calculate the climate impact according to IPCC [58]. For other environmental impacts, we use the life cycle impact assessment method of ReCiPe [59]. We consider the cradle-to-grave environmental impacts of the required products for the supply chain of CCUS by mineralization (ESI Section S16). The cost of the supply chains is calculated according to the techno-economic assessment method described by Zimmerman et al. [60] and the study of Strunge et al. [19].

For utilization of the mineralization byproduct (SiO_2), the SiO_2 is assumed to be sold to cement plants to substitute 20 wt% of cement and produce CEM II. The CEM II already counts for 58% of the European cement market and can be used in most cement applications. Thus, we assume that the blended cement's (CEM II) performance and cost are equal to conventional cement (CEM I) [8,49–51,61,62].

We analyze the avoided GHG emission by introducing CCUS by mineralization in the industry sector. The GHG emission mitigation due to CCUS by mineralization is the difference between the GHG emissions of the industry sector with and without CCUS by mineralization. Since sound data for Europe is available, we choose Europe for the regional scope of our study. It is worth noting that our study can be expanded using other regions of the world if data is available.

3. Methods: supply-chain design approach

The cost-optimal supply chain for CCUS by mineralization employs the most cost-efficient mineralization plants and their supply chain while fulfilling design constraints and the GHG mitigation target. Using a single-stage optimization problem to design cost-optimal supply chains requires simultaneously considering all direct and indirect connections for the CO_2 sinks and the CO_2 sources, 1067 and 1500 locations, respectively. The resulting combination complexity considerably increases the size of the optimization problem and, consequently, the computational time to solve the optimization problem. Middleton and Bielicki [63] concluded that the exact configuration of the CO_2 pipeline network has a limited impact on the total costs of a CCS supply chain. Here, we assume that decompressing the problem into a two-step problem has a limited effect on the quality of our results. Thus, following the literature on supply chains for CO_2 capture and storage, we design cost-optimal supply chains for CCUS by mineralization via solving two optimization problems (Fig. 2): 1) sink-source matching and subsequent 2) local pipeline network design [11,64–66]. The sink-source matching optimization (Section ↱3.1) connects each CO_2 source (i) directly to a CO_2 sink (j) to minimize the total annual cost of the entire supply chain while achieving the GHG mitigation target (Fig. 2). The connected CO_2 sources and CO_2 sinks are carried to the local pipeline network design optimization (Section ↱3.2). The local pipeline network design optimization minimizes the total annual cost of operating and building the required CO_2 pipeline network by allowing indirect connections through other CO_2 sources and thereby modifying the local CO_2 pipeline network (Fig. 2). We present the considered scenarios for our study in Section ↱3.3.

3.1. First optimization problem: sink-source matching

The cost of a mineralization plant depends on its location (e.g., transport distances, energy cost, etc.) and the configuration of the supply chain (e.g., available product market, available CO_2 source, etc.). The sink-source matching optimization matches the mineralization plants to CO_2 and solid feedstock sources to design the most cost-efficient supply chain while fulfilling the GHG mitigation target. Our

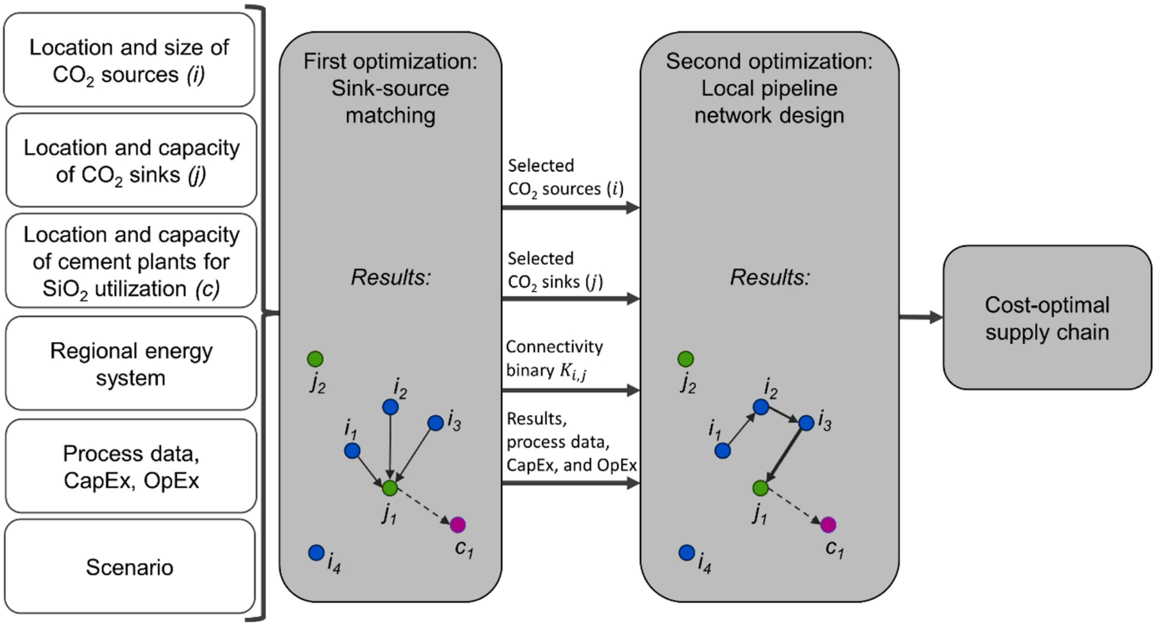

Fig. 2. Illustration of the sink-source matching and the local pipeline network design optimization problems and their solutions for cost-optimal supply chain. (i) marks CO_2 sources.(j) indicates possible locations for CO_2 sinks. We assumed that the byproducts of CO_2 mineralization is utilized in cement plants (c) to partially substitute cement.

Table 1
Parameters and variables of the sink-source matching optimization for cost-optimal supply chain (cf. ESI Section S13).

Variables	Parameters
$W_{c,j}$, $Y_{i,j}$, Z_j, $Mass_j^{ExcessSiO2}$	$Cost_{i,j}^{CCSM}$, $Revenue_{c,j}^{Utilization}$, $D_{c,j}$, $D_j^{ToStorage}$, $Cost^{SolidTransport}$, $Cost^{SiteConstruction}$, F_i, $Size_j^{Max}$, $Size_j^{Min}$, $D^{LongestCO2}$, $Mass_{i,j}^{ProducedSiO2}$, $CapEx_i^{capture}$, $OpEx_i^{capture}$, $\overline{OpEx}_{i,j}^{CO2Transport}$, $\overline{CapEx}_{i,j}^{CO2Transport}$, $CapEx_{i,j}^{mineralization}$, $OpEx_{i,j}^{mineralization}$, $Cost_{i,j}^{mining}$, $Cost_{i,j}^{CarbonateTransport}$ $Cost_{i,j}^{FeedstockTransport}$, $OpEx_{i,j}^{other}$, $Mass_{c,j}^{UtilizedSiO2}$, $D^{LongestSiO2}$, $GHG_{i,j}^{avoidedbyCCS}$, $GHG_{c,j}^{avoidedbyCCU}$, $GHG^{SolidTransport}$, $GHG^{SiteConstruction}$, GHG^{target}

sink-source matching optimization model is a modified version of the mixed-integer linear program (MILP) optimization model developed by Hasan et al. [65]. The objective function minimizes the total annual cost (TAC) of the supply chain for CCUS by mineralization (Eq. 1 and Table 1).

Objective function

$$\min_{W_{c,j},Y_{i,j},Z_j,Mass_j^{ExcessSiO2}} \sum_{i\epsilon I}\sum_{j\epsilon J}\left(Cost_{i,j}^{CCSM}\cdot Y_{i,j}\right)-\sum_{c\epsilon C}\sum_{j\epsilon J}\left(Revenue_{c,j}^{Utilization}\cdot W_{c,j}\right)+\sum_{j\epsilon J}\left(Cost^{SolidTransport}\cdot Mass_j^{ExcessSiO2}\cdot D_j^{ToStorage}\right)+\sum_{j\epsilon J}\left(Cost^{SiteConstruction}\cdot Z_j\right). \tag{1}$$

Here, i indicates a CO_2 source, e.g., ammonia, cement plants, etc., c marks a cement plant, and j expresses a CO_2 sink, i.e., a potential location for a CO_2 mineralization plant (cf. ESI Section S15). Each mineralization plant can be supplied from only one solid feedstock source within a radius of 500 km (cf. ESI Section S15). The 500 km is the typical maximum distance for transporting cement or cheap bulk material [67]. We define the set C as a subdomain of I that includes only cement plants ($c \in C \subseteq I$).

The considered objective function for the sink-source matching optimization (Eq. 1) consists of four parts:

i) Cost of carbon capture and storage by mineralization. $Cost_{i,j}^{CCSM}$ is the sum of annualized $CapEx_{i,j}^{CCSM}$ and $OpEx_{i,j}^{CCSM}$ if CO_2 source i supplies CO_2 sink j:

$$Cost_{i,j}^{CCSM} = CapEx_{i,j}^{CCSM} + OpEx_{i,j}^{CCSM}. \tag{2}$$

$CapEx_{i,j}^{CCSM}$ presents annualized capital expenditures for the CO_2 mineralization plant, CO_2 capture & compression plant, and the CO_2 transport (for direct connection):

$$CapEx_{i,j}^{CCSM} = CapEx_{i,j}^{mineralization} + CapEx_i^{capture} + \overline{CapEx}_{i,j}^{CO2Transport}. \tag{3}$$

$OpEx_{i,j}^{CCSM}$ is the sum of the expenditures for utility, feedstock, and additive demand of CO_2 mineralization and capture processes plus expenditures for transport of CO_2, carbonates, and feedstock, as well as for mining and other expenditures:

$$\begin{aligned} OpEx_{i,j}^{CCSM} = {} & OpEx_{i,j}^{mineralization} + OpEx_i^{capture} + \overline{OpEx}_{i,j}^{CO2Transport} \\ & + Cost_{i,j}^{CarbonateTransport} + Cost_{i,j}^{FeedstockTransport} \\ & + Cost_{i,j}^{mining} + OpEx_{i,j}^{Other}. \end{aligned} \tag{4}$$

$CapEx_i^{capture}$ & $OpEx_i^{capture}$ quantify the annualized capital expenditures and operational expenditures of capturing CO_2 from the CO_2 source i. $\overline{CapEx}_{i,j}^{CO2Transport}$ & $\overline{OpEx}_{i,j}^{CO2Transport}$ present the annualized capital and operational expenditures of transporting CO_2 from the CO_2 source i to the CO_2 sink j by an individual direct pipe. $\overline{CapEx}_{i,j}^{CO2Transport}$ & $\overline{OpEx}_{i,j}^{CO2Transport}$ are based on a pipe diameter of 150 mm [68]. The pipe diameter expenditures of CO_2 transport are refined in the local pipeline network design optimization (cf. Section 3.2).

$CapEx_{i,j}^{mineralization}$ & $OpEx_{i,j}^{mineralization}$ are the annualized capital expenditures and operational expenditures of the mineralization plant if CO_2 source i supplies mineralization plant j. $Cost_{i,j}^{mining}$ quantifies the costs of mining for mineralization plant j to mineralize CO_2 from CO_2 source i. $Cost_{i,j}^{CarbonateTransport}$ presents the cost for transporting carbonates yielded from mineralizing CO_2 of CO_2 source i in mineralization plant j back to the solid feedstock site of mineralization plant j for permanent storage. $Cost_{i,j}^{FeedstockTransport}$ is the cost of CO_2 sink j due to transporting the required solid feedstock for mineralizing CO_2 of CO_2 source i. $OpEx_{i,j}^{other}$ represent other operational expenditures such as labor, maintenance, overhead, administration costs, etc., that occur if the CO_2 source i supplies the CO_2 sink j [39].

In the objective function, the variable $Y_{i,j} \in [0,1]$ demonstrates whether and to what extent CO_2 source i supplies CO_2 sink j. For example, a $Y_{i,j} = 0.7$ means that the CO_2 source i supplies 70 wt% of its available CO_2 to CO_2 sink j. The 30 wt% rest CO_2 from the CO_2 source i could be provided to other CO_2 sinks j' or emitted into the atmosphere.

ii) Revenue due to utilization of byproduct. $Revenue_{c,j}^{Utilization}$ quantifies the annual revenue if the SiO_2 produced in mineralization plant j substitutes 20 wt% of cement at cement plant c. $Revenue_{c,j}^{Utilization}$ includes the cost reduction of cement production due to cement substitution and the cost caused by transporting SiO_2 from mineralization plant j to cement plant c.

$$\begin{aligned} Revenue_{c,j}^{Utilization} = {} & Cost^{Cementproduction}\cdot Mass_{c,j}^{UtilizedSiO2} \\ & - \left(Cost^{SolidTransport}\cdot D_{c,j}\cdot Mass_{c,j}^{UtilizedSiO2}\right). \end{aligned} \tag{5}$$

Here, $Cost^{Cementproduction}$ is the production cost of 1 ton of conventional cement, $Mass_{c,j}^{UtilizedSiO2}$ quantifies the amount of utilized SiO_2 if the SiO_2 from CO_2 sink j is transferred to cement plant c, $D_{c,j}$ marks the distance between the mineralization plant j and the utilization site c, i.e., cement plant c, and $Cost^{SolidTransport}$ is the cost of transporting 1 ton of material for 1 kilometer by truck. In the objective function, the variable $W_{c,j} \in [0,1]$ demonstrates whether and to what extent SiO_2 from the mineralization plant j is utilized at cement plant c.

iii) Cost of storing the excess silicate. To permanently store the excess silicate (SiO_2) of mineralization plant j, the excess SiO_2 is transported back to the site of solid feedstock. In the objective function, $D_j^{ToStorage}$ indicates the distance between the mineralization plant j and the site for refilling. The excess amount of SiO_2 that is produced at mineralization plant j but not utilized is indicated by variable $Mass_j^{ExcessSiO2} \in R^+$.

iv) Cost of site construction. $Cost^{SiteConstruction}$ quantifies the annualized cost due to land acquisition and site preparation for a new mineralization plant and a new mine. We assume that the impact of mineralization plant size on land acquisition and site preparation is negligible since the factory can be expanded vertically. In the objective function, the binary variable $Z_j \in \{0,1\}$ demonstrates whether a CO_2 mineralization plant is constructed at location *j*.

To model the cost-optimal supply chain for CCUS by mineralization, we define five types of constraints for: *a) GHG mitigation target, b) Plant size, c) Mass balance, d) Transport distance, and e) Electricity demand.* In the following, we explain the GHG mitigation target constraints. The other four constraints are presented in the ESI Section S13 and discussed extensively in our previous study [11].

a) *GHG mitigation target constraint*.

The GHG mitigation target constraint ensures that the total of the GHG emissions avoided both directly and indirectly by the supply chain for CCUS by mineralization are higher than or equal to the GHG mitigation target GHG^{target} while also accounting for caused GHG emissions:

$$\sum_{i\in I}\sum_{j\in J}\left(GHG_{i,j}^{avoidedbyCCSM}\cdot Y_{i,j}\right)+\sum_{c\in C}\sum_{j\in J}\left(GHG_{c,j}^{avoidedbyUtilization}\cdot W_{c,j}\right)-\sum_{j\in J}\left(GHG^{SolidTransport}\cdot Mass_{j}^{ExcessSiO2}\cdot D_{j}^{ToStorage}\right)-\sum_{j\in J}\left(GHG^{SiteConstruction}\cdot Z_{j}\right) \geq GHG^{target}. \tag{6}$$

The total GHG mitigation, shown in Eq. 6, is divided into four parts:

i) Carbon capture and storage. $GHG_{i,j}^{avoidedbyCCSM}$ indicates the GHG emissions avoided by CO_2 capture and storage if CO_2 source *i* supplies CO_2 sink *j*. $GHG_{i,j}^{avoidedbyCCSM}$considers GHG emissions due to capturing CO_2, transporting CO_2, mineralizing CO_2, mining, transporting solid feedstock and carbonates (cf. ESI Section S16).

ii) Utilization of the product. $GHG_{c,j}^{avoidedbyUtilization}$ presents the GHG emissions avoided by substituting cement in cement plant *c* by SiO_2 from CO_2 mineralization plant *j*. $GHG_{c,j}^{avoidedbyUtilization}$ considers not only the avoided GHG emissions in the cement plant but also the emitted GHGs due to the transport of SiO_2 (cf. ESI Section S16).

iii) Storage of excess silicate. The third part of the total GHG mitigation quantifies the GHG emissions due to transporting the excess silicate from CO_2 sink *j* to its solid feedstock location for permanent storage. $GHG^{SolidTransport}$ presents the GHG emissions caused by transporting 1 ton of material for 1 kilometer using truck.

iv) Site construction. $GHG^{SiteConstruction}$ indicates the GHG emissions caused by preparing and constructing the site for a new mineralization plant and a new open-pit mine (cf. ESI Section S16).

GHG mitigation target. GHG^{target} presents a target for the amount of annual GHG mitigation by the CCUS supply chain. The maximum GHG^{target} is the GHG mitigation that can be achieved by the climate-optimal supply chain for CCUS derived in earlier work [11]. Based on this maximum value, we set several GHG mitigation targets (GHG^{target}) to assess the trade-offs with the economics of CO_2 mineralization (cf. Section ↱3.3).

3.2. Second optimization problem: local pipeline network design

After the sink-source optimization matches CO_2 sources with CO_2 sinks (CO_2 mineralization plants), the local pipeline network design optimization minimizes the expenditures of operating and building the required CO_2 pipeline network. For this purpose, the local pipeline network design optimization merges CO_2 pipes into larger-sized pipes and allows for indirect connections through other CO_2 sources to benefit from the economy of scale. The local pipeline network design optimization of our study is based on a modified version of the MILP optimization model developed by Zhou et al. [66].

The sink-source matching optimization generates three pieces of information used in the local pipeline network design: a) the selected CO_2 sinks (*j*), b) the selected CO_2 sources (*i*), and c) the connectivity binary $K_{i,j} \in \{0,1\}$.The connectivity binary $K_{i,j}$ indicates whether CO_2 source *i* is connected to CO_2 sink *j*. The connectivity binary $K_{i,j}$ is obtained from the results of continuous variable $Y_{i,j}$ in the sink-source matching optimization ($K_{i,j} = \lceil Y_{i,j} \rceil$). In case CO_2 source *i* supplies CO_2 to more than one CO_2 sink, the CO_2 source *i* is virtually divided into several CO_2 sources based on their capture fraction $Y_{i,j}$.

The objective function of the local pipeline network design minimizes the total annual cost (TAC) of the CO_2 pipeline network according to Eq. 7 and Table 2.

Objective function

$$\min_{H_{i,l,j},Mass_{i,l,t}^{CO2}}\sum_{i\in I}\sum_{l\in L}\sum_{t\in T}\left(Cost_{t}^{CO2Transport}\cdot Mass_{i,l,t}^{CO2}+\left(Cost_{t}^{Pipe}+Cost^{Landpreparation}\right)\cdot H_{i,l,t}\right)\cdot D_{i,l}, \tag{7}$$

where *i* and *j* are the CO_2 source and sink selected in the sink-source matching; *t* indicates a pipe diameter ranging from 50 mm to 600 mm according to the ASTM A53 standard; *l* indicates either CO_2 sink or CO_2 source ($L = I \cup J$). The local pipeline network design optimization allows CO_2 source *i* to be connected either to CO_2 source *i′* or to CO_2 sink *j*. Thus, *l* illustrates all possible destinations from a CO_2 source.

The considered objective function for the local pipeline network design optimization (Eq. 7) can be divided into two parts:

i) Cost of operating the pipeline. $Cost_{t}^{CO2Transport}$ quantifies the annual specific cost of transporting CO_2 in a pipeline of the diameter *t* (cf. ESI Section S12). The variable $Mass_{i,l,t}^{CO2} \in R^{+}$ presents the annual amount of CO_2 that is transported between CO_2 source *i* and possible destinations *l* via a pipeline of diameter *t*. $D_{i,l}$ indicates the distance from CO_2 source *i* to possible destinations *l*.

ii) Cost of producing and installing the pipe. $Cost_{t}^{Pipe}$ quantifies the annualized cost per kilometer due to the installation and construction of a CO_2 pipeline with diameter *t*. $Cost^{Landpreparation}$presents the annualized cost per kilometer due to land acquisition, site preparation, and trenching for installing a CO_2 pipeline. The binary variable $H_{i,l,t} \in \{0,1\}$

Table 2
Parameters and variables of the local pipeline network design optimization for cost-optimal supply chain (cf. ESI Section S14).

Variables	Parameters
$H_{i,l,t}$, $Mass_{i,l,t}^{CO2}$	$Cost_{t}^{CO2Transport}$, $Cost_{t}^{Pipe}$, $Cost^{Landpreparation}$, $GHG_{t}^{CO2Transport}$, GHG_{t}^{Pipe}, $GHG^{Trenching}$, $D_{i,l}$, $K_{i,j}$, $Mass_{t}^{maxCO2}$, $Mass_{t}^{minCO2}$

specifies a connection between CO_2 source *i* and destination *l* via a pipeline with diameter *t*.

To model the local pipeline network design of cost-optimal supply chains, we define four types of constraints for: a) matching partners, b) pipeline threshold, c) CO_2 mass balance, and d) integer. The four constraints are presented in ESI Section S14 and discussed extensively in our previous study [11].

Our model does not consider rivers, mountains, or national borders for designing the CO_2 pipeline network. Political or geographical constraints could affect the configuration of the CO_2 pipeline network. However, the exact configuration of the CO_2 pipeline network has a limited impact on the economics of a CCS supply chain [63].

To design cost-optimal supply chains, the background data of Section ↱2 and the mathematical optimization problems of Sections ↱3.1 and ↱3.2 are implemented in Python™ [69]. The resulting mixed-integer linear program (MILP) optimization model is solved by the Gurobi™ Optimizer [70].

3.3. Scenarios for CCUS by mineralization supply chain

Mineralization is still not implemented on a large scale, and thus, real-world data on the supply chain of mineralization is unavailable. In Section ↱2, we describe several options for the supply of a) CO_2, b) solid feedstock, and c) energy. The selection of an option depends strongly on uncertain parameters that are imposed externally. Yet, the chosen option can affect not only the GHG mitigation potential of the supply chain for CCUS by mineralization but also its configuration [11] and, consequently, could vary the economics of CO_2 mineralization.

To reflect the broad range of options, we define six scenario groups for analyzing the economics of supply chains for CCUS by mineralization following our work on climate-optimal supply chains [11]. To analyze the effect of the GHG mitigation target, we divide the maximum GHG mitigation into several steps for each scenario group (Table 3). We vary the GHG mitigation target in step sizes of 20 Mt CO_{2e}/year, and explicitly include the 4 Mt CO_{2e}/year value for the current solid feedstock scenario. As a result, we use 40 scenarios in our study (see Fig. 5).

In our previous study, we identified the required infrastructure for large-scale implementation of CCUS by mineralization. We intensively analyzed the impact of the infrastructure on the potential of CCUS by mineralization and concluded that the base-case scenario is a representative scenario for the large-scale implementation of CCUS by mineralization. The base-case scenario employs the currently available energy mix and CO_2 sources, as well as the potentially available large-scale natural solid feedstock and CO_2 pipeline. Using the supply chain for the base-case scenario, up to 130 Mt CO_{2e}/year can be avoided [11].

The low-emission energy scenario can illustrate the effect of low-emission energy on supply chains for CCUS by mineralization, since the only difference compared to the base-case scenario is its energy mix of Europe 2040. The low-emission energy for 2040 increases the maximum GHG mitigation to 160 Mt CO_{2e}/year. By using only trucks to transport CO_2, the CO_2 road transport scenario employs the currently available infrastructure for energy and CO_2 supply, and can highlight the impact of the CO_2 transportation method. The GHG mitigation potential of the CO_2 road transport scenario is 2 Mt CO_{2e}/year lower than the one for the base-case scenario.

In the carbon-negative scenario, CO_2 is captured via direct air capture (DAC) and subsequently stored by CO_2 mineralization. The stored CO_2 is removed permanently from the atmosphere, and thus, the avoided CO_{2e} emissions are carbon negative [71]. In contrast, capturing CO_2 from industrial point sources and storing it by CO_2 mineralization could reduce the GHG emissions but not reach negative emissions [25]. The carbon-negative scenario can avoid up to 160 Mt CO_{2e}/year; thereof, 24 Mt CO_{2e} avoided/year stems from the utilization of mineralization byproducts in the cement industry. The remaining 136 Mt CO_{2e} avoided/year are negative emissions.

The current solid feedstock scenario presents the potential of CCUS by mineralization in Europe (4 Mt CO_{2e}/year) using only currently available solid feedstock, energy supply, and CO_2 sources. To highlight the impact of solid feedstock extraction capacity, the low-extraction-capacity scenario reduces the extraction capacity from 10 Mt minerals/year of the base-case scenario by 75% down to 2.5 Mt minerals/year. Consequently, the GHG mitigation potential of the low-extraction-capacity scenario is 88 Mt CO_{2e}/year, i.e., a 32% reduction in comparison to the base-case scenario.

The effect of the six scenario groups on the GHG mitigation potential is discussed extensively in our previous study [11].

4. Results and discussion

Section ↱4.1 analyzes the cost-optimal supply chain of CCUS by mineralization for the base-case scenario with a GHG mitigation target of 120 Mt CO_{2e}/year as a representative scenario. In Section ↱4.2, we investigate the effect of uncertain parameters (cf. Section ↱3.3) on the large-scale economics of mineralization using scenario analysis. On the basis of the scenario analysis, we identify five promising locations for CO_2 mineralization in Section ↱4.3.

4.1. Cost-optimal supply chain for the base-case scenario

Avoiding 120 Mt CO_{2e}/year costs about 20.6 B€/year via the cost-optimal supply chain of CCUS by mineralization for the base-case scenario. Thus, the supply chain avoids GHG emissions with an average CO_{2e} abatement cost of 172 €/ton CO_{2e} avoided (Fig. 3). The CO_{2e} abatement cost varies strongly for individual mineralization plants ranging from 110 to 312 €/ton CO_{2e} avoided (Table 4 and Fig. 3). The wide range of CO_{2e} abatement costs stems from the supply-chain-related parameters that are specific for each mineralization plant.

The main contributors to the CO_{2e} abatement cost of individual

Table 3

Summary of the six scenario groups for analyzing the effect of uncertain parameters on the economics of the CO_2 mineralization. The maximum GHG mitigation is taken from the climate-optimal supply chain [11].

Scenario group name	Natural solid feedstock locations	Mine extraction capacity [Mt minerals/year]	CO_2 sources	CO_2 transportation method	Energy supply	Maximum GHG mitigation [Mt CO_{2e}/year]
Base-case	Active & potential	10	Industry	Pipeline	Current energy mix	130
Low-emission energy	Active & potential	10	Industry	Pipeline	**Europe 2040**	160
CO_2 road transport	Active & potential	10	Industry	**Truck**	Current energy mix	128
Carbon-negative	Active & potential	10	**Direct air capture**	-	**Europe 2040**	160
Current solid feedstock	**Only active**	**Depends on mine**	Industry	Pipeline	Current energy mix	4
Low extraction capacity	Active & potential	**2.5**	Industry	Pipeline	Current energy mix	88

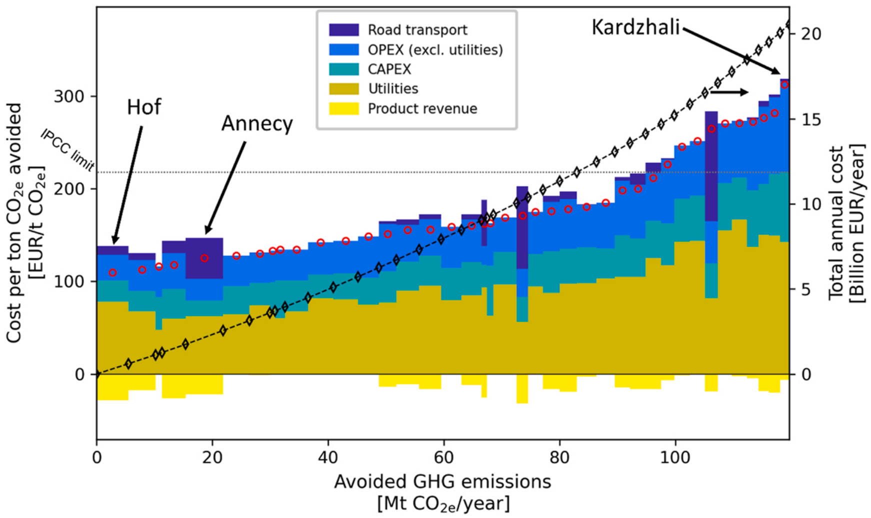

Fig. 3. The CO_{2e} abatement cost curve of CCUS by mineralization supply chain for the base-case scenario that mitigates 120 Mt CO_{2e} per year. Each bar expresses a mineralization plant. The colors show the cost contribution for each mineralization plant (left axis). The red circles show the total CO_{2e} abatement cost of each mineralization plant (left axis). The dashed line shows the total annual cost over the avoided CO_{2e} per year (right axis). The dotted line shows the IPCC limit (210 €/ton CO_{2e}).

mineralization plants are: a) utility cost –on average about 55 % of the total cost– and b) OpEx (excl. utility and road transport cost) –on average about 27 % of the total cost– (Fig. 3). Both utility cost and further OpEx of a mineralization plant are mainly controlled by its avoided CO_{2e} per ton of CO_2 captured. The avoided CO_{2e} per ton of CO_2 captured for a mineralization plant is a supply-chain-related parameter that depends, among other things, on the regional energy system, percentage of byproduct utilization, and distance of feedstock transport (cf. Table 4 and ESI Section S1). Generally, a CO_2 mineralization plant with a low avoided CO_{2e} per ton of CO_2 captured has a high CO_{2e} abatement cost (cf. Table 4 and ESI section S1). However, high costs of road transport can cause deviations from this trend (cf. ESI Section S1).

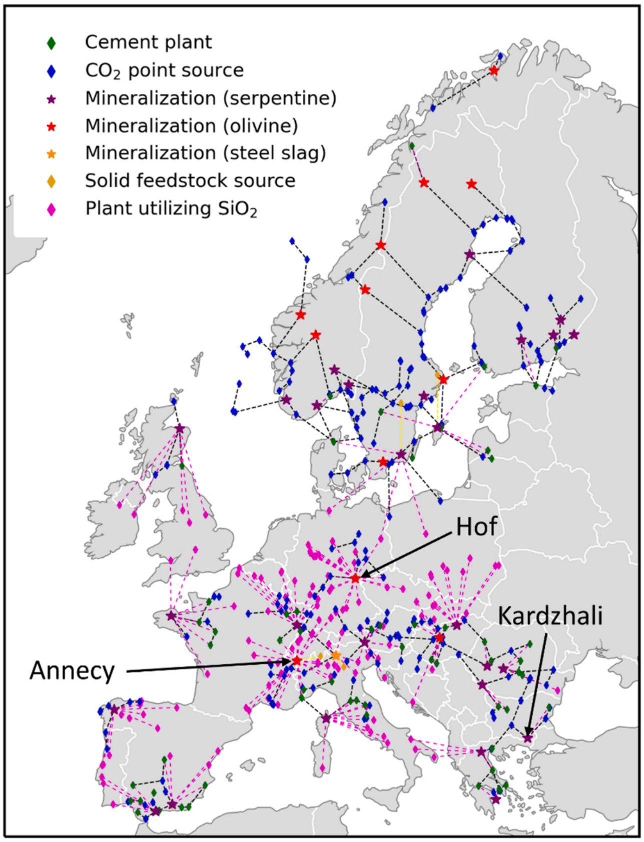

Fig. 4. Map of the cost-optimal supply chain of CCUS by mineralization in Europe for the base-case scenario avoiding 120 Mt CO_{2e} per year. Co-located mineralization plants and solid feedstock sources are illustrated by the mineralization plant only.

According to the IPCC report, technologies with CO_{2e} abatement costs lower than 220 \$/ton CO_{2e} (about 210 €/ton CO_{2e}) could be implemented by 2030 [1]. Imposing this limit on CO_{2e} abatement costs allows for avoiding 95 Mt CO_{2e}/year via the supply chain for CCUS by mineralization (Fig. 3).

The cost-optimal and climate-optimal supply chains for CCUS by mineralization are similar at GHG mitigation targets close to the maximum GHG mitigation potential (cf. Fig. 4 and ESI Section S2). Yet, due to the high cost of solid feedstock transport, the cost-optimal supply chain transports less solid feedstock than the climate-optimal supply chain (cf. Fig. 4, ESI Section S2). Moreover, in contrast to the climate-optimal supply chain, the cost-optimal supply chain prioritizes utilizing the byproduct to avoid GHG emissions and gain revenue rather than connecting a new CO_2 source to the supply chain (cf. Fig. 4 and ESI section S2).

The ten mineralization plants with the lowest CO_{2e} abatement costs are located nearby cement plants (e.g., in the west of Germany and in the east of France), or where low-emission and low-price energy are available (e.g., Norway and Sweden). To analyze the effect of the supply chain on the economics of individual mineralization plants, here, we discuss three outstanding mineralization plants: Hof, Kardzhali, and Annecy (Table 4, Fig. 3, and Fig. 4).

The mineralization plant near Hof has the lowest CO_{2e} abatement cost: 110 €/ton CO_{2e} avoided. The low CO_{2e} abatement cost of mineralization plant Hof is due to a) its location and b) its interaction within the supply chain. On the one hand, the mineralization plant Hof is located where not only large product markets are available, i.e., several

Table 4
Three outstanding mineralization plants in the base-case scenario avoiding 120 Mt CO_{2e}/year. Bold font indicates the criteria in which the plant stands out.

Mineralization plant	CO_{2e} abatement cost [€/ton CO_{2e}]	Avoided CO_{2e} per ton of CO_2 captured [t CO_{2e}/t CO_2]	Avoided CO_2 [Mt CO_{2e}/ year]	Byproduct utilization percentage
Hof	**110**	1.1[a]	5.5	100%
Annecy	125	1.3[a]	**6.5**	90%
Kardzhali	**312**	0.4	1.6	6%

[a] The avoided CO_{2e} per ton of CO_2 captured for a mineralization plant can exceed 1 ton CO_{2e} avoided/ton CO_2 captured when a high share of the produced SiO_2 substitutes cement.

cement plants are nearby, but also CO_2 sources requiring low capture energy are available, i.e., two ammonia plants and three pulp and paper plants are nearby. The availability of large product markets and high-purity CO_2 sources can increase not only the percentage of byproduct utilization but also the avoided CO_{2e} per ton of CO_2 captured. On the other hand, the configuration of the CCUS supply chain allows the mineralization plant Hof to be the only mineralization plant in that area, i.e., the benefits of the location are not shared between several mineralization plants (Fig. 4). This configuration of the CCUS supply chain is due to the type of solid feedstock and lower GHG emissions and cost of energy supply for the mineralization plant Hof than the alternative neighboring locations. Hence, the mineralization plant Hof has 1) high avoided CO_{2e} per ton of CO_2 captured (1.1 t CO_{2e}/t CO_2), and 2) high percentage of byproduct utilization (100%) (Table 4 and Fig. 3). High avoided CO_{2e} per ton of CO_2 captured reduces the required utility & material demand for avoiding 1 ton CO_{2e} and consequently reduces the corresponding costs. The high percentage of byproduct utilization decreases the CO_{2e} abatement cost by two mechanisms: a) increasing the revenue and b) increasing the avoided CO_{2e} per ton of CO_2 captured. Thus, the mineralization plant Hof can achieve the lowest CO_{2e} abatement cost in the CCUS supply chain (110 €/ton CO_{2e} avoided).

With 312 €/ton CO_{2e} avoided, the mineralization plant near Kardzhali has the highest CO_{2e} abatement cost in the supply chain for the base-case scenario. Its low avoided CO_{2e} per ton of CO_2 captured (0.4 t CO_{2e}/t CO_2), and its low percentage of byproduct utilization (6 %) lead to its high CO_{2e} abatement cost (Table 4 and Fig. 3). The CCUS supply chain connects available product markets and high-purity CO_2 sources to mineralization plants that can achieve the lowest CO_{2e} abatement cost due to, e.g., their low-emission and cheap energy supply. Since, the energy supply for the mineralization plant near Kardzhali has higher GHG emissions and costs than the energy supply for neighboring mineralization plants, the mineralization plant near Kardzhali is left with CO_2 sources requiring high capture energy and no product market (Fig. 4). Therefore, the CO_{2e} abatement cost of the plant near Kardzhali is about three times higher than the one for the plant near Hof, 312 and 110 €/ton CO_{2e} avoided, respectively (Table 4, and Fig. 3).

Strunge et al. investigated the economics of CO_2 mineralization for a single plant and concluded that the byproduct utilization is essential for a business case of mineralization [19]. Our findings on the supply chains of CCUS by mineralization illustrate the importance of byproduct utilization for mineralization on a large scale.

The mineralization plant close to Annecy avoids the most CO_{2e} in total. The location of Annecy is favorable due to low-cost and low-emission energy supply, large amounts of nearby CO_2 sources and byproduct markets. Furthermore, the mineralization plant Annecy is the only mineralization plant located in that area due to the configuration of the supply chain. The combination of favorable location with supply chain configuration leads to a) high avoided CO_{2e} per ton of CO_2 captured (1.3 t CO_{2e}/t CO_2), b) high percentage of byproduct utilization (90 %), and consequently, relatively low CO_{2e} abatement costs for the mineralization plant Annecy (125 €/ ton CO_{2e}) (Table 4, Fig. 3, and Fig. 4). These main characteristics of the mineralization plant close to Annecy contribute to its high total CO_{2e} avoided annually.

All three mineralization plants capture CO_2 from industrial sources and store it by mineralization in the supply chain for the base-case scenario. Yet, their size and CO_{2e} abatement costs vary substantially. This variation is due to a) their location, e.g., the availability of CO_2 sources requiring low capture energy, availability of product market, cost and GHG emission of energy supply, type of available solid feedstock, and b) their interaction within the supply chain, such as competitive neighboring mineralization plants. The plant-level cost assessments study the economics of an individual mineralization plant located at a specific site while ignoring the competition between neighboring mineralization plants. Hence, individual plant-level cost assessments cannot reflect the economics of mineralization on a large scale. Our results underline that understanding the economics of CO_2 mineralization on a large scale requires designing the entire supply chain for CCUS by mineralization and identifying the supply-chain-related parameters for individual mineralization plants.

4.2. Scenario analysis for supply chains of CCUS by mineralization

This section employs scenario analysis to assess the effect of uncertain parameters on the large-scale economics of CO_2 mineralization (cf. Section ↱3.3). We design cost-optimal supply chains of CCUS by mineralization for the six scenario groups and several mitigation targets (Fig. 5).

For all scenarios, both the total annual cost of the entire supply chain and the average CO_{2e} abatement cost increase by increasing the GHG mitigation target. The CCUS supply chain of the low-emission energy scenario could avoid up to 140 Mt CO_{2e}/year at an average CO_{2e} abatement cost lower than the 210 €/ton CO_{2e} IPCC marginal cost estimate for 2030 [1].

For GHG mitigation targets up to 60 Mt CO_{2e}/year, the average CO_{2e} abatement cost is comparable for all scenarios to the CO_2 capture and geological storage (CCGS, 50–120 €/ton avoided CO_2) [20,72,73]. The only exception is the carbon-negative scenario. With an average CO_{2e} abatement cost of 217 €/ton CO_{2e}, the carbon-negative scenario could avoid up to 60 Mt CO_{2e}/year, 22 Mt CO_{2e}/year of which are avoided CO_{2e} emissions due to byproduct utilization. The remaining 38 Mt CO_{2e}/year are negative emissions with an average CO_{2e} abatement cost of 343 €/ton CO_{2e}. The average CO_{2e} abatement cost of negative

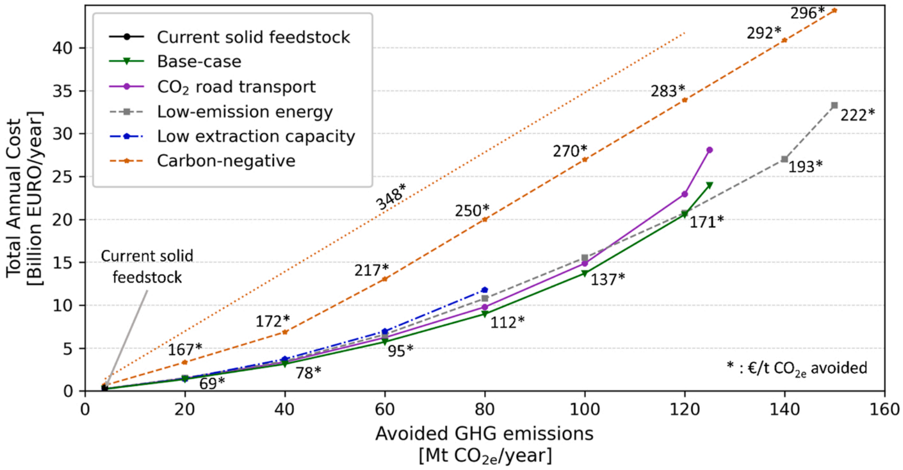

Fig. 5. Trade-off between the total annual cost and GHG mitigation of CCUS by mineralization supply chain for the six scenarios (Table 3). Each point represents a cost-optimal CCUS by mineralization supply chain (cf. ESI Section S4-S11). Average CO_{2e} abatement costs are given for the specific scenario and GHG mitigation target. * indicates €/ton CO_{2e} avoided. The average CO_{2e} abatement cost of the base-case and the carbon-negative scenarios for avoiding 4 Mt CO_{2e}/year are 57 and 165 €/ton $CO_{2e,}$ respectively. The dotted yellow line shows the total annual cost of the carbon-negative scenario without the utilization of mineralization byproduct.

emissions from CCUS by mineralization is higher than the reported cost for bioenergy with carbon capture and storage (BECCS, 180 €/ton CO_{2e}) [74], yet, comparable with direct air CO_2 capture and geological storage (DACCGS, 90–280 €/ton CO_{2e}) [75].

The total annual costs and the average CO_{2e} abatement costs depend strongly on the scenarios (Fig. 5). For most of the GHG mitigation targets, the base-case scenario has the lowest average CO_{2e} abatement cost. The average CO_{2e} abatement costs of the CO_2 road transport scenario are about 9 % higher than the one for the base-case scenario due to the costs of transporting CO_2 by trucks. Yet, both scenarios could achieve a GHG mitigation target of up to about 125 Mt CO_{2e}/year. Using low-emission electricity increases the potential for GHG emission mitigation up to more than 150 Mt CO_{2e}/year. However, the higher cost of low-emission electricity (0.08 €/kWh) increases the CO_{2e} abatement cost of the low-emission energy scenario by about 13 % on average compared to the base-case scenario [29,48].

The decreased availability of solid feedstock in the low-extraction capacity scenario, reduces the GHG emission mitigation potential of the supply chain down to about 80 Mt CO_{2e}/year and increases its CO_{2e} abatement cost by about 12 % on average compared to the base-case scenario. The higher CO_{2e} abatement costs of the low-extraction capacity scenario stem from an increased number of mineralization plants required and the corresponding costs.

The carbon-negative scenario has the highest CO_{2e} abatement cost. Due to the additional costs of DAC plants, the CO_{2e} abatement costs of the carbon-negative scenario are roughly 120 % higher than the base-case scenario. Yet, the carbon-negative scenario could provide negative emissions and achieve the largest GHG mitigation.

Independent of the scenarios, the total annual cost increases almost linearly over the GHG mitigation target ranging from 4 to 40 Mt CO_{2e}/year (Fig. 5). This linear increase is due to the fact that the mineralization plants providing between 4 and 40 Mt CO_{2e}/year for all scenarios have similar CO_{2e} abatement costs (cf. ESI Section S4-S6).

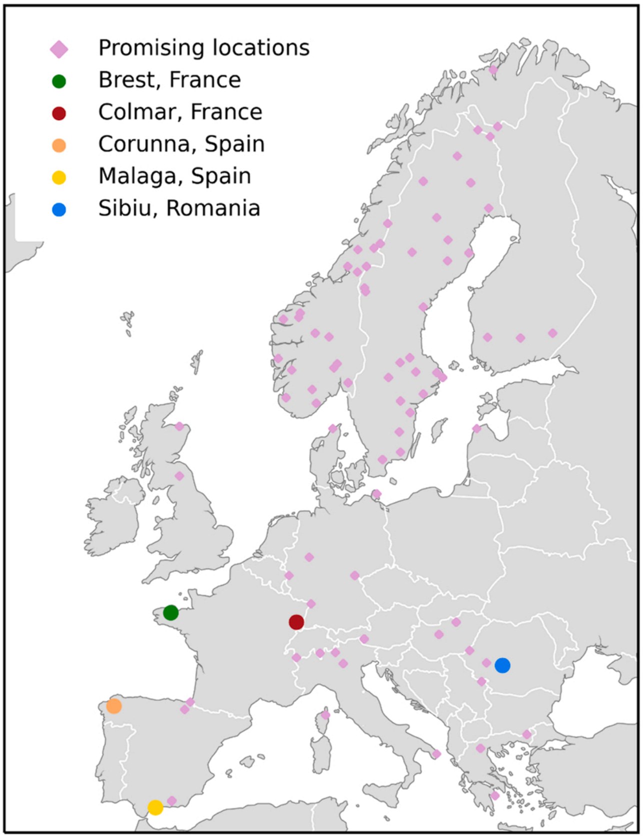

Fig. 6. Map of mineralization plants with a CO_2 abatement cost lower than 210 €/t CO_{2e}. The mineralization plants in the promising locations have a CO_2 abatement cost lower than 210 €/t CO_{2e} in at least one of the 40 scenarios. The Colmar, Brest, Malaga, Corunna, and Sibiu plants have a CO_2 abatement cost lower than 210 €/t CO_{2e} for more than 30 of the 40 scenarios.

The total annual cost of the carbon-negative scenario increases linearly over the GHG mitigation from 40 to 150 Mt CO_{2e}/year (cf. Fig. 5), i.e., newly constructed mineralization plants have similar CO_{2e} abatement costs as the rest of the mineralization plants (cf. ESI Section S6-S11). In contrast, for all other scenarios, the total annual cost increases nonlinearly over the GHG mitigation of 40–150 Mt CO_{2e}/year (cf. Fig. 5), i.e., to achieve higher GHG mitigation, more expensive mineralization plants are built (cf. ESI Section S6-S11). The mineralization plants with the highest CO_{2e} abatement cost are added to the supply chain at GHG mitigation targets that are close to the maximum GHG mitigation of the corresponding scenario. This can be confirmed by the remarkable cost increase for the base-case scenario to avoid 125 Mt CO_{2e}/year. Johnsson et al. calculated the CO_2 abatement cost curves for supply chains of CO_2 capture and geological storage. Similar to our study, they concluded that the CO_2 abatement cost depends strongly on location [20].

All considered supply chains for CCUS by mineralization can reduce GHG emissions (Fig. 1). However, due to their energy and material demands, the CCUS by mineralization supply chain could increase several other environmental impacts (cf. ESI Section S3). Thus, before the large-scale implementation of CCUS by mineralization, its environmental trade-offs should be closely investigated and, if possible, reduced. Employing renewable energy and further developing the mineralization technology could reduce potential environmental trade-offs (cf. ESI Section S3).

The economics of CO_2 mineralization depends not only on the supply-chain-related parameters (cf. Section 4.1) but also on uncertain parameters (Fig. 5). Due to the uncertain parameters, the average CO_{2e} abatement costs of the supply chains range from 57 to 348 €/ton CO_{2e} avoided. Thus, the actual setting is essential to determine the economics of CO_2 mineralization on a large scale.

4.3. *Promising locations for mineralization*

The scenario analysis (cf. Section 4.2) shows that uncertain parameters substantially affect the CO_{2e} abatement cost curve of supply chains for CCUS by mineralization. Consequently, the economics of individual mineralization plants vary considerably. Therefore, determining promising locations for the first mineralization plants is not trivial, although necessary for attracting investors.

We identify 55 promising locations for mineralization plants that achieve a CO_2 abatement cost lower than 210 €/ ton CO_{2e}, the IPCC marginal cost estimate for 2030 [1], in at least one scenario (Fig. 6). The mineralization plants in the five most promising locations have even a CO_{2e} abatement cost lower than 210 €/ ton CO_{2e} for more than 30 of the 40 scenarios; thus, they could offer a robust business case (Fig. 6 and Table 5). For this purpose, we create an inventory of all mineralization plants in the 40 scenarios and select the mineralization plants that achieve at least in one scenario a CO_2 abatement cost lower than 210 €/ ton CO_{2e} (cf. ESI Section S4-S11).

Table 5
The five most promising locations for CO_2 mineralization.

Mineralization plant	CO_{2e} abatement cost [€/t CO_{2e}]	Annual avoided CO_{2e} [Mt CO_{2e}]	Scenarios where the plant's CO_2 abatement cost is lower than 210 €/t CO_{2e}
Colmar	58–185	1.6–6.1	37/40
Brest	68–194	0.9–3.9	30/40
Sibiu	64–200	1.0–3.8	35/40
Corunna	80–180	0.4–4.2	33/40
Malaga	70–188	1.3–4.1	34/40

The CO_{2e} abatement cost and the annual avoided CO_{2e} emissions of the mineralization plants located in the five most promising locations range from 58 to 200 €/ton avoided CO_{2e} and from 0.4 to 6.1 Mt CO_{2e}/year, respectively. Thus, the CO_{2e} abatement cost and the optimal size of these five mineralization plants still depend on scenarios. More than 75 % of the scenarios selected the five most promising locations. Thus, these locations are essential for most scenarios. The five most promising locations are placed where: a) solid feedstock is available without transport, b) high-purity CO_2 sources are close by, and c) several cement plants are in close range (see Fig. 6 and ESI Section S15). Our systematic analysis confirms the recommendations of Kremer et al. investigating the options for CO_2 mineralization in Europe [28].

All in all, the five most promising locations offer starting points to scale up the supply chain for CCUS by mineralization in Europe [28].

5. Conclusion

The large-scale economics of CO_2 mineralization is analyzed by designing cost-optimal supply chains for CCUS by mineralization considering uncertain parameters via scenarios.

Our results show that the CO_{2e} abatement cost of individual mineralization plants can range from 110 to 312 €/ton CO_{2e} avoided in the cost-optimal supply chain for the base-case scenario. The main contributors to CO_{2e} abatement costs are utility costs and further OpEx, which are mainly controlled by the avoided CO_{2e} per ton of captured CO_2 in individual CO_2 mineralization plants. Both avoided CO_{2e} per ton of captured CO_2, and CO_{2e} abatement cost of individual mineralization plants depend on a) plant location, e.g., the availability of high-purity CO_2 sources, availability of product market, cost and GHG emission of energy supply, type of available solid feedstock, and b) plant interaction within the supply chain, such as competitive neighboring mineralization plants. Thus, the economics of CO_2 mineralization can only be determined by designing the entire supply chain and not by individual plant-level cost assessments.

Our scenario analysis illustrates that the economics of CO_2 mineralization are sensitive to uncertain parameters affecting the supply of CO_2, energy, and solid feedstock. Therefore, the average CO_{2e} abatement costs of the supply chains range from 57 to 348 €/ton CO_{2e} avoided. Thus, assessing the economics of CO_2 mineralization requires a detailed investigation of the uncertain parameters, such as the cost and carbon footprint of the energy system.

Despite the strong effect of uncertain parameters, we identify five promising locations for CCUS by mineralization in Europe, namely Colmar, Brest, Malaga, Corunna, and Sibiu. These five locations seem particularly suited for the first installations of the CCUS by mineralization in Europe due to the proximity of mines, CO_2 sources, and cement plants. Thus, the next step toward implementing the CCUS by mineralization should be a detailed study on solid feedstock deposits, available infrastructures, and social acceptance in these five promising locations [76].

Currently, implementing CCUS by mineralization in Europe is not profitable and requires government support or incentives. However, the estimated price of 129 €/ ton CO_2 for the emission trading system (ETS) by 2030 [19,77] could already incentivize the implementation of a supply chain for CCUS by mineralization that avoids 60 Mt CO_{2e}/year in Europe. The 129 €/ ton CO_{2e} is comparable to the CO_{2e} abatement cost of common GHG mitigation approaches such as carbon, capture, and geological storage (CCGS). The CO_{2e} abatement cost of CO_2 mineralization could be reduced in the future by decreasing the energy and material demands of CCUS by mineralization or by exploring alternative markets for the main and byproducts of mineralization. Another interesting approach for reducing the CO_{2e} abatement cost is combining the supply chain for CCUS by mineralization with other CO_2 capture, storage, or utilization technologies to share the infrastructure and corresponding expenditures.

Overall, CO_2 mineralization shall be added to the GHG mitigation portfolio of Europe not as a silver bullet but as a technology that could reduce 11 % of industrial emissions at competitive costs.

CRediT authorship contribution statement

Hesam Ostovari: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, **Luis Kuhrmann:** Validation, Formal analysis, Investigation, Data curation, **Fabian Mayer:** Methodology, Writing – review & editing, **Hannah Minten:** Methodology, Writing – review & editing, **André Bardow:** Conceptualization, Funding acquisition, Methodology, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jcou.2023.102496.

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