Supplementary Information to *Towards a business case for CO_2 mineralisation in the cement industry*

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Content

Supplementary Notes

Supplementary Note 1: Market analysis for CO_2 mineralisation products

The goal of implementing CO_2 mineralisation in a cement production facility is to capture most of the plant's emissions while creating revenue through utilizing mineralisation products. Numerous small volume applications have been proposed to use carbonates (e.g., carbonates used as polymer additives or aggregate feedstock for land reclamation projects) [1,2]. While at first these seem promising, niche markets offer only limited CO_2 storage potential[1,2] . Furthermore, these markets may not be located close to the cement production facilities[3] or have stringent product specifications which can only be achieved at high costs[1]. Carbonating only the process-inherent emissions of cement would lead to a production of magnesite/calcite and silica 60x and 200x respectively greater than the current European market (Supplementary Figure 1). Therefore, targeting niche markets such as selling high purity magnesium carbonate ($MgCO_3$) or calcium carbonate ($CaCO_3$) and silica, i.e., silicon dioxide (SiO_2), will not significantly lower emissions from cement production. Instead, we consider the use of these materials in cement products.

Supplementary Note 2: Scope definition for the assessment

A typical European cement production facility has an annual capacity of 1.4 million tonnes of cement per annum (Mt_{cement}/a) emitting $850kt_{CO2}/a$[4], and will be used as the baseline in this work. We propose retrofitting post-combustion capture onto this facility to obtain a pure CO_2 gas with sufficient capacity to meet the demands of a mineralisation system that will be located on the same site. Suitable feedstock minerals occur in distinct locations in south and northern Europe[5-7], we assume a transport of 1200 km via a combination of train, ship and truck, which would allow to transport mineral from a site in Norway (Region of Steinsvik) to northern Germany (Region of Hamburg), where multiple cement plants are located[8]. On the cement site the carbonation products are used as supplementary cementitious material (SCM) to create blended cement. The stoichiometry of the carbonation reaction produces inert material (carbonates) with limited application in cementitious products[2]. Unused material is stored in the limestone quarry, which are assumed to be located within 10 km of the cement production facility.

Supplementary Note 3: SCM_{CCU} product specification

The by-product silica (SiO_2) from mineralisation reactions has been described of being of amorphous nature[6,9,10]. Amorphous silica is a widely accepted pozzolanic additive in cement production. When added to cement, amorphous silica and calcium hydroxide react to produce additional binding products (e.g., calcium silicate hydrates), leading to a comparable or increased strength to using cement alone[11,12]. Experimental work suggests that replacing 5-30wt% of cement using silica increases the strength by 5-38 weight percent (wt%), with the strongest effect observed at 10-15wt% replacement[11,13-15]. Initial applicability studies by Benhelal, et al. [9] showed that a mixture of at least 5wt% carbonated material could be used as an SCM (hereafter SCM_{CCU}) without significant workability (i.e. curing time, water demand) and strength changes of resulting mortars. As such, SCMs must have high concentrations of small particles of silica as the major drivers for the pozzolanic effect[9,16]. Fine particle silica increases the surface area of the cement, resulting in increased water requirements or the need for a superplasticizer to maintain workability[11,16]. Commonly, replacing cement with silica does not exceed 10 wt%[17]. As the literature review was not conclusive on the precise compositions (i.e., content of silica and inert material in SCM) and the potential share of a subsequently resulting SCM_{CCU} in cement blends, we contacted two experts from this field who considered 25-35wt% replacement of ordinary Portland cement by carbonated material containing 30-50wt% silica to be the upper limit[18,19], while maintaining similar product properties as ordinary Portland cement (e.g., compressive strength, curing time, water

demand). As cement is highly standardized we additionally reviewed the European standard for cement products EN-197[12] showing that all cement types currently allow the usage of up to 5wt% of SCM via CO_2 mineralisation (Supplementary Table 2). Additionally, if carbonated minerals can be classified as natural pozzolanic material they could be used as SCM in certain blends (e.g., Portland pozzolana cement). That would allow displacements of up to 35wt% or 55wt% under current product specifications. For using silica in cement blends, which is the reactive component of the SCM_{CCU}, EN-197[12] additionally limits the share of silica in the cement blend to maximal 10wt%.

Following these investigations, we assume a share of 10-25% of SCM_{CCU} in cement with shares of 50%-30% of silica in the SCM_{CCU}: pessimistic scenario: 10% SCM_{CCU} in cement and 50% silica in SCM_{CCU} (total: 5% silica in cement blend); mid scenario: 20% SCM_{CCU} in cement and 40% silica in SCM_{CCU} (total: 8% silica in cement blend); optimistic scenario: 25% SCM_{CCU} in cement and 30% silica in SCM_{CCU} (total: 7.5% silica in cement blend). Within these ranges we expect a blend to be formulated with similar product properties as ordinary Portland cement while respecting the current the European standard for cement products EN-197[12] (i.e., current limits for shares of silica and SCM of standardized cement blends).

Supplementary Note 4: Improved process designs for SCM production

Two pathways for mineral carbonation are typically distinguished[5]: a direct pathway where ground minerals are reacted with CO_2 in a pressurized stirred tank using an aqueous slurry with additives such as NaCl and $NaHCO_3$[10,20-23]; and an indirect pathway where alkaline earth metal oxides are first extracted and in a later step reacted with CO_2 to form carbonates. We selected one direct route and one indirect route to analyse and compare their technical and economic performance. We only selected processes that use natural minerals as feedstock: availability of some industrial wastes[24] might be limited in the future due to more sustainable production processes, and heavy metal contents of some wastes might limit their usability[25]. Due to the availability of the mg-rich silicates in Europe[5-7], we focused our assessment on olivine and serpentine-bearing feedstocks.

We compared multiple reaction conditions for the selection of a direct route which either use serpentine or olivine bearing rocks and differ in pressure, temperature, additive concentration as well as mechanical pre-treatment. Post-combustion CO_2 capture (i.e., monoethanolamine (MEA) post-combustion capture) was used to capture the CO_2 from the cement kiln flue gas[20,22,26]. The minerals are first mined, crushed and grinded. In the case of serpentine, thermal pre-treatment was added to activate the minerals. In a next step the water and the additives sodium bicarbonate ($NaHCO_3$) and sodium chloride (NaCl) are added, and the mixture is compressed to the desired reaction pressure (100-150 bar) and heated in a heat exchanger, recovering the heat from the reaction solution leaving the reactor. To create a process that resembles a large scale process as close as possible we implemented heat integration proposed by Ostovari, et al. [2] and developed a separation process based on initial findings from Kremer and Wotruba [27] that allows us to increase the efficiency of using mineral feedstock and to produce a SCM with alterable silica concentrations. As the reaction of the direct process are not complete, when leaving the reactor, we here propose a post-processing train; first, cyclones are used to partially separate unreacted mineral via gravity separation (<10-75µm, depending on the grinding size)[21,22] from the reaction products (3-5µm for magnesite and <1µm for silica)[27]. Unreacted mineral is cycled back into the process to increase the efficiency of utilizing the mineral feedstock. In a second step a share of the resulting product-rich slurry is fed into a classification centrifuge where magnesite and unreacted mineral are separated from the stream. Afterwards this silica-rich slurry is added to the residual slurry, producing a desired silica content. The SCM_{CCU} is dewatered using solid bowl centrifuges, which have been reported

to be suitable for this task[28]. The SCM_{CCU} is assumed to be used with a residual humidity of 10%. We selected the conditions with the lowest costs (Supplementary Figure 5) leading to a design for a direct carbonation route based on Eikeland, et al. [22] (Olivine, 100bar, 190°C).

As one of the most eminent indirect routes we selected a liquid/liquid approach, also referred to as the Nottingham route[2,29]. The Nottingham route uses serpentine as a feedstock, which is crushed, grinded and reacted in a three-step aqueous process; First, an ammonium bisulphate solution (NH_4HSO_{4aq}) is used to extract magnesium oxide and impurities (e.g., iron oxide), leaving silica behind. Second, impurities are precipitated via pH adjustment. Third, the extracted magnesium reacts with ammonium bicarbonate (NH_4HCO_{3aq}) which acts as CO_2 carrier and is recycled in an integrated post-combustion capture process, in which ammonia reacts with the flue gas-inherent CO_2 to ammonium bicarbonate. After the separation of the carbonation products, the remainder of the ammonium sulphate–rich solution ($(NH_4)_2SO_4$), is evaporated leading to a thermal treatment to recover NH_3 and NH_4HSO_4[30-33]. Here, a jacked mechanical scraped-surface crystallizer was selected to evaporate water from the additive (ammonium sulphate) and a indirect rotary drum dryer was selected for the thermal treatment. We selected this route for this study because it is possible to obtain high purity separated products[2] so no purification step has to be designed. We implemented heat integration proposed by Ostovari, et al. [2] which also incorporates recompression of steam created during the additive regeneration. To produce the $SCM_{CCU,}$ silica is separated from the slurry after the first reaction and blended with separated carbonates from the third reaction. Solid bowl centrifuges are again used for dewatering. Simplified flowsheets are[34] shown in Supplementary Figure 2.

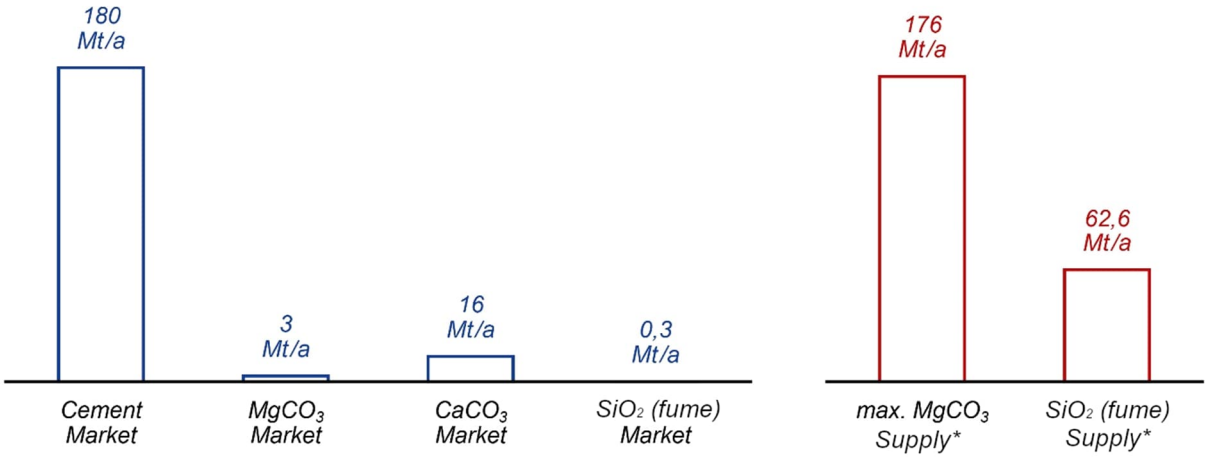
Supplementary Note 5: Comparison of CO_2 mineralisation to other emission reduction strategies

To achieve significant emission reductions, the cement industry is limited in its options due to high process-inherent emissions. A review of academic literature and policy advice reports revealed that a set of strategies will be needed to combat CO_2 emission reduction in the cement industry. Because the cement industry's emissions result from both the high energy demand (i.e., energy-related emissions) and the calcination reaction itself (i.e., process-inherent emissions), we must differentiate between measures to reduce either or both. Tackling energy-related emissions can be archived using efficiency and substitution measures. While many efficiency gains have been achieved in conventional cement production processes in recent decades[35] which tackle energy-related emissions, currently predominantly the use of alternative fuels[16,35-39] and process electrification[40] is suggested to further reduce these emissions. Since these measures will at best reduce energy-related emissions to zero, additional measures are needed to tackle the remaining process-inherent emissions (approx. 60 % of total emissions[41]). Conventionally, the cement industry used clinker substitutes called supplementary cementitious materials (SCM) to tackle these emissions, which can be industrial wastes (e.g., steel slag, fly ash) or virgin minerals (e.g., limestone, natural pozzolans)[16,35,39,42,43]. Given overall strength or workability limitations (i.e. increased water requirements and altered curing time) with the use of SCM[16] these measures will not be sufficient to mitigate all process-inherent emissions. An overview of the emission reduction approaches with high emission reduction potentials[35] can be summarised as:

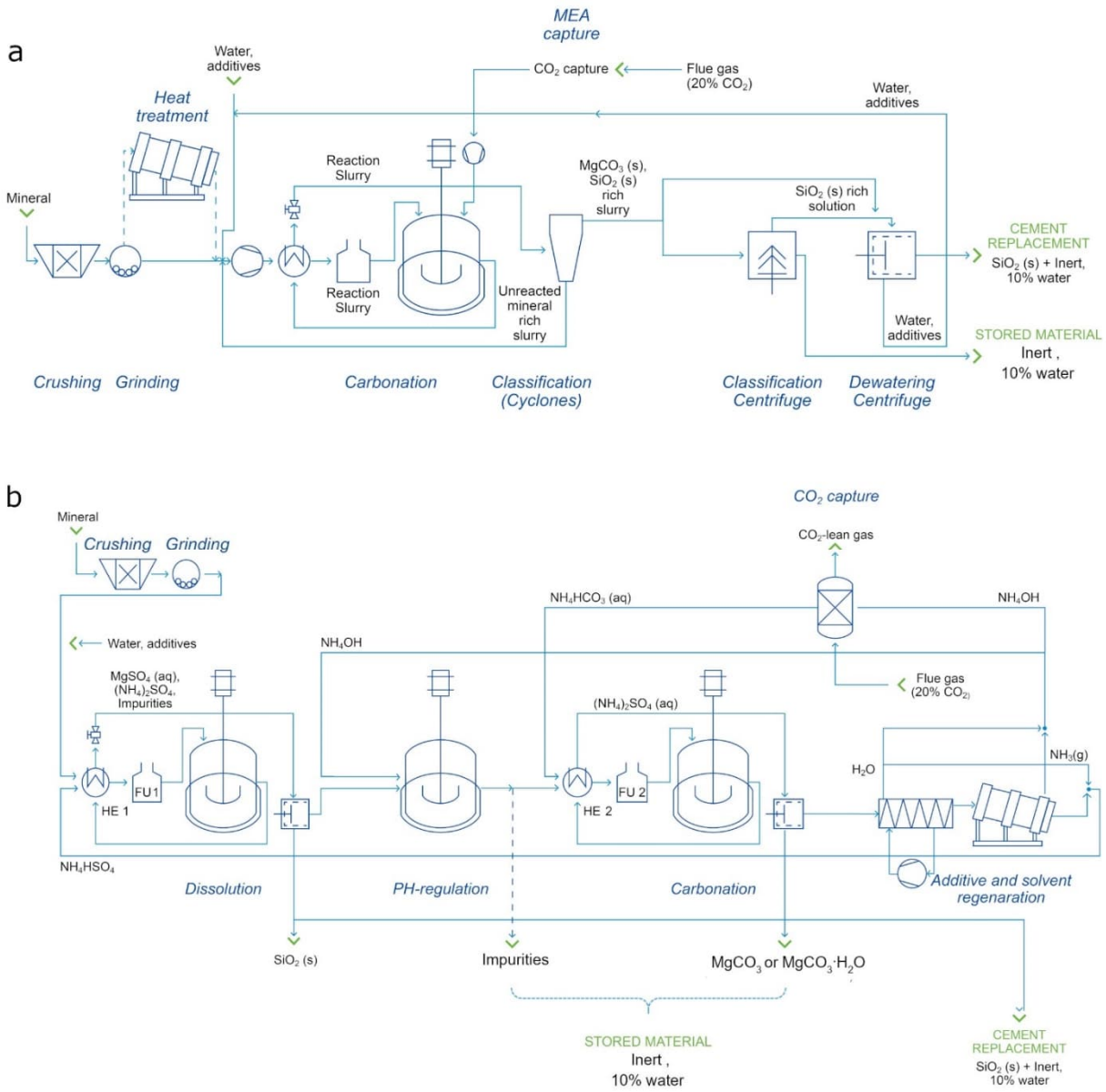
- Alternative fuels or electrification
- Alternative supplementary cementitious materials
- Carbon capture and storage and/or carbon capture and utilisation
- Alternative clinkers

For this assessment we compared CO_2 mineralisation to alternative fuels (i.e., biofuel in form of biomass or biomass by-products), other alternative SCMs (i.e., calcinated clay) and geological storage (i.e., MEA post combustion capture and Oxy fuel combustion with offshore storage). We excluded the use of traditional SCMs from waste streams (fly ash and blast furnace slag) as they have been used extensively to reduce emissions and are unlikely to be able to significantly reduce the emissions further[35] as well as alternative clinkers, which are expected to only be used for niche products in the future[35]. Additionally, we exclude other means of carbon capture and utilisation, where CO_2 is not stored in minerals (e.g., production of fuels) since it does not lead to permanent storage of CO_2. As the baseline we use the production of ordinary Portland cement with a clinker content of 100% (following EN-197[12] this must be >95%, see Supplementary Table 2), as this cement type can be used to produce all other cement blends. All considered processes and scopes are shown in Supplementary Figure 4. The used equations are provided in Supplementary Table 14 and the used assumptions in Supplementary Table 15.

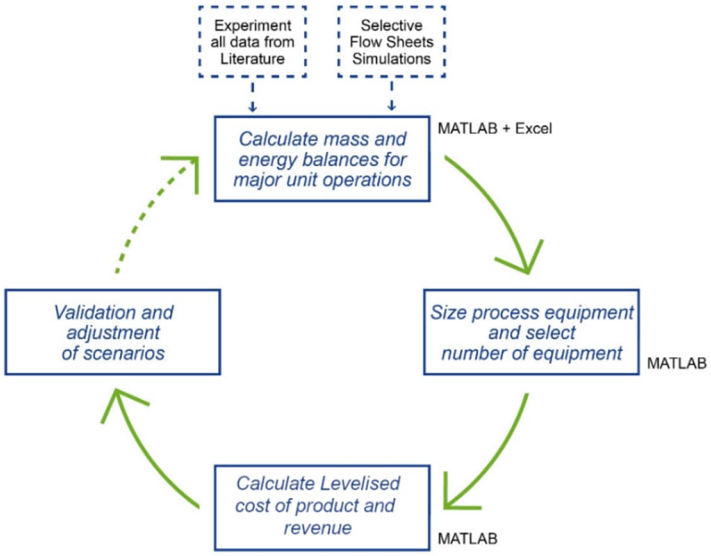
Supplementary Figures



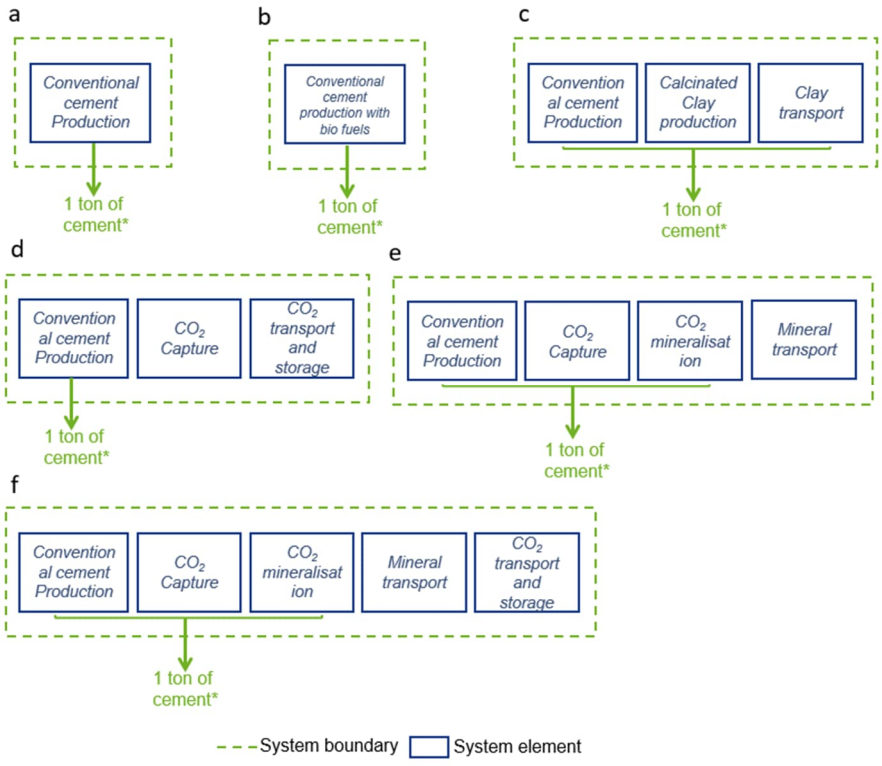
Supplementary Figure 1: Current demands in Europe and the potential supply from CO_2 carbonation; Left, market sizes for cement, magnesium carbonate ($MgCO_3$), calcium carbonate ($CaCO_3$) and silica (SiO_2)[44-48]. Right, supply from potential reaction of CO_2 with forsterite (Mg_2SiO_4); *Stoichiometric reaction yield assumed, only process CO_2 emissions (60% of total emissions) taken into amount. Illustration designed by Wernerwerke, Cordes + Werner GbR ©2021.



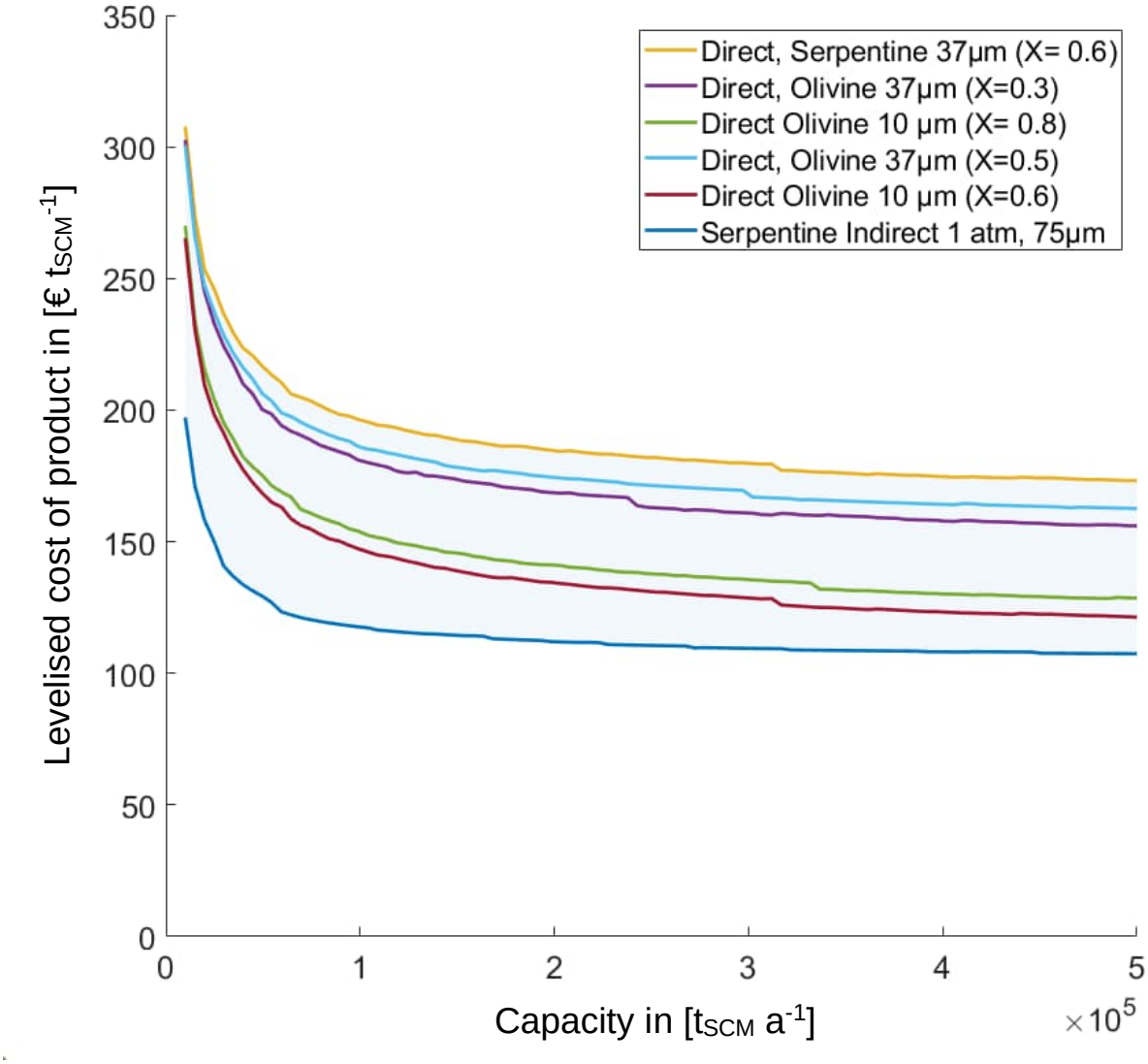
Supplementary Figure 2: Flowsheets of proposed full-scale processes . Panel a :direct process based on Eikeland, et al. [22] with heat treatment only being considered when serpentine is used as mineral feedstock. Panel b: indirect process based on Wang and Maroto-Valer [30] and Ostovari, et al. [2]. Illustration designed by Wernerwerke, Cordes + Werner GbR ©2021.



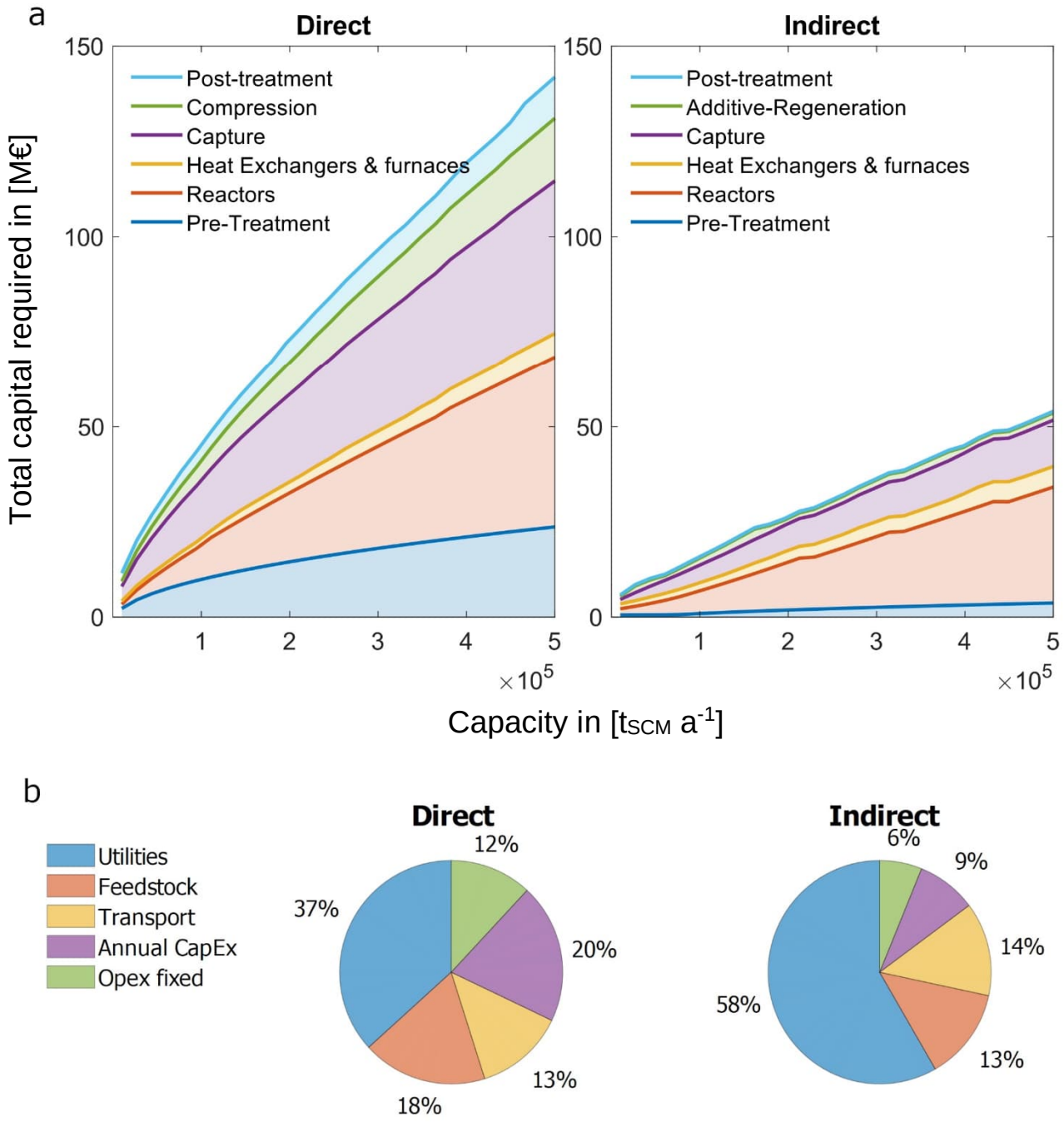
Supplementary Figure 3: Description of the techno-economic modelling sequence used in this study. Illustration designed by Wernerwerke, Cordes + Werner GbR ©2021.



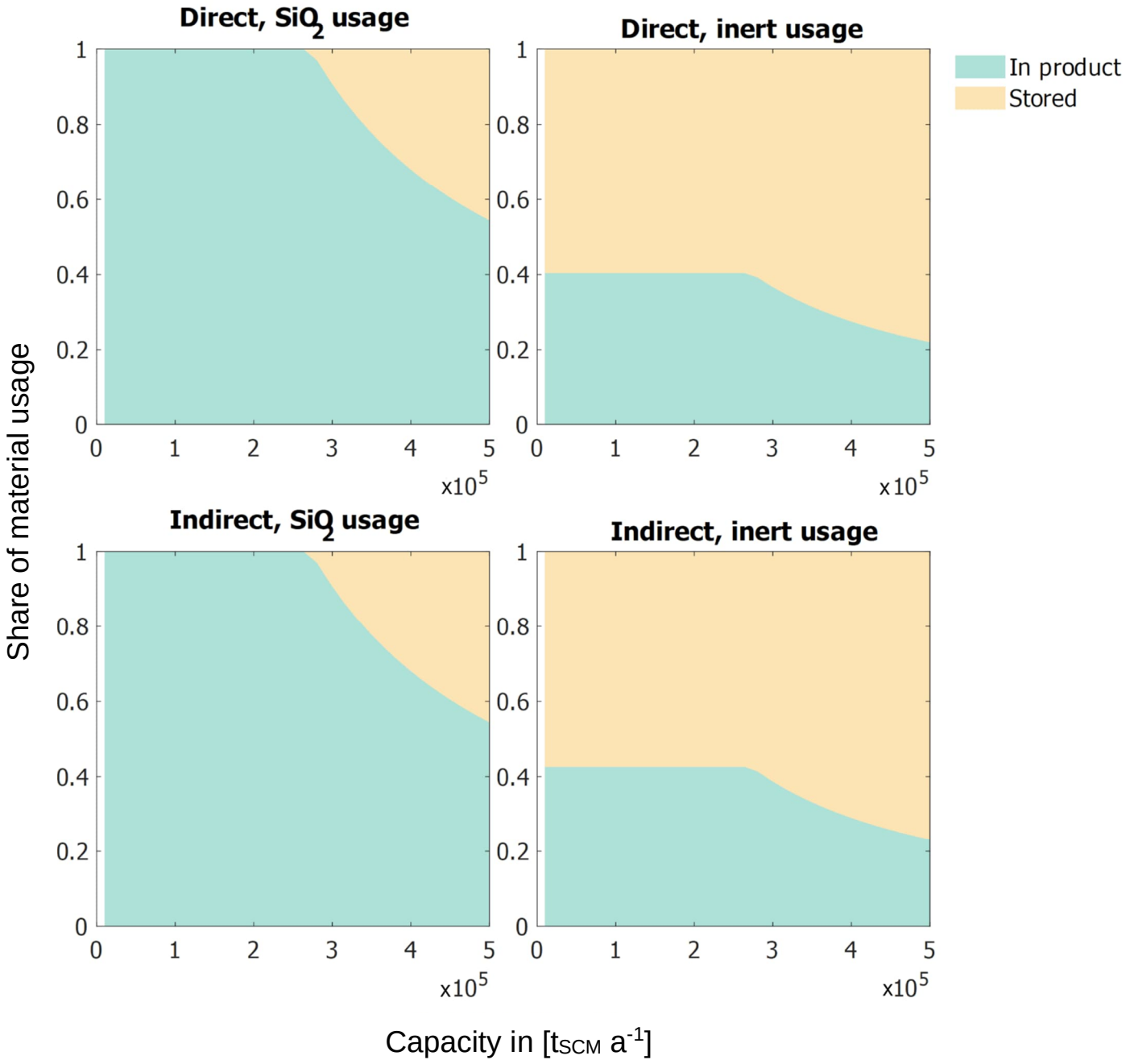
Supplementary Figure 4: Scope of the assessment for the comparison of different CO_{2e} emission reduction measures : panel a: Baseline, panel b: Biofuels, panel c: Calcined clay cement, d: Cement production with CO_2 capture and off-shore geological storage, e: Cement production with CO_2 capture and CO_2 mineralisation, f: Cement production with CO_2 capture and off-shore geological storage and CO_2 mineralisation. *The functional unit is defined as 1 ton of cement with the equivalent performance of 1 ton of ordinary Portland cement.



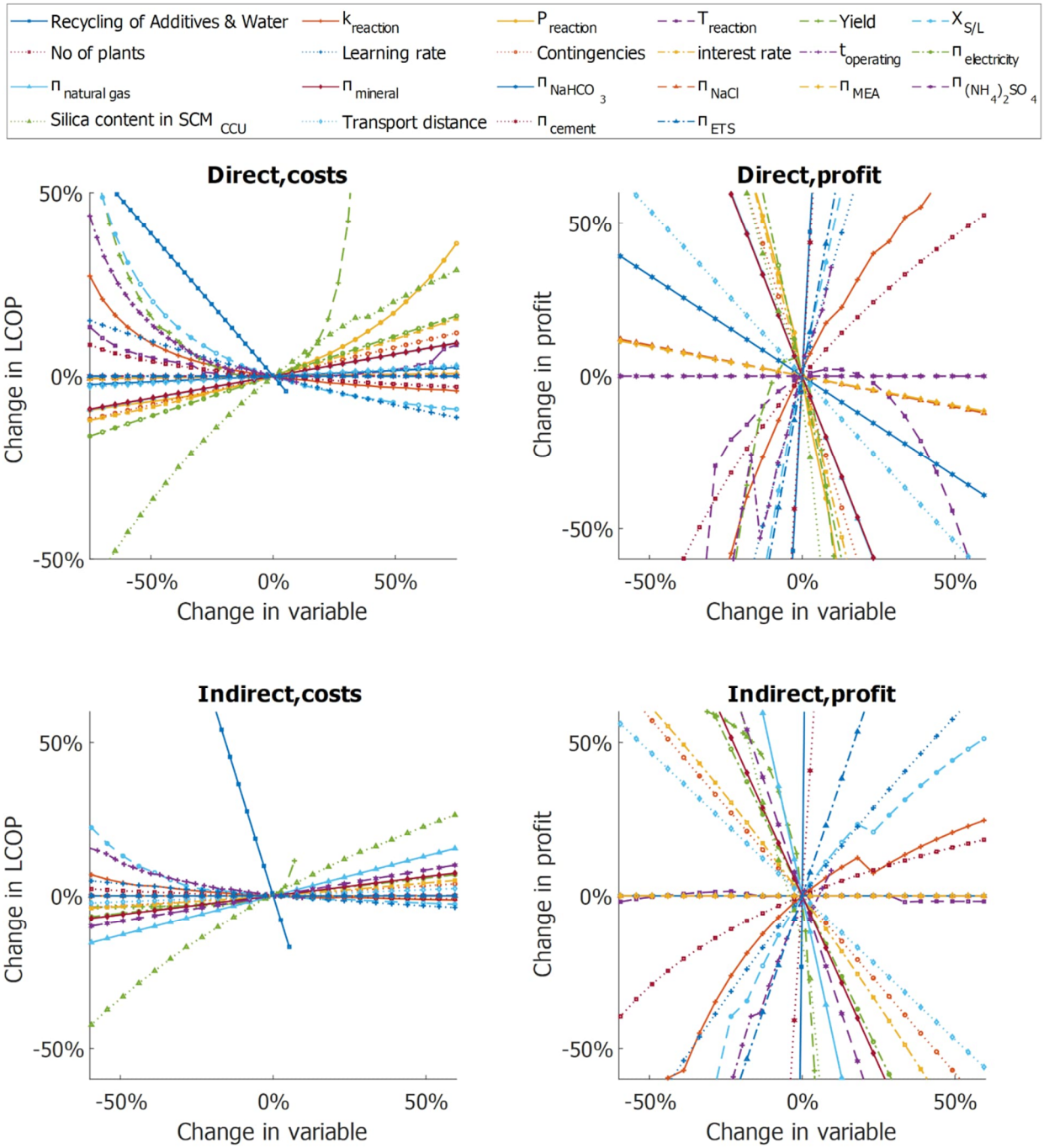
Supplementary Figure 5: Cost comparison of different process routes and mid scenario . Process assumptions are shown in Supplementary Table 3. Note all mentioning in the main article of "direct process" refers to "Direct, Olivine, 10µm (X=0.6)" and "indirect process" refers to "Indirect, Serpentine 75µ". Adapted from Strunge [49].



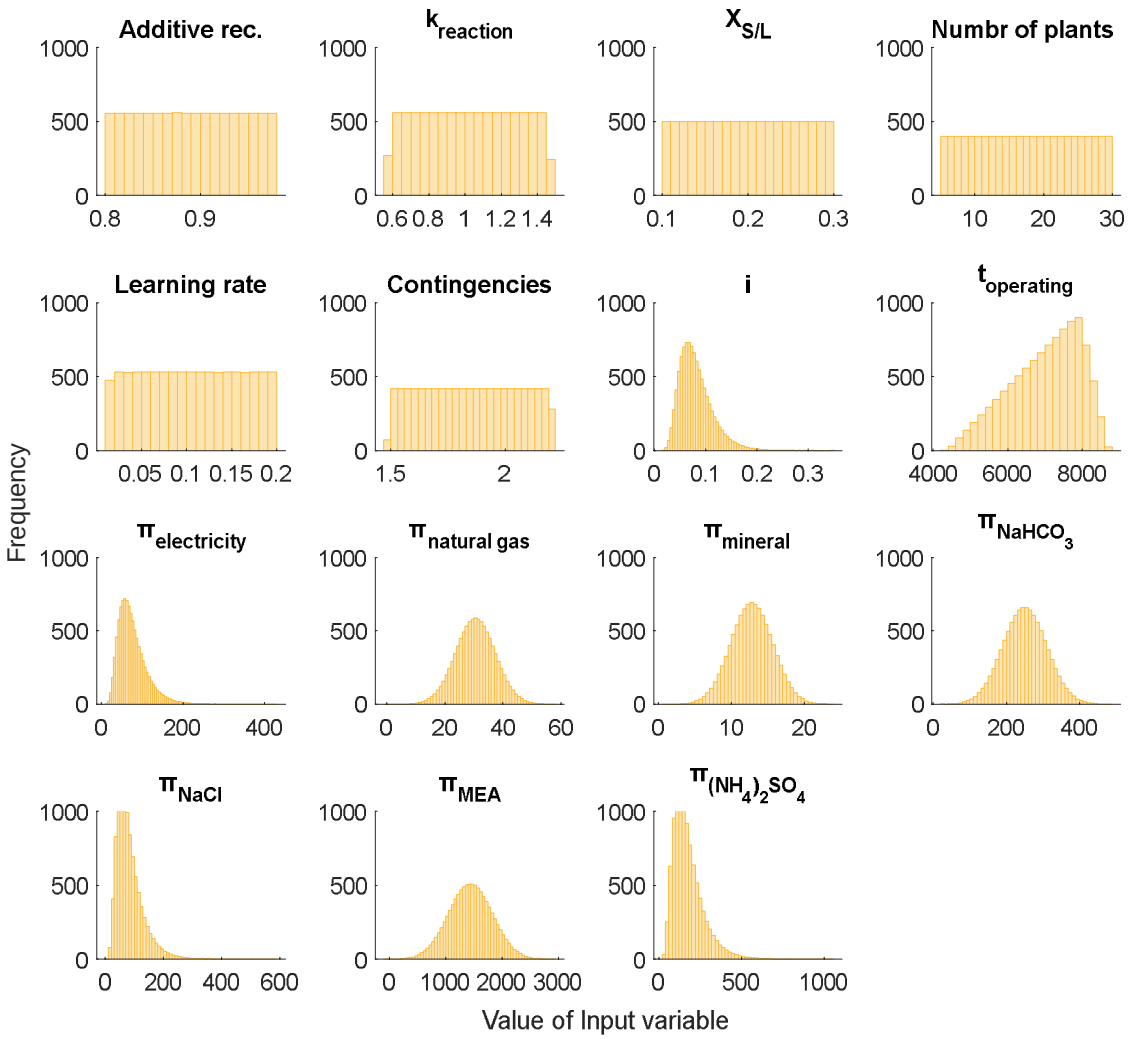
Supplementary Figure 6: Distribution of costs for the mid scenario: Panel a: Total capital required; Panel b: distribution of levelised costs of product.



Supplementary Figure 7: Material use for the mid scenario. Note, this figure displays the amount of material being used for the production of SCM_{CCU} (In product) and how much material has to be stored (Stored). Inert material consists of unreacted mineral, carbonate and impurities.



Supplementary Figure 8: Sensitivity analysis with the assumptions of the mid scenario and changing input parameters: additive recovery (Recycling of Additives & Water), reaction constant ($k_{reaction}$), reaction pressure ($P_{reaction}$), reaction temperature ($T_{reaction}$), reaction yield (Yield), solid-liquid ratio in reactor ($X_{S/L}$), Number of plants to reach NOAK (No of plants), Learning rate on CAPEX (Learning rate), combined process and project contingencies (Contingencies), interest rate on capital (i), operation hours per year ($t_{operating}$), electricity price ($\pi_{electricity}$), natural gas price ($\pi_{natural\ gas}$), mineral price ($\pi_{mineral}$), Sodium bicarbonate price (π_{NaHCO3}), Sodium chloride price (π_{NaCl}), monoethanolamine price (π_{MEA}), Ammonium sulphate price ($\pi_{(NH4)2SO4}$) , content of SiO_2 in product (Silica content in SCM_{CCU}), distance of feedstock minerals (Transport distance), cement price (π_{cement}), ETS price (π_{ETS}). Note that only one factor is changed at a time even when related (e.g. an increase in pressure does not change the yield). Hence, for the Monte Carlo Simulations only the reaction constant is used to cover the reaction conditions (see "Sensitive factors to lower costs" in the main article).



Supplementary Figure 9: Probability density functions for the input parameters for the MonteCarlo simulations using 10,000 runs: additive recovery (Additive Rec.), reaction constant ($k_{reaction}$), solid-liquid ratio in reactor ($X_{S/L}$), Number of plants to reach NOAK (No of plants), Learning rate on (Learning rate), combined process and project contingencies (Contingencies), interest rate on capital (i), operation hours per year ($t_{operating}$), electricity price ($\pi_{electricity}$), natural gas price ($\pi_{natural\ gas}$), mineral price ($\pi_{mineral}$), Sodium bicarbonate price (π_{NaHCO3}), Sodium chloride price (π_{NaCl}), monoethanolamine price (π_{MEA}), Ammonium sulphate price ($\pi_{(NH4)2SO4}$).

Supplementary Tables

Supplementary Table 1: Literature review of existing economic assessments in the field of CO_2 carbonation

Author	Costs	Unit	Comment	Feedstock
Sanna, et al. [5]	44-264*	€ $t_{CO2,\ sequestered}^{-1}$	/	mg -silicates
Hitch and Dipple [50]	73*[+]	€ $t_{CO2,\ sequestered}^{-1}$	direct	mg -silicates
IEA GHG 2000	95*	€ $t_{CO2,\ avoided}^{-1}$	direct	mg-silicate
IEA GHG 2000	>150*	€ $t_{CO2,\ avoided}^{-1}$	indirect	mg-silicate
Naraharisetti, et al. [51]	410*[#]	€ $t_{CO2,\ avoided}^{-1}$	direct	olivine
Naraharisetti, et al. [51]	443*[#]	€ $t_{CO2,\ avoided}^{-1}$	direct	olivine
W.K. O'Connor and L.R. Penner [21]	65*	€ $t_{CO2,\ avoided}^{-1}$	direct	olivine
Naraharisetti, et al. [51]	302*[#]	€ $t_{CO2,\ avoided}^{-1}$	direct	serpentine
W.K. O'Connor and L.R. Penner [21]	258*	€ $t_{CO2,\ avoided}^{-1}$	direct	serpentine
Sanna, et al. [1]	16-75*[+]	€ $t_{CO2,\ sequestered}^{-1}$	post processing only	serpentine
Naraharisetti, et al. [51]	349*[#]	€ $t_{CO2,\ avoided}^{-1}$	direct	serpentine
Huijgen, et al. [52]	77	€ $t_{CO2,\ avoided}^{-1}$	direct	steel slag
Katsuyama, et al. [53]	128-284*	€ t_{CaCO3}^{-1}	/	waste cement
Iizuka, et al. [54]	25*[++]	€ $t_{CO2,\ avoided}^{-1}$	indirect	waste cement
Naraharisetti, et al. [51]	304*[#]	€ $t_{CO2,\ avoided}^{-1}$	direct	wollastonite
W.K. O'Connor and L.R. Penner [21]	93*	€ $t_{CO2,\ avoided}^{-1}$	direct	wollastonite
Huijgen, et al. [52]	102	€ $t_{CO2,\ avoided}^{-1}$	direct	wollastonite
Kakizawa et al 2001	57*[++]	€ $t_{CO2,\ avoided}^{-1}$	indirect	wollastonite
Pérez-Fortes, et al. [55]	M65.5[§]	€ $t_{CO2,\ sequestered}^{-1}$	direct	fly ash
Mehleri, et al. [56]	228	€ $t_{CO2,\ avoided}^{-1}$	direct	fly ash
Pedraza, et al. [57]	33-39*	€ $t_{CO2,\ sequestered}^{-1}$	direct	Cement kiln dust

* Currency adapted to €
[#] Cost of CO_2 capture included
[+] Only operational expenditures assessed
[§] Only capital expenditures assessed
[++] Only operational expenditures in the form of power generation assessed and revenue from $CaCO_3$ included.

Supplementary Table 2: Review of carbonated material use in standardized cement products following EN 197[12].* Carbonated material has to be acknowledged as a natural pozzolan and must exhibit a silica content of at least 25 wt%.

Description		Max SCM_{CCU} allowance in current standard
CEM I	Portland cement	5%
CEM II	Portland-slag cement	5%
	Portland-silica fume cement	5%
	Portland pozzolana cement	20-35%*
	Portland-fly ash cement	5%
	Portland burnt shale cement	5%
	Portland limestone cement	5%
	Portland composite cement	20-35%*
CEM III	Blast furnace cement	5%
CEM IV	Pozzolanic cement	35-55%*
CEM V	Composite cement	30-50%*

Supplementary Table 3: Process assumptions

Description	Direct, Serpentine 37µm (X= 0.6)[21]	Direct, Olivine 37µm (X= 0.3)[21]	Direct, Olivine 37µm (X= 0.5)[21]	Direct*, Olivine 10 µm (X= 0.6)[22]	Direct, Olivine 10 µm (X= 0.8)[22]	Indirect[30,32,33]*
Yield	0.6	0.3	0.5	0.6	0.8	Overall: 0.87 Mineral diss.: 0.91 PH-Adjus.: 1.0 Carbonation: 0.95
particle size [µm]	37	37	37	10	10	75
***P* [bar]**	115	150	150	100	100	1
***T* [°C]**	155	185	185	190	190	80
c_{NaHCO3} **[mol/l]**	0.64	0.64	0.64	0.5	0.5	/
c_{NaCl} **[mol/l]**	1	1	1	0.75	0.75	/
$c_{(NH4)2SO4}$ **[mol/l]**	/	/	/	/	/	5.96
Reaction rate constant	0.1822**	0.3022**	0.3022**	1.4717**	1.4717**	Mineral diss.:1.2839** Carbonation: 4.186**
* Selected as routes for this study (referred to as "direct process" and "indirect process"). **derived regression of published lab data [21,22,30,32,33]						

Supplementary Table 4: Equations used for mass balance of feed recycling and separation in direct process.

Use	Formula
Recycling unreacted mineral, direct aqueous process	$\dot{m}_{Mg2SiO4,theo} = \frac{\dot{m}_{CO2,reacted}}{M_{CO2}} * \frac{\nu_{Mg2SiO4}}{\nu_{CO2}} * M_{Mg2SiO4}$ $\dot{m}_{Mg2SiO4,real} = \dot{m}_{Mg2SiO42,theo} * \frac{1}{Yield} - \dot{m}_{Mg2SiO42,theo} * \left(\frac{1}{Yield} * (1 - Yield) * recovery\ factor\right)$

Split of stream for classificati on centrifuge	$$z = \frac{1 - \left(\frac{1-x}{x}\right) * \left(\frac{y}{1-y}\right) + \left(\frac{1-y}{y}\right) - \left(\frac{1-x}{x}\right)}{1 + \left(\frac{1-y}{y}\right)}$$ $$x = content\ of\ SiO_2 in\ final\ product$$ $$y = content\ of\ SiO_2 in\ cyclone\ output$$ $$z = split\ of\ stream\ fed\ to\ classification\ centrifuge$$

Supplementary Table 5: Used Equations for Density and viscosity

Description	Equation	Reference
Density slurry	$\rho_{\text{slurry}} = \frac{100}{\left(\frac{X_{\text{solid,liquid}}}{\rho_{\text{solid}} \cdot 1000}\right) + \left(\frac{100 - X_{\text{solid,liquid}}}{\rho_{\text{H2O}} \cdot 1000}\right)}$	Shashi [58]
Viscosity slurry	$\upsilon_{\text{slurry}} = \upsilon_{H_2O} \cdot \left(1 + 2.5 \cdot V_{\text{fraction}} + 10.06 \cdot {V_{\text{fraction}}}^2 \cdot 0.00273 \cdot \exp(16.6 \cdot V_{\text{fraction}})\right)$	Shashi [58]
Density $ABS_{(aq)}$	$\rho_{\text{ABS(aq)}} = 0.99671 + (0.604706 \cdot 10^{-1}) \cdot c_{\text{ABS}} - (0.108981 \cdot 10^{-2}) \cdot {c_{\text{ABS}}}^2 + (0.106394 \cdot 10^{-4}) \cdot {c_{\text{ABS}}}^3$	Stelson and Seinfeld [59]
Density $AS_{(aq)}$	$\rho_{\text{ABS(aq)}} = 0.0771 \cdot {c_{\text{ABS}}}^{0.8463} + 0.9945$	Adapted from The Engineering ToolBox [60]
Density $MS_{(aq)}$	$\rho_{\text{MS}} = 0.9943 + -0.001323 \cdot c_{\text{wt\%,MS}} + 0.003697 \cdot T$	handymath.com [61]

Supplementary Table 6: Heat capacity calculation for different compounds : The integral of the heat capacity is derived using the Shomate equation: $\int_{T_0=25°C}^{T} cp\ dT = a \cdot (T - T_0) + b \cdot \frac{T^2 - T_0^2}{2} + c \cdot \frac{T^3 - T_0^3}{3} + d \cdot \frac{T^4 - T_0^4}{4} - e \cdot \left(((T)^{-1}) - ((T_0)^{-1})\right)$

Description	*a*	*b*	*c*	*d*	*e*	Reference
$H_2O_{(l)}$	-203.606	1523.29	-3196.41	2474.455	3.855326	Chase [62]
$Fe_2(SO_4)_{3(s)}$	85.69794	803.9765	-695.757	215.6099	-0.396145	Chase [62]
$CO_{2(g)}$	24.99735	55.18696	-33.6914	7.948387	-0.136638	Chase [62]
$NH_{3(g)}$	19.99563	49.77119	-15.376	1.921168	0.189174	Chase [62]
SiO_2	-6.076591	251.6755	-324.796	168.5604	0.002548	Chase [62]
$Fe(OH)_{3\ (s)}$	56.70701	132.1357	-83.5997	17.25465	0.711267	Chase [62]
$MgCO_{3\ (s)}$	44.937	149.7085	-74.1827	11.9767	-0.629261	Chase [62]
$H_2O_{(g)}$	30.092	6.832514	6.793435	-2.53448	0.082139	Chase [62]
MgO	47.25995	5.681621	-0.872665	0.1043	-1.053955	Chase [62]
Fe_2O_3	93.43834	108.3577	-50.86447	25.58683	-1.61133	Chase [62]
NH_4OH (l)	9.8	-	-	-	-	Southard and Green [63]
$Mg_3Si_2O_5.(OH)_4$ (s)	1.09	-	-	-	-	Engineering Toolbox [60]
$MgSO_4$ (l)	111.713	-	-	-	-	Southard and Green [63]

NH_4HSO_4 (l)	1.423	-	-	-	-	National Center for Biotechnology Information [64]
$(NH_4)_2SO_4$ (l)	1.419	-	-	-	-	MatWeb [65]
NH_4HCO_3 (l)	1.119	-	-	-	-	Rademaekers, et al. [34]

Supplementary Table 7: Equations for electricity consumption

Description	Equation	Reference
Crushing	$w_{\text{crushing}} = 2 \cdot \dot{m}_{\text{mineral}}$	Gerdemann, et al. [20]
Grinding	$w_{\text{grinding,}\leq 75\mu\text{m}} = 10 \cdot K_{\text{Bond}} \cdot \left(\frac{1}{\sqrt{75}} - \frac{1}{\sqrt{d_{\text{mineral,feed}}}}\right) \cdot \dot{m}_{\text{mineral}}$	Schwister and Leven [66]
	$w_{\text{grinding,75µm to 37µm}} = 70.31 \cdot \dot{m}_{\text{mineral}}$	Gerdemann, et al. [20]
	$w_{\text{grinding,37µm to 10µm}} = 150 \cdot \dot{m}_{\text{mineral}}$	Hangx and Spiers [67]
Slurry Pumping	$w_{\text{pump}} = \left(\frac{\left(\left(\frac{V_{\text{slurry}}}{\tau \cdot 3600}\right)\right) \cdot g_{\text{earth}} \cdot \text{pump}_{\text{head}} \cdot \frac{\rho_{\text{slurry}}}{\eta_{\text{pump}}}}{1000}\right) \cdot t_{\text{operating}}$	Costa, et al. [68]
Slurry stirring	$w_{\text{stirring}} = \frac{V_{\text{slurry}} \cdot \text{rpm}^2 \cdot t_{\text{operating}} \cdot \nu_{\text{slurry}}}{1000}$	Costa, et al. [68]
CO_2 compression (5 stage)	$w_{\text{comp}} = (17.501 \cdot \ln(p) + 12.876) \cdot \dot{m}_{CO_2}$	Aspen Plus Simulation
Steam compression	$w_{\text{compression}} = (52.897 \cdot p - 52.668) \cdot \dot{m}_{\text{steam}}$	Aspen Plus Simulation
Solid bowl centrifuge	$w_{\text{centrifuge}} = (P_{\text{solid}} + P_{\text{water}} + P_{\text{empty}}) \cdot \eta_{\text{motor}} \cdot t_{\text{operation}}$ $P_{\text{solid}} = m_{\text{solid}} \cdot (2 \cdot \pi \cdot u_{\text{bowl}} \cdot r_{\text{exit,solid}})^2$ $P_{\text{liquid}} = m_{\text{solid}} \cdot (2 \cdot \pi \cdot u_{\text{bowl}} \cdot r_{\text{exit,water}})^2$ $P_{\text{loss}} = m_{\text{shell}} \cdot f_{\text{drag}} \cdot g_{\text{earth}} \cdot 2 \cdot \pi \cdot u_{\text{bowl}} \cdot r_{\text{shell}}$	Adapted from Bell [69]
Disc centrifuge	$w_{\text{centrifuge}} = 1.9339 \cdot \exp(0.0039 \cdot \text{diameter})$	Regression from specification sheets

Supplementary Table 8: Used equations for deriving the total direct costs , derived from Aspen capital cost estimator.

Equipment	Limits	Function	Coefficients	R^2
Centr. Pump	V = 10-150L/s P= 10-150bar	$\text{TDC} = a + b \cdot x^n + c \cdot y^m + d \cdot x \cdot y$	a = -5.534e+04 b = 3.169e+04 c = 9.356 d = 19.64	98.81%

			m = 2.306 n = 0.409	
Ball Mill	Power = 290-21540 kW	$TDC = a \cdot x^n + b$	a = 1.233e+05 b = -9.006e+05 n = 0.4977	99.89%
Furnace	V = 50-150L/s Duty = 100-1000MW	$TDC = a + b \cdot x^n + c \cdot y^m$	a = 2.37e+05 b = 6686 c = 7.102 m = 1.988 n = 0.5224	99.91%
Cone Crusher	m = 75-300t/h	$TDC = a \cdot x^n + b$	a = 5040 b = 3.818e+04 n = 0.7435	99.83%
Agitator	Power = 10-75kW	$TDC = a \cdot x^n + b$	a = 909 b = 1.753e+04 n = 1.084	99.84%
Reactor	V = 50-200m3 P = 20-140bar	$TDC = a + b \cdot x^n + c \cdot y^m + d \cdot x \cdot y$	a = 3.153e+05 b = 0.2124 c = 437.7 d = 90.18 m = 1.347 n = 2.698	99.85%
Heat exchanger max 10 bar	A = 25-75m2	$TDC = a \cdot x^n + b$	a = 462 b = 7.943e+04 n = 1	90.05%
	A = 100-200m2	$TDC = a \cdot x^n + b$	a = 169.6 b = 1.261e+05 n = 1	99.24%
	A = 225-500m2	$TDC = a \cdot x^n + b$	a = 164.5 b = 1.577e+05 n = 1	98.64%
	A = 550-900m2	$TDC = a \cdot x^n + b$	a = 114.2 b = 2.074e+05 n = 1	98.71%
	A = 950-1200m2	$TDC = a \cdot x^n + b$	a = 115 b = 2.423e+05 n = 1	100.00%
Heat-exchanger 10-100 bar	A = 100-200m2 P = 10-100bar	$TDC = a + b \cdot x^n + c \cdot y^m + d \cdot x \cdot y$	a = 1.257e+05 b = 4.525 c = 0.02784 d = 1.000 m = 3.284 n = 1.705	99.42%
	A = 225-500m2 P = 10-100bar	$TDC = a + b \cdot x^n + c \cdot y^m + d \cdot x \cdot y$	a = 1.441e+05 b = 44.82 c = 16.96 d = 1 .000 m = 1.999 n = 1.242	97.97%
	A = 600-900m2	$TDC = a + b \cdot x^n + c \cdot y^m + d \cdot x \cdot y$	a = 1.915e+05 b = 14.7 c = 23.76	98.40%

	P = 10-100bar		d = 1 .000 m = 2 .000 n = 1.318	
	A = 950-1200m2 P = 10-100bar	$TDC = a + b \cdot x^n + c \cdot y^m + d \cdot x \cdot y$	a = 9.173e+07 b = -9.052e+07 c = -2.057e+05 d = 6.274 m = 0.1789 n = 0.0009788	98.21%
Heat-exchanger 125-150bar	A = 100-200m2 P = 125-150bar	$TDC = a + b \cdot x^n + c \cdot y^m + d \cdot x \cdot y$	a = 2.474e+05 b = 14.09 c = 31.46 d = 4.678 m = -19.47 n = -5.865	99.03%
	A = 225-500m2 P = 125-150bar	$TDC = a + b \cdot x^n + c \cdot y^m + d \cdot x \cdot y$	a = 2.417e+05 b = 999.2 c = 5.187 d = 2.141 m = 2.000 n = 0.8516	99.93%
	A = 600-900m2 P = 125-150bar	$TDC = a + b \cdot x^n + c \cdot y^m + d \cdot x \cdot y$	a = -1.478e+05 b = 1081 c = 1.899e+05 d = 2.302 m = 0.2334 n = 0.7631	95.76%
	A = 950-1200m2 P = 125-150bar	$TDC = a + b \cdot x^n + c \cdot y^m + d \cdot x \cdot y$	a = 4.067e+05 b = 308.1 c = 3.595e+04 d = 2.465 m = 0.3395 n = 0.9353	99.85%
Mechanical scraped-surface crystalliser	l = 8-150m	$TDC = a + b \cdot x^n$	a = 2238 b = 9615 n = 0.8106	100.00%
Indirect rotary dryer	A = 10-185m^2	$TDC = a + b \cdot x^n$	a = 69.7 b = 6513 n = 0.9392	100.00%
Hydro-cyclones	d = 100-290mm pcs per manifold = 10-100	$TDC = a + b \cdot x^n + c \cdot y^m$	a = -0.4077 b = 27.36 c = 0.0003486 m = 1.616 n = -0.3809	99.80%
	d=300-370mm pcs per manifold = 10-100	$TDC = a + b \cdot x^n + c \cdot y^m$	a = 6.806 b = 1880 c = 0.0001596 m = 1.741 n = -2.428	99.72%
	d=375-500mm pcs per	$TDC = a + b \cdot x^n + c \cdot y^m$	a = -47.25 b = 77.37 c = 0.001123	99.24%

	manifold = 10-100		m = 1.443 n = -0.06914	
Solid bowl centrifuge	d = 450-1250mm l = 750-3000mm	$TDC = a + b \cdot x \cdot y + c \cdot y^m$	a = 4.192e+04 b = 0.1509 c = 13.29 m = 1.384	99.75%
Highspeed disc centrifuge	d = 37.5-125cm	$TDC = a + b \cdot x$	a = 1.848e+05 b = 4.784e+05	99.98%

Supplementary Table 9: Major equipment design assumptions

Equipment	Description	Reference
Reactor	Max size 500 m^3 (for p> 50 bar) Max size 1000 m^3 (for p < 10 bar) Max wall thickness 0.2m Gas phase in reactor: 0.3 (direct), 0.05(indirect) Joint efficiency 1 Vessel security factor 0.1	Own estimation, Towler and Sinnott [70]
Centrifugal Pump and compressor	Pump efficiency 0.80 Isentropic compressor efficiency 0.85	Anantharaman, et al. [4]
Heat exchanger	Minimal Temp difference 10K Heat transfer coefficient liquid-liquid 675 W/m^2K Heat transfer coefficient liquid-gas 40 W/m^2K Heat transfer coefficient steam evaporation 1950 W/m^2K Heat transfer coefficient indirect dryer 293 W/m^2K	Njeng, et al. [71],The Engineering ToolBox [72]
Hydro Cyclone	Separation efficiency unreacted mineral 0.6 Max pressure drop 0.3 bar Max number per manifold 100	Parametric study in Aspen Plus
Classification Centrifuge	Separation efficiency Silica 0.85 Purity of Silica stream 0.99 Speed 4000 rpm	Parametric study in Aspen Plus
Dewatering Centrifuge	Wall thickness 0.02m Speed 3000 rpm	Own estimation, Parametric study in Aspen Plus

Supplementary Table 10: Assumptions carbon footprint reduction assessment : the assessment was adapted from Ostovari, et al. [2]. Multiple values are not displayed, as they belong to propriety datasets. Some propriety data shown here has before been published in Ostovari, et al. [2] with the approval of the GaBi.

Description	Name of data set	Database / Reference	Year	Value	
Electricity grid emission	Electricity grid mix [EU-28]	GaBi ts[73]	2016	417	kg_{CO2e} MWh^{-1}
Natural gas emission	Thermal energy from natural gas [EU-28]	GaBi ts[73]	2016	241.0	kg_{CO2e} MWh^{-1}
Transport train	Rail transport, average train, gross tonne weight 1000t / 726t payload capacity [EU-28]	GaBi ts[73]	2016	0.0258	kg_{CO2e} km^{-1} t^{-1}
Transport truck	Transport, small truck (up to 14 t total cap., 9.3t payload) [EU-28]	GaBi ts[73]	2016	0.0791	kg_{CO2e} km^{-1} t^{-1}

Transport ship	/	Psaraftis and Kontovas [74]	/	0.033	$kg_{CO2e}\ km^{-1}\ t^{-1}$
Water	Process water [EU-28]	GaBi ts[73]	2016	/	$kg_{CO2e}\ t^{-1}$
$NaHCO_3$	Sodium bicarbonate	GaBi ts[73]	2017	/	$kg_{CO2e}\ t^{-1}$
NaCl	Sodium chloride (rock salt) [EU-28]	GaBi ts[73]	2016	/	$kg_{CO2e}\ t^{-1}$
$(NH_4)_2SO_4$	Ammonium sulfate production [RoW]	Ecoinvent 3.71[75]	2019	/	$kg_{CO2e}\ t^{-1}$
Monoethanol-amine	/	Pehnt and Henkel [76]	/	/	$kg_{CO2e}\ t^{-1}$
Construction	/	Ostovari, et al. [2]	/	0.04	$kg_{CO2e}\ t_{CO2stored}^{-1}$
Mining Mineral	/	Ostovari, et al. [2]	/	5.23	$kWh\ t^{-1}$
Cement production	/	Voldsund, et al. [77]	/	850	$kg_{CO2e}\ t_{clinker}^{-1}$

Supplementary Table 11: Capital cost factor assumptions

Description	Value	Basis	Reference
Indirect costs	14%	TDC	Anantharaman, et al. [4]
Process contingencies	40%	EPC	EPRI [78], AACE [79]
Project contingencies	30%	EPC	EPRI [78]
Owner's costs	7%	TPC	Grande, et al. [80]
Learning rate	10.55%	/	Rubin, et al. [81]
Number of plants for NOAK	20	/	Greig, et al. [82]
Lifetime of the plant	30 years	/	/

Supplementary Table 12: Operational cost factor assumptions

Description	Value	Basis	Reference
Insurance and local tax	2%	TPC	Anantharaman, et al. [4]
Maintenance	2.5%	TPC	Anantharaman, et al. [4]
Administration and support	30%	Operating and Maintenance	Anantharaman, et al. [4]

Supplementary Table 13: Probability density function for Monte Carlo Simulation and Scenario definition

Variable	Min	Max	Assumption in mid scenario[#']	Probability density function	Reference
Recycling of Additives & Water	0.8	0.98	0.95	Uniform	own estimations, Wang and Maroto-Valer [30],Eikeland, et al. [22]
Mineral Purity	0.5	0.8	0.8	Uniform	Kremer, et al. [6]
Reaction constant[§]	0.5759* 0.6420**	1.4717* 1.2839**	1.4717* 1.2839**	Uniform	**Wang and Maroto-Valer [30],*Eikeland, et al. [22]
Solid content in Reactor*	0.125	0.3	0.125* 0.3**	Uniform	Wang and Maroto-Valer [30],Eikeland, et al. [22] W.K. O'Connor and L.R. Penner [21]
Number of plants to reach NOAK	5	30	20	Uniform	own estimations, Greig, et al. [82]
Learning rate	1.1%	20%	10.55%	Uniform	Rubin, et al. [81]
Process and project contingencies	30%, 15%	70%, 30%	40% 30%	Uniform	EPRI [78], AACE [79]
Interest rate on debt	1.40%	3.72%	/	/	European Central Bank [83]
Return on equity	5%	20.20%	/	/	Gurufocus [84]
Debt/equity	31.00%	73.00%	/	/	Macrotrends [85,86]
Overall interest [#]	4%	17 %	7.69%	Lognormal	/
Working hours	4380	8688	8000	Triangular	own estimations, Deolalkar [39]
Electricity price (in 2030)	38	200	62	Lognormal	European Commission [87]
Natural gas price (in 2030)	16.18	40.94	32	Normal	Duić, et al. [88]
Extraction Costs Mineral	3.52	22.95	12	Normal	Brown, et al. [89] , Béarat, et al. [90] Huijgen, et al. [52] et al.
Price $NaHCO_3$*	100*	400*	209	Normal	Comparison of vendor prices[91]
Price NaCl*	20*	300*	61.6	Lognormal	Comparison of vendor prices[91]
Price MEA*	600*	2050*	1320	Normal	Comparison of vendor prices[91]
Price $(NH_4)_2SO_4$**	90**	740**	140	Lognormal	Comparison of vendor prices[91]
Cement price[§$]	78	172	102	Lognormal	de Vet, et al. [92], Statista [93]
ETS price (in 2030)[§§]	40	89	32	Triangular	Schjølset [94], Watson [95], Carbon Tracker Initiative [96], Carbon Pulse [97]

* for direct process only
** for indirect process only
[§] Note the reaction constant for the indirect process is taken from the slowest step, the mineral dissolution.
derived from Monte Carlo simulation on interest on debt, ROE and debt/equity ratio
[§§]used for scenario definition.
[##] when multiple assumptions could be used (>5 references), the median was chosen.

Supplementary Table 14: Equations used for the comparisons of different strategies to mitigate CO_{2e} emission reductions.

Description	Equation	Variable description
Baseline	$\mathrm{LCOP}_{\mathrm{cement}} = \mathrm{LCOP}_{\mathrm{clinker}} + e_{\mathrm{clinker}} \cdot \pi_{\mathrm{ETS}}$	
Biofuels	$\mathrm{LCOP}_{\mathrm{cement}} = \mathrm{LCOP}_{\mathrm{clinker}} + \mathrm{MAC}_{\mathrm{bio\ fuel}} \cdot (e_{\mathrm{clinker}} \cdot \Delta e_{\mathrm{cement}}) + (e_{\mathrm{clinker}} \cdot (1 - \Delta e_{\mathrm{cement}})) \cdot \pi_{\mathrm{ETS}}$	$MAC_{bio\ fuel}$: Marginal abatement costs Δe_{cement}: Carbon footprint reduction.
Calcinated clay cement	$\mathrm{LCOP}_{\mathrm{cement}} = \mathrm{LCOP}_{\mathrm{calcinated\ clay\ cement}} + e_{\mathrm{clinker}} \cdot (1 - \Delta e_{\mathrm{cement}}) \cdot \pi_{\mathrm{ETS}} + \dot{m}_{\mathrm{feedstock}} \cdot d_{\mathrm{Transport}} \cdot \pi_{\mathrm{Transport}}$	
Cement production with off-shore CCS	$\mathrm{LCOP}_{\mathrm{cement}} = \mathrm{LCOP}_{\mathrm{clinker\ with\ CCS}} + e_{\mathrm{clinker}} \cdot (1 - \Delta e_{\mathrm{cement}}) \cdot \pi_{\mathrm{ETS}} + \dot{m}_{\mathrm{CO_2\ stored}} \cdot d_{\mathrm{Transport}} \cdot \pi_{\mathrm{Transport}}$	
Cement production with CO_2 mineralisation	$L\mathrm{COP}_{\mathrm{cement}} = \mathrm{LCOP}_{\mathrm{clinker}} \cdot (1 - X_{\mathrm{replaced}}) + \mathrm{LCOP}_{\mathrm{SCM_{CCU}}} \cdot X_{\mathrm{replaced}} + (e_{\mathrm{clinker\ with\ CCS}} + e_{\mathrm{SCM_{CCU}}}) \cdot \pi_{\mathrm{ETS}}$	$X_{replaced}$: Share of cement replaced
Cement production with off-shore CCS and CO_2 mineralisation	$\mathrm{LCOP}_{\mathrm{cement}} = \mathrm{LCOP}_{\mathrm{clinker}} \cdot (1 - X_{\mathrm{replaced}}) + \mathrm{LCOP}_{\mathrm{capture}} \cdot \dot{m}_{\mathrm{CO_2\ captured}} + (\mathrm{LCOP}_{\mathrm{SCM_{CCU}}} - \mathrm{LCOP}_{\mathrm{capture}} \cdot \dot{m}_{\mathrm{CO_2\ stored,CCU}}) \cdot X_{\mathrm{replaced}} + (e_{\mathrm{clinker\ with\ CCS}} + e_{\mathrm{SCM_{CCU},direct}}) \cdot \pi_{\mathrm{ETS}}$	$e_{SCM_{CCU},direct}$:Direct process emissions of SCM_{CCU} production.

Supplementary Table 15: Assumptions used for the comparisons of different strategies to mitigate CO_{2e} emission reductions.

	Carbon capture and storage	Calcinated clay cement	CO_2 mineralisation	Biofuels
Reservoir locations in Europe	Reservoirs for CO_2 storage are located in the North Sea and Mediterranean Sea[98].	Reservoirs of kaolinite clays are located in the Czech Republic, Hungary, Poland, South of Germany[99].	Reservoirs of olivine bearing rocks are located in Norway, Portugal, Spain, Greece, Italy[6].	Feedstock locations are included in the used range for costs.
Transport assumptions for the model	Pipeline transport 100-2000km	Mineral transport: 100-2000km (truck and train)	Mineral transport in Scenario: 1200 km (truck, train and ship)	/

Costs	MEA[77]: $LCOP_{clinker\ with\ CSS}$ = €107.4$t_{clinker}^{-1}$ Oxy-fuel combustion[77]: $LCOP_{clinker\ with\ CCS}$ = €93$t_{clinker}^{-1}$ CO_2 transport derived from Zero Emission Platform [100] for pipeline transport and offshore storage: $\pi_{CO_2,transport} = 0.0099 \cdot d_{Transport} + 1.2185$ with $d_{transport}$ being distance in [km].	Calcined clay cement[101]: $LCOP_{calcinated\ clay\ cement}$ 54.66* €/t_{cement} $\dot{m}_{feedstock} = 0.5 \cdot \dot{m}_{cement}$ Mineral transport[89]: $\pi_{transport,truck}$ = €0.04t^{-1} km^{-1} $\pi_{transport,train}$ = €0.032t^{-1} km^{-1}	$LCOP_{SCM_{CCU}}$ is calculated for each scenario by the model presented in this paper. Mineral transport[89]: $\pi_{transport,truck}$ = €0.04t^{-1} km^{-1} $\pi_{transport,train}$ = €0.032t^{-1} km^{-1} $\pi_{transport,ship}$ = €0.0032t^{-1} km^{-1}	Marginal abatement costs[36]: $MAC_{bio\ fuel}$ = €15 – €50$t_{CO2e,avoided}^{-1}$
Carbon footprint reduction#	MEA[77]: Δe_{cement} = 0.64 Oxy-fuel combustion[77]: Δe_{cement} = 0.82	Calcined clay cement[101]: Δe_{cement} = 0.34	Carbon footprint reductions are calculated for each scenario by the model presented in this paper.	Alternative fuels§[102]: Δe_{cement} = 0.25

* Currency adapted to €.
# Reductions calculated in comparison to ordinary Portland Cement.
§ 70% of fossil fuels are replaced by alternative fuels.

Supplementary Table 16: List of abbreviations and symbols.

Abbreviation	Description	Unit
ABS	Ammonium bisulphate	/
Additive Rec.	Additive recovery	[fraction]
AS	Ammonium sulphate	/
$\propto$	Levelisation factor	[fraction]
c_{A_0}	Initial concentration of educt A	[mol l^{-1}]
C_i	Cost of i	[€ a^{-1}]
$CaCO_3$	Calcium carbonate	/
CAPEX	Capital expenditures	/
$CaSiO_3$	Wollastonite	/
CCS	Carbon capture and storage	/
CCU	Carbon capture and utilisation	/
CCU_M	Carbon capture and utilisation through mineralisation	/
CO_2	Carbon dioxide	/
CO_{2e}	Carbon dioxide equivalent	/
CSTR	Continuously stirred tank reactors	/
d	Diameter	[m]
DER	Dept to equity ratio	[fraction]
dist	Distance	[km]
Δ_i	Change of i	/
E	Experience factor	[fraction]
e_i	CO_{2e} emissions of i	[t_{CO2e} a^{-1}]
ETS	European emission trading system	/
η	Efficiency	[fraction]
f_i	Costing factor i	[fraction]
FOAK	First-of-a-kind	/
h	Height	[m]
$\dot{H}$	Enthalpy stream	[KW]
i	Interest rate on capital	[fraction]

I	Capital cost index	[real number]
k	Heat exchange coefficient	[W m^{-2} K^{-1}]
$k_{reaction}$	Reaction rate constant	[1 s^{-1}]
l	Length	[m]
LCOP	Levelised cost of product	[€ t^{-1}]
LR	Learning rate	[fraction]
$\dot{m}$	Mass flow	[t a^{-1}]
MEA	Monoethanolamine	/
MEA CCS	Monoethanolamine post combustion capture with offshore geological CO_2 storage	/
Mg_2SiO_4	Forsterite	/
$Mg_3Si_2O_5(OH)_4$	Lizardite	/
$MgCO_3$	Magnesium carbonate	/
MS	Magnesium sulphate	/
No of plants	Number of plants to reach maturity	[natural number]
NOAK	N^{th}-of-a-kind	/
OPEX	Operational expenditures	/
Oxy-fuel CCS	Oxy-fuel combustion with offshore geological CO_2 storage	/
$\dot{Q}$	Heat stream	[KW]
ρ	Density	[kg m^{-3}]
π_i	Price of i	[€ t^{-1}] or [€ MWh^{-1}]
R	Revenue	[€ t^{-1}]
r	Radius	[m]
r_A	Reaction rate for educt A	[mol l^{-1} s^{-1}]
ROE	Return on equity	[fraction]
rpm	Centrifugal speed	[rpm]
SCM	Supplementary cementitious material	/
SCM_{CCU}	Supplementary cementitious material produced via CO_2 mineralisation	/
SiO_2	Silica	/
T	Temperature	[K] or [°C]
TEA	Techno-economic assessment	/
$t_{construction}$	Estimated time for construction	[years]
TCR	Total capital required	[€]
TDC	Total direct costs	[€]
$t_{operating}$	Operation hours per year	[h a^{-1}]
TPC	Total plant costs	[€]
TRL	Technology readiness level	/
t_w	Wall thickness	[m]
τ	Space time	[s]
V	Volume	[m^3]
$\dot{v}$	Volume flow	[m^3 a^{-1}]
v	Viscosity	[10^-6Pa s]
w	Electrical work	[KWh]
X	Extend of reaction	[fraction]
X_i	Share of material i in cement blend	[fraction]
$X_{S/L}$	Solid-liquid ratio in reactor	[fraction]

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