Supplementary Information (SI) for Energy & Environmental Science.

Supporting Information for
Scalable Electrified Cementitious Materials Production and Recycling

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Experimental methods

Chemicals

All experiments are performed with ultrapure Milli-Q water (18.2 MΩ-cm) unless otherwise specified. Wollastonite (99%, reagent grade), sodium nitrate (99.0% certified ACS), sodium chloride (granular, J.T. Baker), and potassium hydroxide (certified ACS) were purchased from Thermo Fisher. Sulfuric acid (99.999%) and hydrogen peroxide (30 wt%) were purchased from Sigma Aldrich.

Membrane preparation

Cation exchange membranes (Aquivion E98-09S) were boiled at 80 °C in 0.5 M H_2SO_4, 3 wt% H_2O_2, and Milli-Q water for 1 h, sequentially, and stored in Milli-Q water. Anion exchange membranes (Sustainion X37-50 Grade RT, Dioxide Materials) were soaked in 1 M KOH for at least 24 h, followed by removal of plastic support. Bipolar membranes (Fumasep FBM) were soaked in 1 M NaCl for at least 24 h.

Electrochemical experiments

Custom designed H-cells (borosilicate glass) were filled with 40 mL of 1 M $NaNO_3$ total. Nickel foam (1.6 mm, MTI Corp.) and platinum foil (99.9%, Beantown Chemical) are used as cathode and anode, respectively. The electrodes are 1 x 5 cm^2 and are separated by two pieces of cellulose filter paper (VWR Grade 413) at the beam to prevent passivation. Typically, 0.8 g $CaSiO_3$ powder was added to the anode compartment. Electrochemical experiments were carried out with a potentiostat (VSP, Bio-logic) at room temperature. The electrochemical protocol is a linear sweep voltammogram (LSV) to a desired voltage followed by chronoamperometry (CA) at the desired voltage. Series resistance between the electrodes measured by electrochemical impedance spectroscopy (EIS) at open circuit voltage (OCV) before electrolysis is typically ~40 Ω.

Flow cells were built with 5 cm^2 titanium flow fields (Dioxide Materials) and two custom made Teflon chambers. The flow cell contains four chambers in order: cathode, product, precursor, and anode. Sustainion anion exchange membrane separates the cathode and product chambers; Aquivion cation exchange membrane separates the product and precursor chambers; and Fumasep bipolar membrane (Fumasep FBM) separates the precursor and anode chambers. Two pieces of 3 x 3 cm^2 Ni foam are used as electrodes. Cathode and anode chambers are flowed with 40 mL/min of 1 M KOH controlled by a peristaltic pump (Golander BT100L with YZ15 pump heads). Precursor and product chambers are flowed with 20 mL/min of 1 M $NaNO_3$. Precursor $CaSiO_3$ is placed in the precursor reservoir. Electrochemical experiments were conducted using a potentiostat with a 2 A booster (Bio-logic). Similar electrochemical protocol as the H-cell is employed, which includes a linear sweep voltammetry to and then a chronoamperometric hold at 7 V. Series resistance between the electrodes measured by EIS before electrolysis is ~10 Ω.

The zero-gap electrolyzer contained two 5 cm^2 titanium flow fields and Teflon gaskets. Electrodes were fabricated by spray coating 1 mg/cm^2 Pt on carbon (20 wt% Pt, Alfa Aesar) and 1 mg/cm^2 Ir black (Fuel cell store) on platinized titanium felt (high porosity, Fuel Cell Store). Aquivion cation exchange membrane was used as the separator. 100 mL of Deionized water and 100mL of 1 M $NaNO_3$ were circulated in the cathodic and anodic compartments respectively at 10 mL/min by a peristaltic pump.

The zero-gap electrolyzer with catalyst coated membrane contained two 5 cm^2 titanium flow fields and one 300 µm Teflon gasket. Catalyst coated membrane was made by a decal method. First, an ink comprised of 30 mg Ir black,1 mL H_2O, 2 mL IPA, and 75 µL Nafion D520 solution (Ion Power) was sonicated for 1 hour, then air sprayed onto a Teflon sheet over a 80 °C hot plate. After drying, a piece of Nafion N115 membrane (Ion Power) was sandwiched between the catalyst-containing Teflon sheet and another clean Teflon sheet. The assembly was hot pressed (PHI Hydraulics) at 6.9 MPa and 130 °C for 10 min. Resulting loading of anode catalyst is 1.0 mg_{Ir}/cm^2. The cathode contained 1.0 $mg_{Pt/C}/cm^2$ air sprayed onto carbon paper (Sigracet 39BB). The anode porous transport layer was a platinized titanium felt. The assembly was tightened to 6 Nm by a torque wrench. Deionized water at 80 °C was first flowed through the electrolzyer at 100 mL/min to warm up to steady state. Then, 1 M $NaNO_3$ and deionized water was flowed as the anolyte and catholyte, respectively, both at 100 mL/min and 80 °C. Electrochemical impedance spectroscopy was collected with perturbations of 20 mA/cm^2 to determine the high frequency resistance. Linear sweep voltammetry was collected 50 mV/s after 20 min conditioning at 1 A/cm^2.

Hydrated cement preparation

ASTM Type I Portland Cement (PC) was hydrated at a water-to-cement mass ratio of 0.5. The resulting hydrated cement paste was sealed and cured for 7 days at 23°C then water-bath cured at 50°C for 90 days. This well-accepted hydration-aging protocol allows the chemistry and microstructure of the accelerated hydrated paste to be comparable to those of pastes cured at 20°C at the age of 1 year or longer. Hydrated cement paste was then finely ground to powder using a mortar and pestle and used as the electrochemical precursor in representation of recycled cement paste. The chemistry, microstructure, and compressive strength of pastes at the age of 1 year and 50 years (the typical lifetime of concrete) are similar because cement hydration and strength gain mostly develop in the first 90 days of curing.

Electrolyte pH and ion concentration measurements

Solution pH of H-cell electrolytes was measured by inserting the pH probe (Orion, Fisher) 1 cm below the surface of the electrolyte. The concentration of dissolved Ca^{2+} species in electrolyte was measured by an ion-selective electrode (Cole-Palmer) after neutralizing the solution to pH 5-9 with 1 M KOH.

Materials characterization

Raman spectra were collected on a laser confocal microscopy Raman instrument (Horiba LabRAM HR) with laser excitation of 632.8 nm. Thermogravimetric analysis was conducted on a Hitachi STA7300 thermogravimetric analyzer under 50 cm^3/min N_2 (99.999%, Linde) at 20 °C/min ramp rate with 10 mg sample. Particle size distribution analysis was performed on a laser diffraction-based instrument (Malvern Mastersizer 3000) with water as the solvent. X-ray diffraction (XRD) patterns were collected at beamline 12.2.2 at the Advanced Light Source of Lawrence Berkeley National Laboratory. The energy of the incident X-ray beam was 25 keV. The exposure time of each sample was 360 s. The XRD pattern of belite was collected using a PANalytical X'Pert PRO with X'Celerator® position sensitive detector operating at 40 kV with 40 mA and a cobalt target (Co Kα wavelength 1.79 Å). The scans were collected from 5 to 75° 2θ at a 0.6°/min scan rate. Scanning electron microscopy was conducted on FEI Versa 3D DualBeam or Hitachi SU8030 equipped with an EDX (Bruker Quantax200, XFlash 6|60 detector or Oxford Aztec X-max 80 SDD). A high-resolution transmission electron microscope (TEM, ThemIS) was used to collect images under laboratory conditions. The filtered solids were dispersed in 99+% isopropanol, followed by sonication for 1 min. The suspension samples were then dropped onto copper TEM grids (Lacey-carbon film). Soft X-ray scanning transmission X-ray microscopy was conducted at beamline 5.3.2.2 at the Advanced Light Source at Ca L-edge at room temperature. Each powdered sample was mixed with 99+% isopropanol at liquid-to-solid mass ratio of 10. The suspension was drop-cast onto a SiN window (Norcarda, 100 nm thickness), then transferred to a helium-filled microscope chamber at 1/3 atmospheric pressure.

Isothermal calorimetry

Commercial Portland Cement (ASTM Type I, 94% clinker and 4% calcium sulfates[1]) was partially replaced by electrochemically produced products. Cement was blended with e-$CaCO_3$ or a-SiO_2 and added with water at water-to-binder mass ratio of 0.5 at 23°C. ~5 g paste was mixed for 3 min at 150 rpm and loaded into an ampoule, then transferred into an isothermal calorimeter (TAM Air, TA Instruments) at 23°C.

Uniaxial compressive strength measurement

Commercial Portland Cement was partially replaced by electrochemically produced products. Pastes at water-to-binder mass ratio of 0.5 were casted into 25.4 mm diameter by 25.4 mm height cylindrical high-density polyethylene molds and cured in saturated lime water at 21-23°C until testing. At least four cylinders of each same group were compressed at a loading rate of 0.5 MPa/s using a universal mechanical testing machine (Baldwin).

Belite synthesis

e-$CaCO_3$ was mixed with grounded quartz (99.9%, Gilson) at a 2:1 molar ratio. The powders were mixed into a slurry with isopropanol and then dried at 40 °C. The resulting blend was pressed into a pellet using a compressing die (MTI). The pellet was placed on a Pt crucible in a muffle furnace (MTI) and heated at 1°C per min to 1450°C, followed by holding at the maximum temperature for 6 h. The sample was then quenched by air and grounded.

Supplementary Note 1: Energy consumption analysis

The production of 1 kg of e-$CaCO_3$ (10 mol e-$CaCO_3$) requires 10 mol CO_2 and 20 mol H^+ using precursor $CaSiO_3$. The minimum thermodynamic requirement for direct air captured (DAC) CO_2 to 1 bar pressure is 20 kJ/mol CO_2 with an assumed 10% efficiency, hence 2 MJ/kg of e-$CaCO_3$ is required. The minimum electrolyzer energy requirement is calculated based on 20 mol H^+ produced at the anode to leach out Ca^{2+}, which requires 2.86 MJ/kg e-$CaCO_3$. At 10% DAC efficiency 75% electrolyzer efficiency, a total energy of 5.81 MJ/kg e-$CaCO_3$ produced.[2, 3]

The production of 1 kg of e-$CaCO_3$ using our reactor with the $CaSiO_3$ precursor requires a minimum of 2.86 MJ of electrical energy[4]. In other words, the minimum energy required for capturing 1 kg of air CO_2 is 6.5 MJ. For 1 kg of ordinary Portland cement production, ~1.17 kg of $CaCO_3$ is needed. Assuming a water electrolyzer operating at 50 to 75% efficiency (ranging from lower than to similar as the state-of-the-art efficiency at the industry scale), the input electrical energy required for 1 kg of $CaCO_3$ is 3.81 to 5.72 MJ, corresponding to the electricity requirement for 1 kg of CO_2 capture and storage in a range of 8.7-13.0 MJ[5].Alternatively, the production of 1 kg of $CaCO_3$ using our reactor with the precursor recycled cement paste (representative for the reactive compounds in recycled concrete fines, a gigaton urban waste currently landfilled or used as a low-value road bed) requires a minimum of 5.40 MJ of electrical energy due to the different chemical composition and reaction pathways. Recycled cement paste is assumed to have the same chemical composition as the ASTM-standard Type I cement hydrated at water-to-cement mass ratio of 0.5[6]. The assumption for the average typical chemical composition of the recycled cement paste is in Table S1. Note that O content of 23.9 wt% is originated from the anhydrous cement in the form of various oxides while the rest 29.6 wt% is originated from the water addition. It is assumed that only the former will contribute to the electrochemical reactions of oxides dissolution and lead to electrical energy consumption which we intend to estimate.

Table S1. Average composition of recycled cement paste hydrated from the ASTM-standard Type I Portland cement at water-to-cement mass ratio of 0.5.

Element	Weight percentage
Ca	31.7%
O	53.5%
Si	6.5%
Al	1.4%
S	1.0%
Fe	0.8%
Mg	0.9%
Na	0.2%
K	0.2%
Ti	0.07%
Mn	0.03%
H	3.7%

We assume that the electrolyzer is fully powered by renewable electricity, while the cement clinker formation processes modeled in our novel cement manufacturing scheme remain “business as usual”, i.e., local electricity grid for plant operations (average California grid[7], with a grid mix comprising of majorly natural gas-fired, nuclear, and renewable resources) and conventional fuels (mainly coal/coke with minor solid waste such as municipal solid waste and biomass) for combustion[8], unless specifically stated of using e-produced green H_2 for cement pyroprocessing.

The following Supplementary Note 2 on life cycle assessment will detail the process-based energy use during cement production after the electrochemical production of the cement feedstock.

Supplementary Note 2: Life cycle assessment

A process-based life cycle assessment (LCA) was conducted using a cradle-to-gate approach from the extraction of raw materials as the cradle to the mixing and batching of (blended) cement as the gate, considering a functional unit of 1 kg blended cement produced[9]. The system boundary includes upstream and downstream materials processing, production, and transportation. The electrochemical production was modeled onsite a cement plant. The scope, materials flow, and system boundaries are presented in main text Fig. 5.

We consider three models (emission of concentrated CO_2 flue gas, CO_2 circulation, and CO_2 CCS) with eight scenarios (Emission-conv/FF/H2, Circulation-FF/H2, and CCS-conv/FF/H2) as listed in Table S2 with their full process flow diagrams in Fig. 5. Under each scenario involving electrochemical production, we consider separate cases of using $CaSiO_3$ or recycled cement as the electrochemical precursor and four blended cement compositions with varying ordinary Portland cement (OPC) levels of 65-100%.

Table S2. LCA scenarios of cement production and CO_2 use.

		Model 1 **CO_2 emission to atm.**	**Model 2** **CO_2 circulation**	**Model 3** **CO_2 CCS**
Conventional cement manufacturing using limestone feedstocks		Emission-conv (business as usual, conventional)	(N/A)	CCS-conv (conventional, w/ cement kiln flue gas CCS)
Electrochemical production of cement feedstocks	Cement kiln fueled by **fossil fuel**	Emission-FF	Circulation-FF	CCS-FF
	Cement kiln fueled by **green H_2**	Emission-H2	Circulation-H2	CCS-H2

Scenario Emission-conv is the baseline business-as-usual, conventional cement manufacturing using conventional limestone feedstocks. For this, we consider the following processes: raw limestone quarrying; fly ash acquisition and processing; limestone processing for use as supplementary cementitious materials (SCMs); limestone and fly ash transporting to a cement plant (via truck class 8b); raw materials grinding, blending, and homogenization; in-cement plant conveying; pyroprocessing with fossil fuels; finish milling and grinding; and blending.

For scenarios Emission-FF and Emission-H2 of electrochemical production of Portland cement feedstock from $CaSiO_3$, we consider the following processes: $CaSiO_3$ quarrying; $CaSiO_3$ transporting to cement plant; $CaSiO_3$ grinding; renewable electricity-supplied, direct air capture (DAC) of CO_2 to feed electrolyzer; renewable electricity for electrolyzer operation; filtering of e-$CaCO_3$ and a-SiO_2; in-cement plant conveying; pyroprocessing, powered by fossil fuels in scenario "Emission-FF" or electrochemically produced green H_2 in scenario "Emission-H2"; finish milling and grinding; and blending.

On the basis of scenarios "Emission-FF" and "Emission-H2", scenarios "Circulation-FF" and "Circulation-H2" has the DAC process replaced by the circulation of the cement kiln flue gas consisting of concentrated CO_2 to feed the electrolyzer. The energy cost of pumping concentrated CO_2 gas is considered; additionally, when fueling pyroprocessing with electrochemically produced green H_2, the additional process of pumping hydrogen gas is considered as well in scenarios "Emission-H2", "Circulation-H2", and "CCS-H2". On the other hand, on the basis of scenarios "Emission-conv", "Emission-FF", and "Emission-H2", scenarios "CCS-conv", "CCS-FF", and "CCS-H2" additional involve the process of CCS of the cement kiln flue gas consisting of concentrated CO_2. The CCS process involves carbon capture using the pressure-swing adsorption (PSA) technology and CO_2 transport (pipeline) with storage (geological storage via injection), where generic energy consumptions and GWP intensity are used based on the respective referenced LCA studies.[10-12] Note that:

1. When using as-received or as-precipitated fine powdery feedstock in replacement of coarse counterparts directly from quarrying, the saving in the process of materials grinding is considered.
2. The process of pumping CO_2 gas to supply the electrochemical reactor is considered; additionally, when fueling pyroprocessing with electrochemically produced green H_2, the additional process of pumping hydrogen gas is considered as well.
3. Filtering of solid electrochemical products for subsequent cement kiln pyroprocessing or blending is considered as an additional process for the electrochemical production schemes.
4. In the alternative scenario of using recycled cement instead of $CaSiO_3$ as the electrochemical precursor, recycled cement is considered as a readily available dust-like powdery byproduct from concrete recycling and aggregate reclaim. Despite academic explorations on the value addition of recycled fines at the lab scale, the present-day industry remains lacking a valued outlet for recycled cement at scale; thus, the recycled cement has mostly been used as low-value road bed or landfilled, causing additional land use environmental impacts and concerns. Therefore, in the present LCA, the recycled cement is assumed to be readily available and not require as intensive raw materials grinding as is required by quarried $CaSiO_3$ from natural reservoirs.

In the life cycle inventory analysis, we evaluated (i) materials flow for raw precursors (e.g., $CaSiO_3$ and recycled cement, CO_2, and water), intermediate products (e.g., green H_2 and e-$CaCO_3$), and final products (e.g. blended cement) and (ii) energy consumptions, with the following assumptions:

1. The electrochemical production is assumed to be fully powered by renewable electricity at the industry-relevant efficiency range of 50-75%. The raw materials processing and cement-plant operations are assumed to be powered by the local grid (California average, a mixture of primarily natural gas-fired, nuclear, and renewable sources) for electricity, by fossil fuels (specifically, diesel) for raw solid materials transportation via truck (class 8b), and by fossil fuels (scenarios "Emission-FF", "Circulation-FF", and "CCS-FF") or green H_2 (scenarios "Emission-H2", "Circulation-H2", and "CCS-H2") for cement kiln pyroprocessing[7, 13].

1. We assume a state-of-the-art cement kiln with a thermal energy requirement of 3.0 MJ/kg ordinary PC (OPC) produced during the coke/coal-fueled pyroprocessing process[5]. After cement pyroprocessing, the sequestrated carbon from direct air capture is concentrated into a point source, flue gas, with no supplementary energy input.
2. When fueled alternatively with electrochemically produced green H_2 for cases under scenarios "Emission-H2", "Circulation-H2", and "CCS-H2", the pyroprocessing thermal efficiency and energy demand is assumed to remain the same as the conventional process. The potential improvement in thermal efficiency of pyro-processing by switching from conventional fuels to green H_2 is not considered. Because the green H_2 is formed within the system boundary, when calculating lifecycle energy consumptions, the energy supplied by green H_2 is considered as fossil fuels energy savings and thus leads to significantly lowered total energy consumptions.
3. In the scenario "Circulation-FF", the extra CO_2 generation from cement kiln fossil fuels combustion is considered for CCS and treated identically as in the CCS scenarios, which is not needed for scenario "Circulation-H2" due to the replacement of fossil fuel with electrochemically produced green H_2 for energy supply of cement kiln. Instead, in scenario "Circulation-H2", supplementary DAC may be incorporated for blended Portland cement designs containing e-$CaCO_3$ as a partial cement substitute because of its net removal of CO_2 from the circular system.

As this study focuses on CO_2 abatement, our life-cycle impact assessment only includes global warming potential (GWP-100), expressed in the unit of $kgCO_2$–eq. based on TRACI 2.1 (the Tool for the Reduction and Assessment of Chemical and other environmental Impacts[14]). The state-of-the-art cement kiln pyroprocessing, which as stated above, has thermal energy requirement of 3.0 MJ/kg OPC produced, is associated with a global warming potential (GWP) value of 0.9 kg CO_2-eq/kg OPC produced[5]. When fueled with electrochemically produced green H_2 under scenarios "Emission-H2", "Circulation-H2", and "CCS-H2", this fossil fuel combustion-induced CO_2 emissions are assumed to be eliminated. Note that a-SiO_2 and green H_2 are regarded as co-products to electrochemical e-$CaCO_3$ production and not individually assigned with embodied carbon.

A list of additional process-specific assumptions is provided below:

Table S3. List of process-based LCA assumptions.

	Energy & materials consumption	GWP	Reference(s)
For conventional cement manufacturing			
Raw materials (limestone, clay, etc.) quarrying	1.52E-01 MJ/kg OPC produced	7.04E-03 kg CO_2-eq./kg OPC produced	Ref[7, 13]
Raw materials grinding, blending, & homogenization	2.24E-01 MJ/kg OPC produced	7.037E-03 kg CO_2-eq./kg OPC produced	Ref[7, 13]
Fly ash acquisition & processing	4.51E-01 MJ/kg	2.42E-02 kg CO_2-eq./kg	Ref[7, 13]
Limestone as a cement substitute	9.07E-02 MJ/kg	4.33E-03 kg CO_2-eq./kg	Ref[7, 13]
For electrochemical production scenarios			
Raw materials ($CaSiO_3$, clay, etc.) quarrying	9.09E-02 MJ/kg	4.22E-03 kg CO_2-eq./kg	Ref[7, 13]
Raw materials grinding	1.22E-02 MJ/kg	3.82E-03 kg CO_2-eq./kg	Ref[7, 13]
CO_2 pumping	1.09E-01 MJ/kg CO_2 pumped	3.44E-03 kg CO_2-eq./kg CO_2 pumped	Ref[7, 15]
Electrolyzer operation with renewable electricity (precursor: $CaSiO_3$, wollastonite)	2.86 MJ/kg e-$CaCO_3$ produced at 100% efficiency	(varying with renewable electricity GWP intensity – see sensitivity analysis)	Ref[4, 16]
Electrolyzer operation with renewable electricity (precursor: recycled cement)	5.40 MJ/kg e-$CaCO_3$ produced at 100% efficiency	(varying with renewable electricity GWP intensity – see sensitivity analysis)	
Filtering	1.80E-01 MJ/kg	5.66E-03 kg CO_2-eq./kg	Ref[17]
Electrolyzer solid feedstock usage efficiency = 85%; CO_2 usage efficiency = 85%; electrolyzer energy efficiency = 50-75%; H_2 pumping has equal impacts as CO_2 pumping per standard volume.			
For both conventional cement manufacturing and electrochemical production schemes			

Truck (class 8b) transport	7.60E-04 MJ/kg/km	1.28E-04 kg CO_2-eq./kg/km	Ref[13]
In-cement plant convey	2.55E-03 MJ/kg	8.03E-05 kg CO_2-eq./kg	Ref[13]
Finish milling & grinding	3.93E-01 MJ/kg	1.24E-02 kg CO_2-eq./kg	Ref[13]
Blending	8.47E-03 MJ/kg	2.66E-04 kg CO_2-eq./kg	Ref[13]

For gas separation, transport, and capture

Theoretical entropic penalty of CO_2 separation from air (CO_2 level = 400 ppm)	0.2 MJ/kg e-$CaCO_3$ produced		Ref[2]
Actual direct air capture (DAC) energy efficiency	10%		Ref[3]
DAC	2 MJ/kg e-$CaCO_3$ produced	(varying with renewable electricity GWP intensity – see sensitivity analysis)	
CO_2 circulation using cement kiln flue gas to feed electrolyzer	1.09E-01 MJ/kg CO_2 pumped		Ref[7, 15]
Carbon capture (PSA technology) of concentrated CO_2 from cement kiln flue gas	0.4 MJ/kg CO_2 captured		Ref[10]
CO_2 transport (pipeline) and (geological) storage	4.32E-2 MJ/kg CO_2 stored	0.1 kg CO_2-eq./kg CO_2 stored	Ref[11, 12]

Life cycle inventory analysis of energy consumption. By our calculation, conventional cement manufacturing requires 3.84 MJ/kg OPC produced, 0.27 MJ from raw materials acquisition and transportation prior to in-cement plant processes and 3.57 MJ from in-cement plant operations (3 MJ thermal energy from fossil fuels for pyroprocessing and 0.57 MJ from electricity during other processes). The presently calculated energy consumption at the business-as-usual cement plant of 3.57 MJ thus agrees well the literature value of ~3.5 MJ/kg OPC for the total energy use of cement manufacturing at a state-of-the-art plant[5]. The energy consumption calculations for electrochemical processes are detailed in Supplementary Note 1.

Sensitivity analyses of total GWP and total energy consumption are performed for renewable electricity embodied carbon footprint and electrolyzer efficiency (Table S4). See Tables S9-14 and Tables S15-20 for GWP of scenarios based on wollastonite and recycled cement paste as the precursor, respectively, and Tables S21-22 and Tables S23-24 for energy consumptions of scenarios based on wollastonite and recycled cement paste as the precursor, respectively.

Table S4. Parameter variations in the sensitivity analysis.

Renewable electricity GWP intensity levels (kg CO_2-eq./MJ)			
Low intensity	Land-based wind	3.06E-3	Ref[4, 16]
Medium intensity	Photovoltaics (PV)	1.20E-2	Ref[4, 16]
High intensity	PV with Li-ion battery storage	3.44E-2	Ref[18]
Electrolyzer energy consumption levels (MJ/kg e-$CaCO_3$ produced)			
High efficiency 75%	$CaSiO_3$	3.81	Ref[19, 20]
	Recycled cement paste	7.20	
Low efficiency 50%	$CaSiO_3$	5.72	Ref[4]
	Recycled cement paste	10.80	

Supplementary Note 3: Techno-economic analysis

The techno-economic analysis (TEA) assesses the benefits of the electrochemical ordinary Portland cement manufacturing scheme based on representative business models as considered in the LCA (Fig. S1). The functional unit is chosen to be the economic benefit per metric ton of CO_2 utilized by the electrochemical process. All scenarios evaluate the cost and economic benefit differences in reference to the conventional cement manufacturing scenario. Such differences include: additional cost from raw materials, electricity power, capital expenditures (capex), and so on; additional benefits from the sale of electrochemical (co)products, fossil fuel energy savings, carbon credits, and so on.

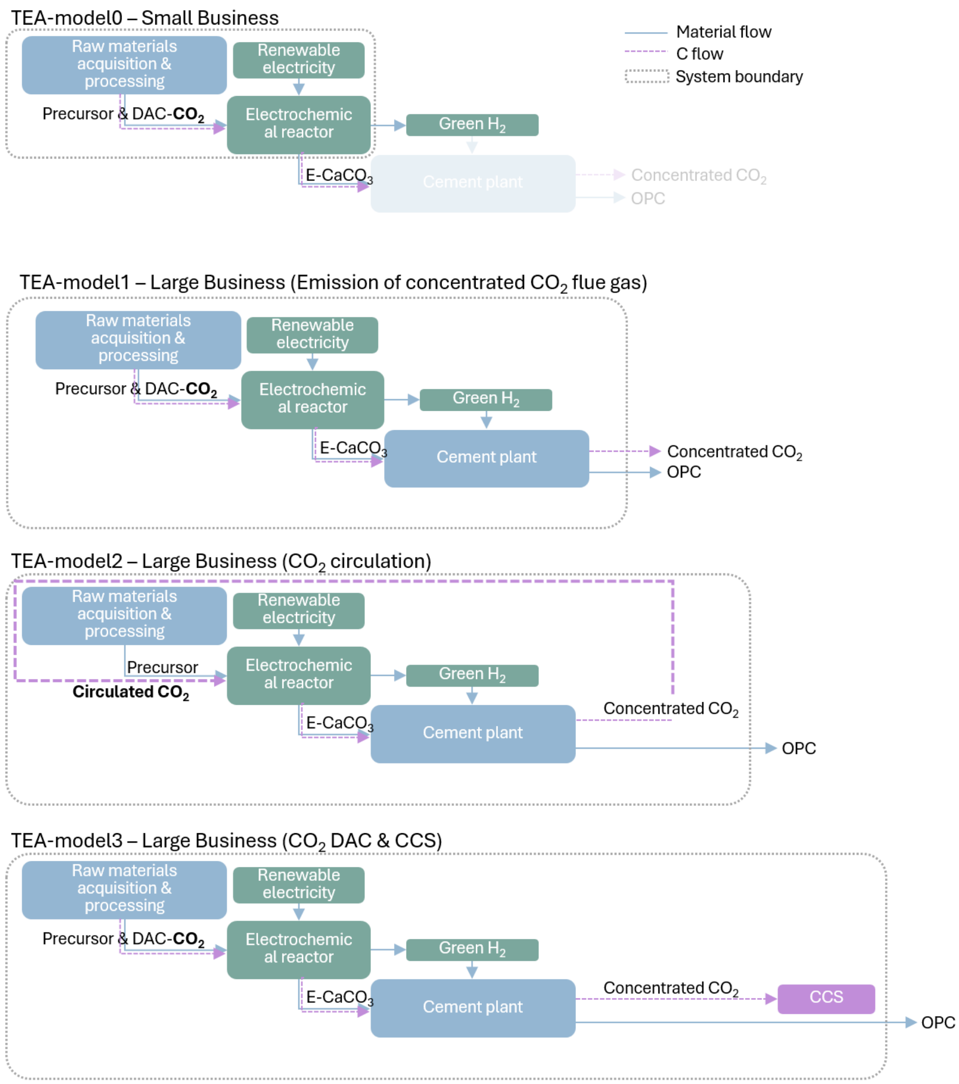

Fig. S1. TEA model schematics.

TEA-model0 evaluates the business of running the electrochemical e-$CaCO_3$ production only, without modifications to the business-as-usual industrial cement plants; thus TEA-model0 is referred to as the Small Business Model, accordingly associated with low capital investment, including only capex of DAC at \$100/t CO_2 captured.[21] The solid products (e-$CaCO_3$ and a-SiO_2) are sold to cement plants as feedstocks and SCMs at market prices, and all green H_2 from the electrochemical process are assumed to be sold at \$2000/t[22]. The electrochemical process converting atmospheric CO_2 to e-$CaCO_3$ for cement manufacturing allows claiming carbon credit at \$130/t air CO_2 captured and utilized.

TEA-model1, 2, and 3 consider both electrochemical production and cement manufacturing as part of the business where the business owns the existing cement plant to be modified for green H_2 fueling. Differently, TEA-model1 considers DAC & utilization of atmospheric CO_2 (400 ppm) to be converted into concentrated CO_2 flue gas (allowing to claim carbon credit of \$70/t CO_2 captured, equal to the difference between \$130/t DAC-CO_2 utilization and \$60/t concentrated CO_2 CCU/CCS). TEA-model2 evaluates the CO_2 circulation scheme (no carbon credit claimed). TEA-model3 evaluates the CO_2 DAC & CCS scheme (allowing to claim full carbon credit of \$180/t DAC-CO_2 captured and permanently stored). In practice, such businesses would be large corporations in the cement industry as cement plants owners and have sufficient budget for such moderate adjustment to the existing kilns. Thus, TEA-model1, 2, and 3 are referred to as the Large Business Model, accordingly, associated with modestly increased capital investment for fuel switching compared to TEA-model0. But even so, the Large Business Model does not involve establishment of a new cement plant, which is considerably more capital investment-intensive, requiring \$400 million for establishment. Thus, the present Large Business Model of reformulating the existing cement kiln fuel through the effort initiated by large cement corporations represents an economically attractive route for cement industry clean energy transition and decarbonization.

For the TEA-model1, 2, and 3, the energy-intensive cement pyroprocessing process is assumed to be fully fueled by the green H_2 from the electrochemical production. The action leads to the saving of conventional fossil fuels energy for pyroprocessing, estimated based on the market price of bituminous coal at \$67.5/t and with a heating value of 26.5 MJ/kg.[23] Green H_2 consumption for pyroprocessing is estimated based on a heating value of 141.8 MJ/kg, while assuming unchanged energy efficiency of pyroprocessing. Surplus green H_2 is assumed to be sold at the same price as in TEA-model0.

Additional assumptions include:

1. The electricity price for the electrochemical process is ranged based on the price of renewable powers (solar and wind) between \$0.02/kWh and \$0.06/kWh.[24]
2. For TEA-model0, model1, and model3, the DAC which supplies CO_2 to the electrochemical process has a capital cost of \$100/t CO_2 captured and operation cost from renewable electricity consumption estimated using the LCA results.
3. The electrochemical process capital cost is based on \$600/t H_2 produced.[25]
4. The raw material $CaSiO_3$ is estimated to be the same as limestone at \$10/t, and water is used at \$5/t.[26, 27] The raw material recycled cement is treated as a byproduct in concrete recycling and free of cost, while the extra benefits from saving of landfill costs and such are not included in the calculation.
5. The sales prices of the solid products from the electrochemical process are based on the current market price in the cement and concrete industry: $CaCO_3$ at \$10/t and amorphous SiO_2 at the same price as for PC at \$125/t.[26, 28]
6. For TEA-model3, the CCS process incurs additional cost: renewable electricity consumption for operation of carbon capture from concentrated flue gas (using LCA results), sorbent materials cost at 3 kg sorbent/t CO_2 captured and \$40/kg sorbent, and onshore carbon storage via depleted gas/oil fields at \$5/t CO_2 stored.[11, 29, 30]

See Tables S5 for the TEA results and sensitivity analysis summaries for cases with $CaSiO_3$ and recycled cement precursors, respectively, under varying electricity prices and Business Models.

Table S5. TEA results (electrolyzer energy efficiency = 75%) Unit: \$/t CO_2 utilized at the electrolyzer).

Precursor species	Wollastonite		Recycled cement	
renewable electricity price (\$/kWh)	0.02	0.06	0.02	0.06

TEA-model0 Small Business				
raw materials cost	-41	-41	-2	-2
electrolyzer operation cost	-48	-144	-91	-273
electrolyzer capital cost	-27	-27	-27	-27
DAC operation cost	-25	-76	-25	-76
DAC capital cost	-100	-100	-100	-100
CaCO3 sale	23	23	23	23
SiO2 sale	170	170	51	51
H2 sale	91	91	91	91
carbon tax saving	130	130	130	130
TOTAL	172	25	49	-183

TEA-model1 Large Business (Concentrated CO2 flue gas)				
raw materials cost	-41	-41	-2	-2
electrolyzer operation cost	-48	-144	-91	-273
electrolyzer capital cost	-27	-27	-27	-27
DAC operation cost	-25	-76	-25	-76
DAC capital cost	-100	-100	-100	-100
SiO2 sale	170	170	51	51
H2 surplus sale	8	8	8	8
cement plant energy saving	15	15	15	15
carbon tax saving	70	70	70	70
TOTAL	22	-125	-101	-333

TEA-model2 Large Business (Circulation)				
raw materials cost	-41	-41	-2	-2
electrolyzer operation cost	-48	-144	-91	-273
electrolyzer capital cost	-27	-27	-27	-27
DAC operation cost	0	0	0	0
DAC capital cost	0	0	0	0
SiO2 sale	170	170	51	51
H2 surplus sale	8	8	8	8
cement plant energy saving	15	15	15	15
carbon tax saving	0	0	0	0
TOTAL	77	-19	-46	-228

TEA-model3 Large Business (CCS)				
raw materials cost	-41	-41	-2	-2
electrolyzer operation cost	-48	-144	-91	-273
electrolyzer capital cost	-27	-27	-27	-27
DAC operation cost	-25	-76	-25	-76
DAC capital cost	-100	-100	-100	-100
SiO2 sale	170	170	51	51
H2 surplus sale	8	8	8	8
cement plant energy saving	15	15	15	15
carbon tax saving	180	180	180	180
CCS	-127	-132	-127	-132
TOTAL	5	-146	-118	-355

H-cell experiments

Fig. S2A shows the average current of 1-day and 3-day electrolysis with 5 cm^2_{geo} Pt foil and Ni foam electrodes at cell potentials ranging from 3 to 9 V. The difference in pHs of the compartments increases as applied potential, electrolysis time, and charge passed increase (Fig. S2B and S4A). The current during electrolysis increases over initial operation due to increased electrical conductivity from H^+ and OH^- generation (Fig. S3). Dissolved Ca^{2+} content in the anolyte also increases linearly until ~50000 C has passed, at which point the precursor no longer provides dissolvable Ca, and most of the Ca^{2+} has diffused to the cathodic compartment due to electrical potential and concentration gradients (Fig. S4B).

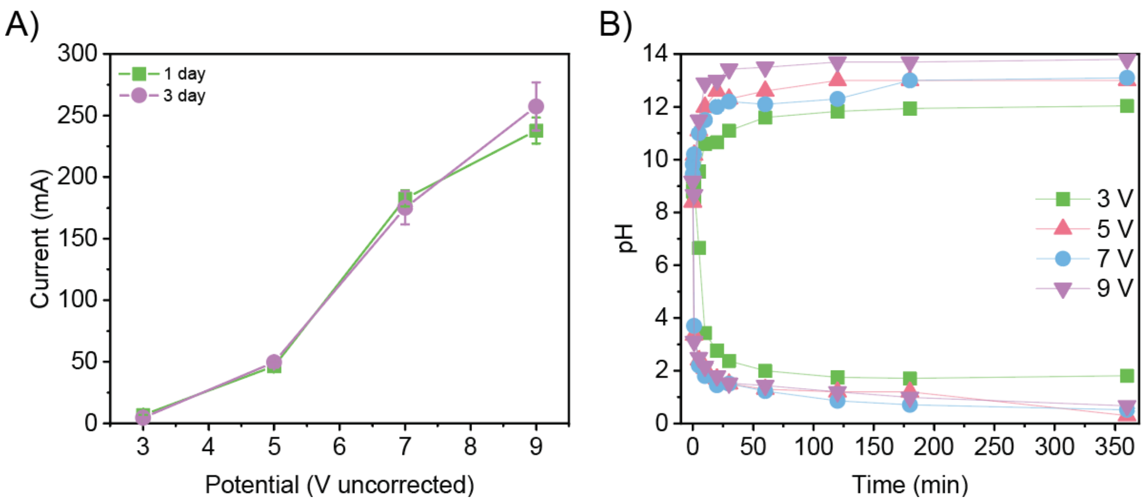

Fig. S2. (A) Average current of 5 cm^2_{geo} Ni foam and Pt foil electrodes at various potentials for 1- and 3-day electrolysis. Potentials are reported without Ohmic drop compensation. (B) pH values of anolyte and catholyte as a function of time at various applied potentials.

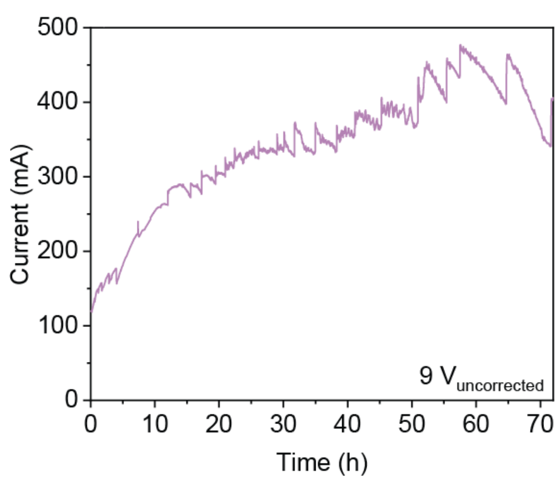

Fig. S3. Example data of a chronoamperometric hold at 9 V for 72 hours with Ni and Pt electrodes in H cell with 1 M $NaNO_3$.

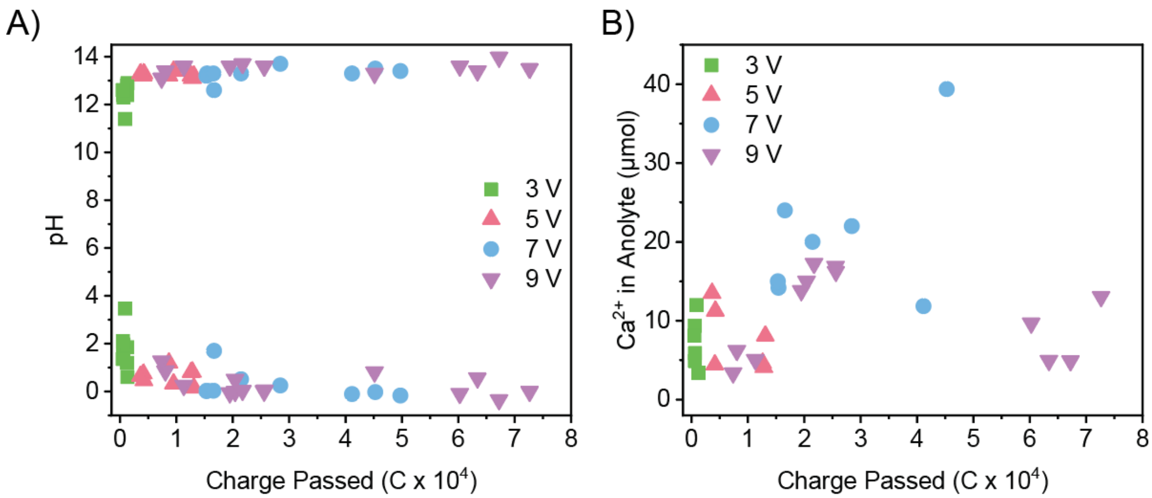

Fig. S4. (A and B) pH of both compartments and Ca^{2+} concentration in anolyte after electrolysis at various amounts of charge passed.

Flow cell electrolyzer experiments

Two types of $CaSiO_3$ weathering experiments were assessed in the flow cell electrolyzer. In Fig. 3D, $CaSiO_3$ was placed in the anodic compartment prior to the start of electrolysis. The current density remained above 30 mA/cm^2 with gradual increase to up to 65 mA/cm^2. On the contrary, in Fig. S5, $CaSiO_3$ was placed in the anolyte reservoir outside the electrolyzer and was flown into the anodic compartment after electrolysis started. Rapid decrease in current density followed by initial influx of $CaSiO_3$ was observed, followed by rapid recovery of current density to >60 mA/cm^2 after 10 h.

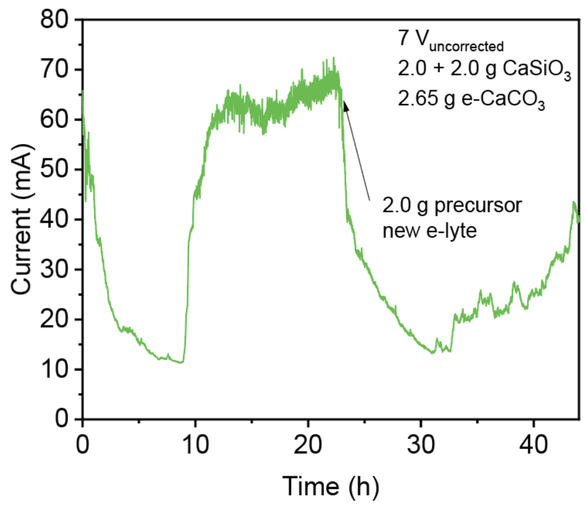

Fig. S5. Current response of a chronoamperometric hold at 7 V for 42 hours in a flow cell electrolyzer with 2 g precursor wollastonite stored in the anodic reservoir initially and replenished at 22 h.

Fig. S6. Photo of Ca-deposited Aquivion cation exchange membrane after 44 h electrolysis.

Zero gap electrolyzer experiments

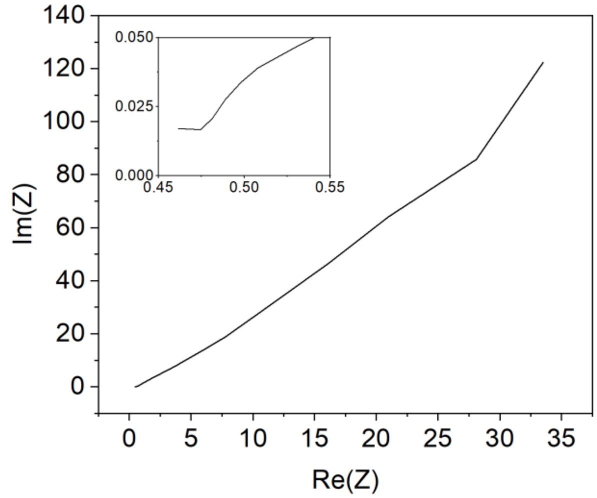

Fig. S7. Electrochemical impedance spectroscopy of room temperature zero gap electrolyzer at open circuit potential.

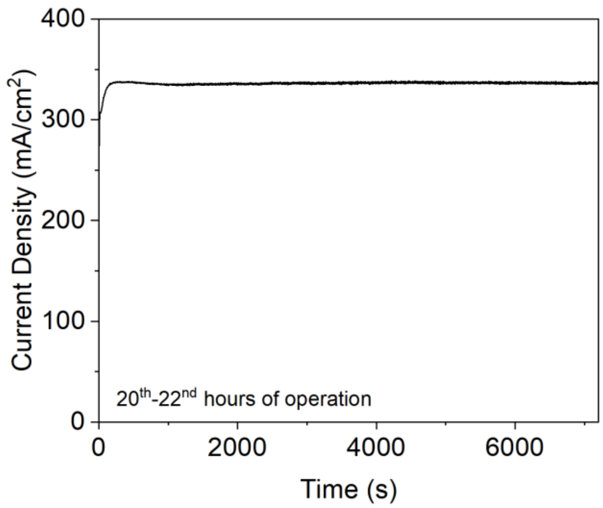

Fig. S8. Typical chronopotentiometry experiment of room temperature zero gap electrolyzer at 3.7 V.

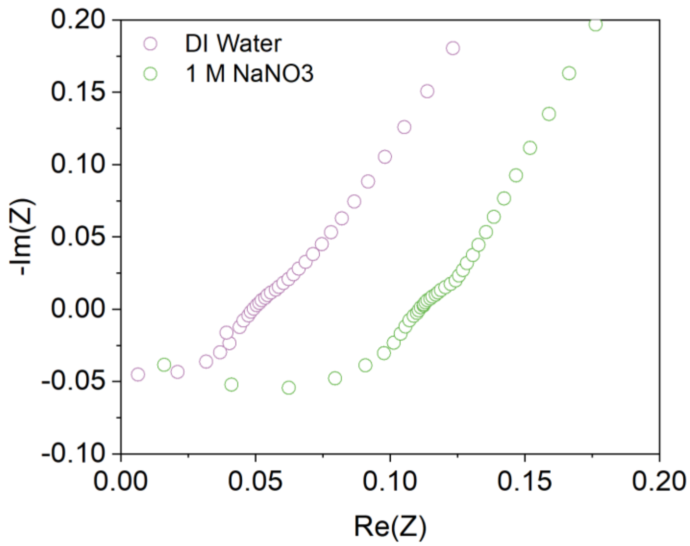

Fig. S9. Electrochemical impedance spectroscopy of 80 °C CCM zero gap electrolyzer with DI water feed and 1 M $NaNO_3$ feed.

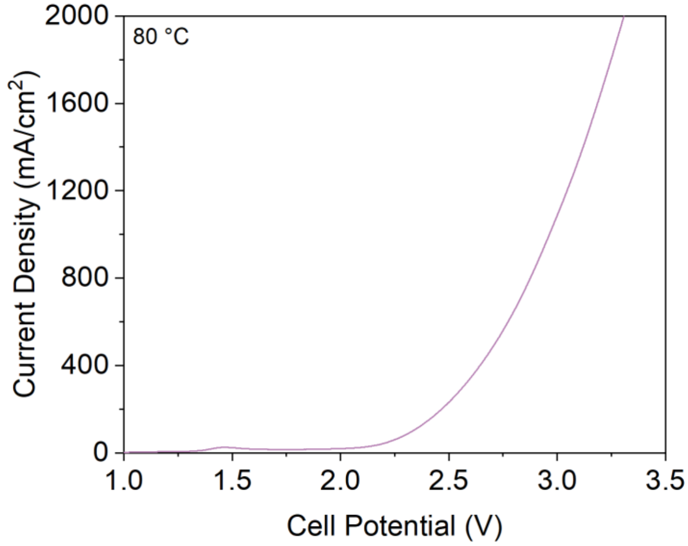

Fig. S10. Linear sweep voltammogram of 80 °C CCM zero gap electrolyzer.

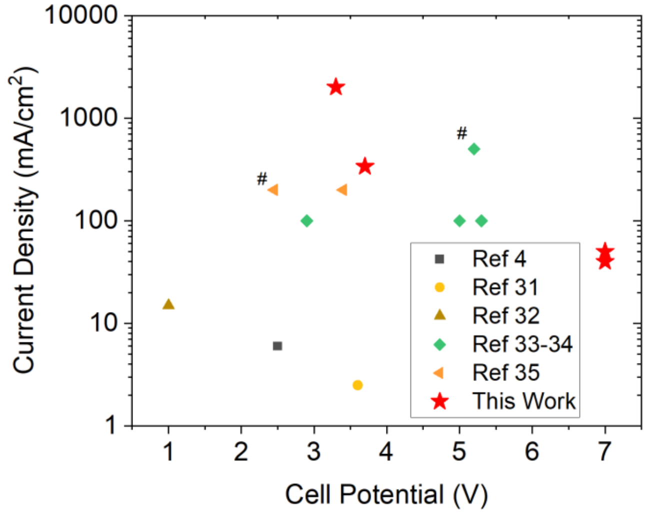

Fig S11. Comparison of current density and full cell potential to literature[4, 31-35]. # symbol indicates alternative anodic reaction used (other than water oxidation). Absolute current plotted when area normalized data was not provided in some H-cell experiments (<10 mA of total current).

Electron microscopy images of a-SiO_2 and e-$CaCO_3$

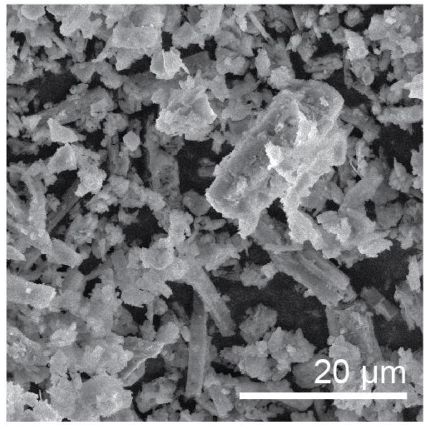

Fig. S12. SEM image of a-SiO_2 from enhanced $CaSiO_3$ weathering.

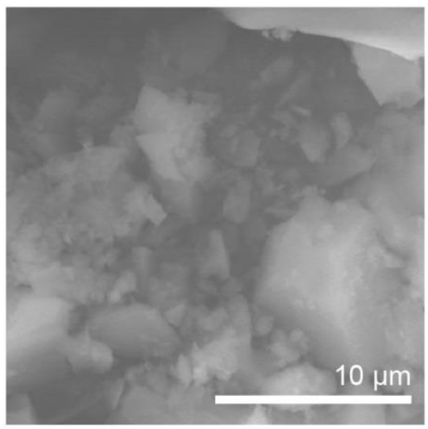

Fig. S13. SEM image of a-SiO_2 from enhanced weathering of recycled cement paste.

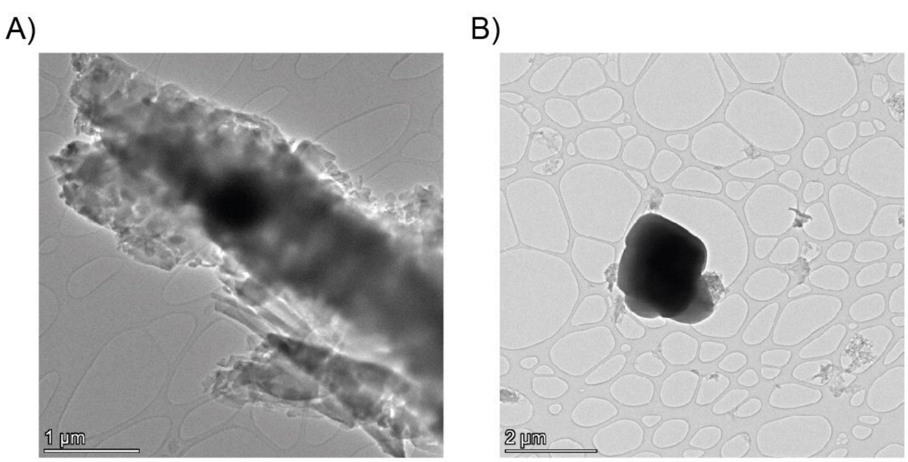

Fig. S14. TEM images of (A) a-SiO_2 and (B) e-$CaCO_3$.

Energy dispersive X-ray spectroscopy result

Table S6. EDX results of a-SiO_2 from enhanced $CaSiO_3$ weathering.

Element	Atom (%)	Absolute Error (%)
Carbon	48.70	2.46
Oxygen	45.06	2.93
Aluminum	0.14	0.03
Silicon	6.04	0.66
Calcium	0.05	0.02

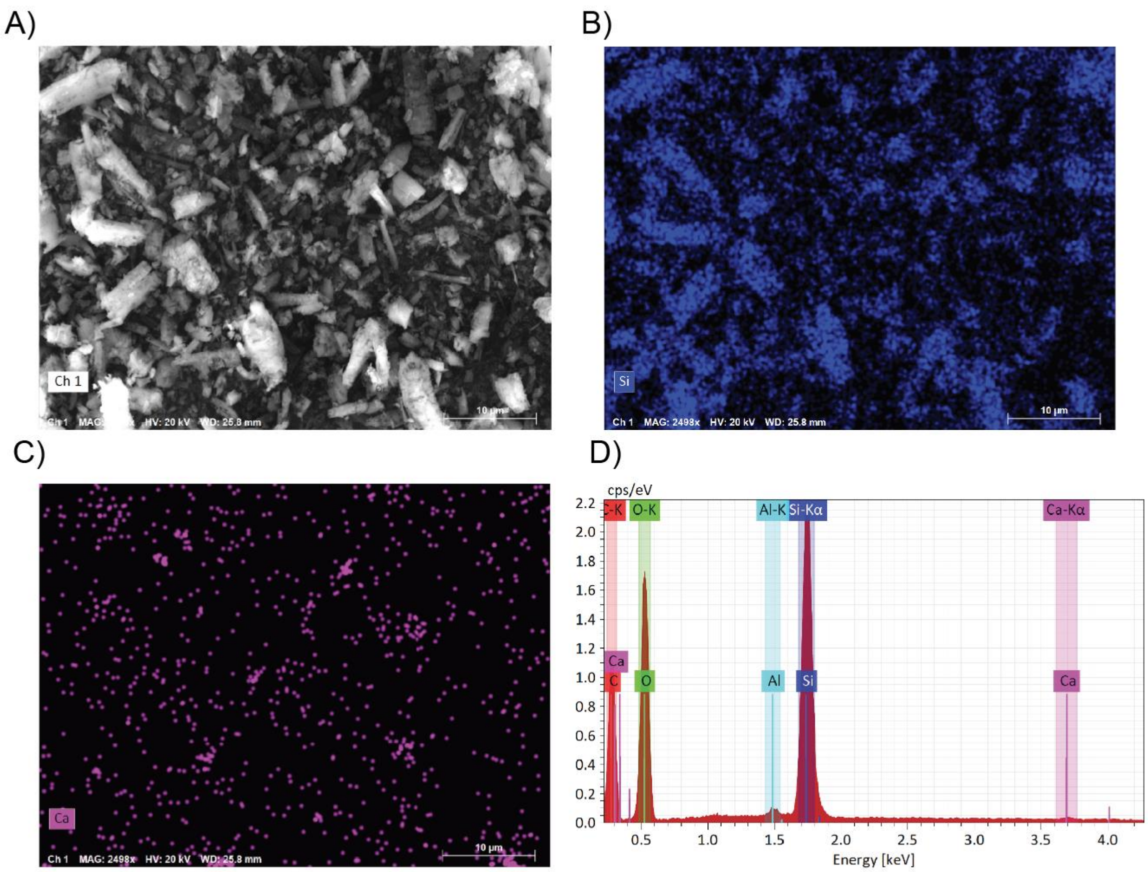

Fig. S15. (A) SEM image of a-SiO_2 from enhanced $CaSiO_3$ weathering. (B) Si mapping of a-SiO_2 (C) Ca mapping of a-SiO_2. (D) Energy dispersive X-ray spectrum of a-SiO_2.

Table S7. EDX results of a-SiO_2 from enhanced weathering of cement paste recycling**.**

Element	Mass Normalized (%)	Absolute Error (%)
Carbon	52.97	0.15
Oxygen	38.17	0.15
Silicon	5.44	0.02
Aluminum	2.32	0.02
Sodium	0.64	0.02
Calcium	0.23	0.01
Iron	0.14	0.01
Indium	0.07	0.01
Titanium	0.05	0.01

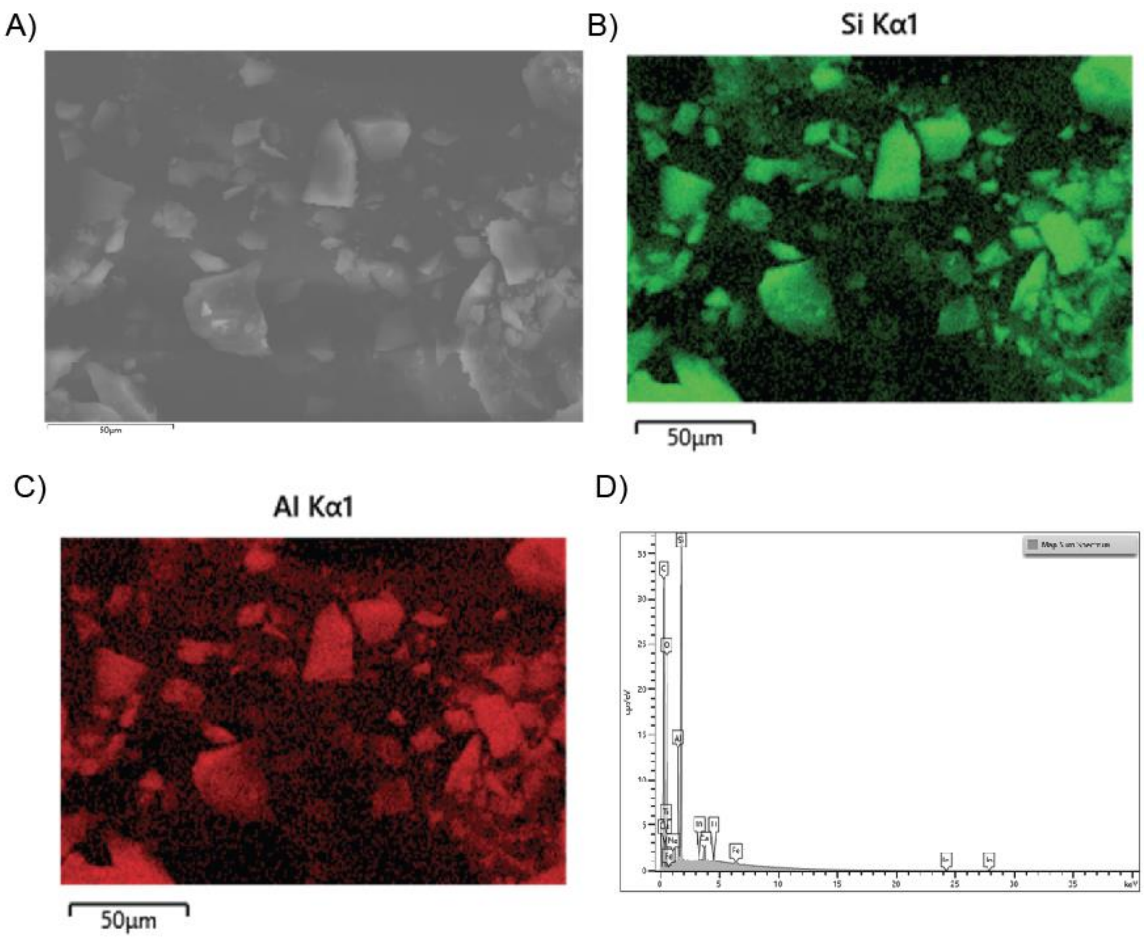

Fig. S16. (A) SEM image of a-SiO_2. (B) Si mapping of a-SiO_2 from enhanced weathering of recycled cement paste. (C) Ca mapping of a-SiO_2. (D) Energy dispersive X-ray spectrum of a-SiO_2.

Particle size distribution of $CaSiO_3$ and a-SiO_2

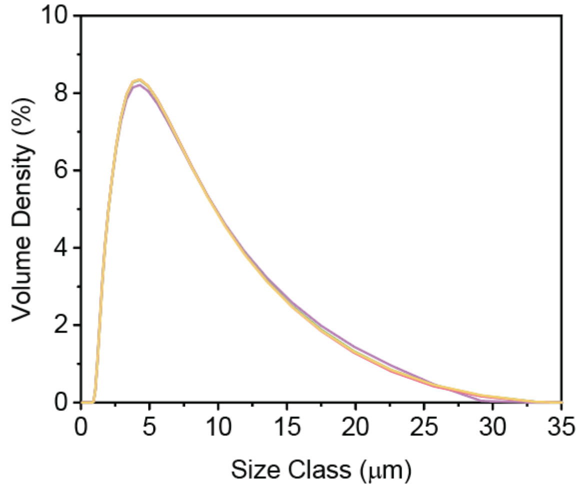

Fig. S17. Particle size distribution of precursor $CaSiO_3$.

Scanning transmission X-ray microscopy (STXM) of E-products

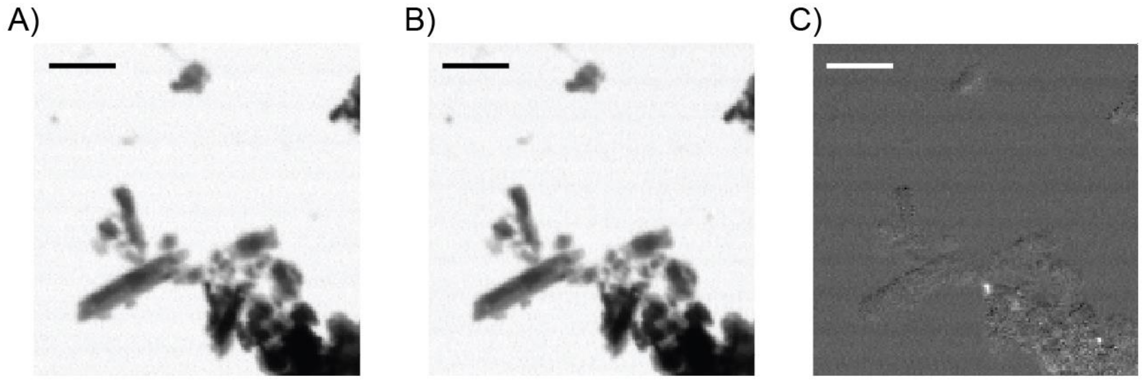

Fig. S18. STXM images of a-SiO_2 taken at (A) 344 eV and (B) 349.4 eV. (C) Ca mapping of a-SiO_2 generated from (A) and (B). Bright regions represent Ca-rich regions. Scale bars shown are 2 µm.

Raman spectra of a-SiO_2 and e-$CaCO_3$

Table S8. Raman peak assignments of a-SiO_2 and e-$CaCO_3$[36, 37].

Peak	Frequency (cm^{-1})	Assignment
a	150	Lattice modes
b	178	Lattice modes
c	272	Lattice modes
d	708	In-plane bending of CO_3^{2-}
e	720	In-plane bending of CO_3^{2-}
f	1063	Symmetric stretching of CO_3^{2-}
g	1082	Symmetric stretching of CO_3^{2-}
h	1049	Symmetric stretching of Q^3

Characterizations of synthesized belite

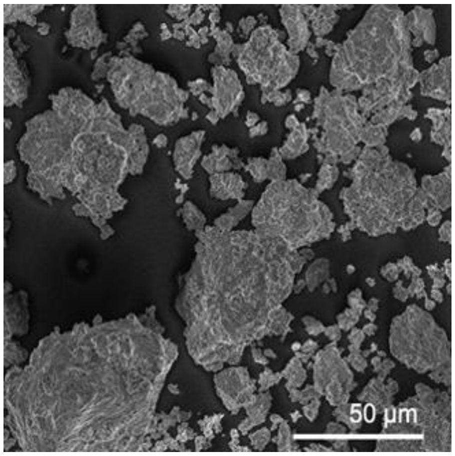

Fig. S19. SEM image of synthesized belite.

Life cycle assessment and sensitivity analysis

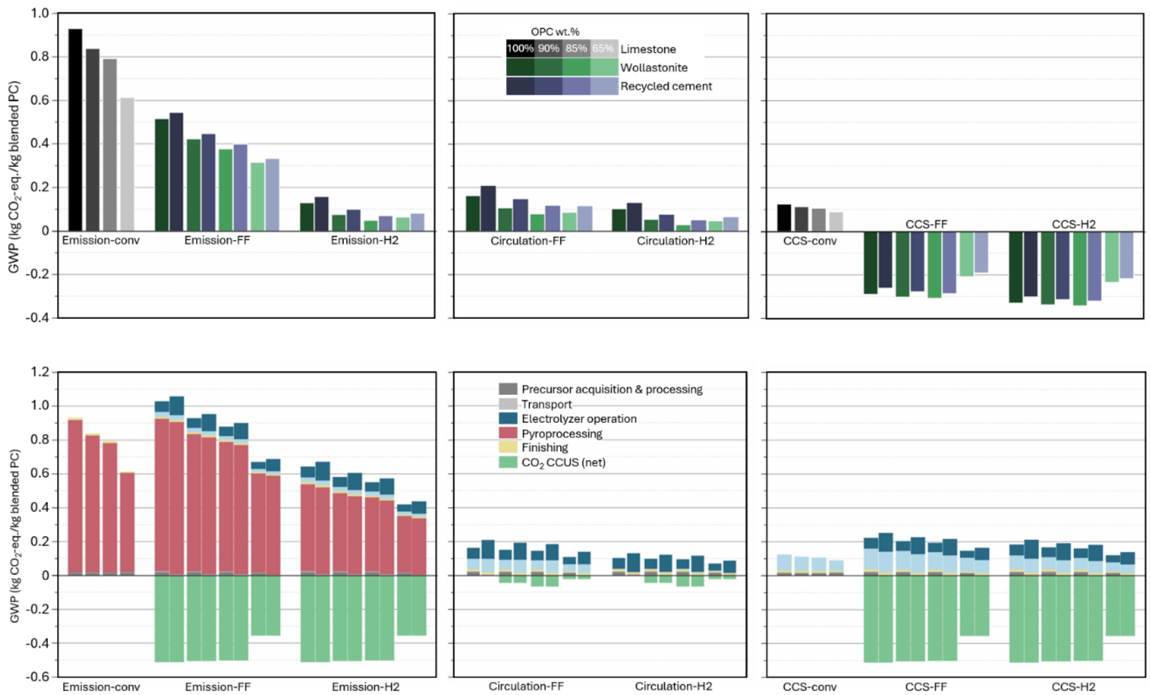

Figure S20. GWP in total (top row) and by process category (bottom row), with vertically aligned columns representing the same precursor choice and blend design. The four blended PC designs are: 100 wt% OPC; 90 wt% OPC with 10 wt% $CaCO_3$; 85 wt% OPC with 15 wt% $CaCO_3$; 65 wt% OPC with 5 wt% $CaCO_3$ and 30 wt% SiO_2.

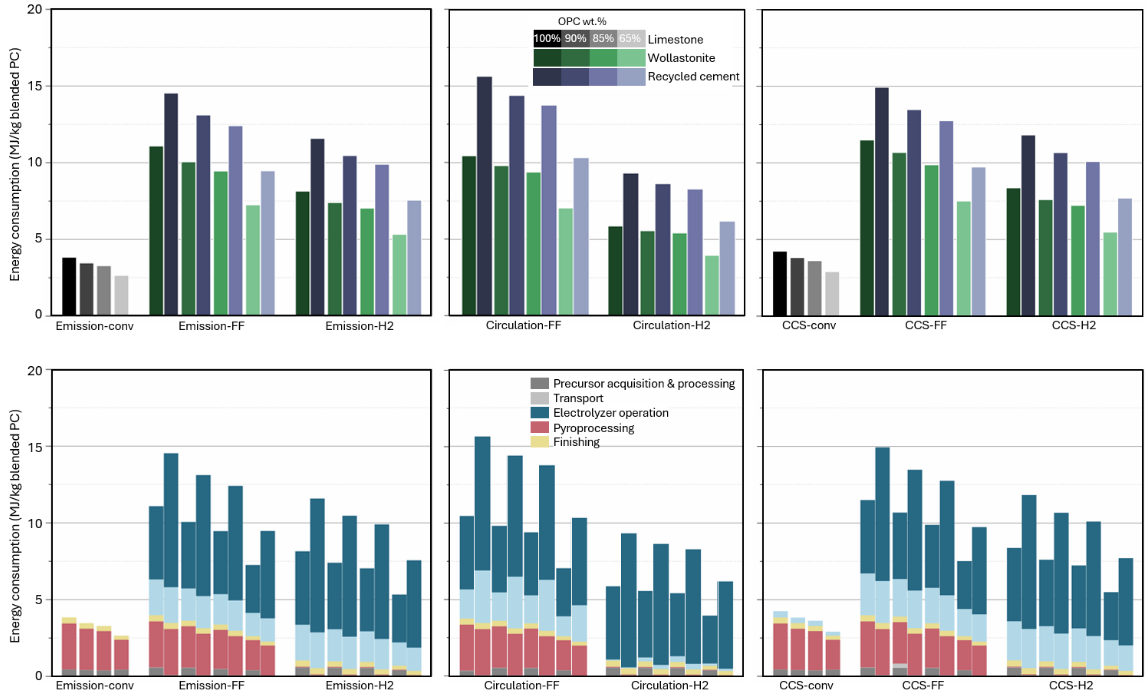

Figure S21. Energy consumption in total (top row) and by process category (bottom row), with vertically aligned columns representing the same precursor choice and blend design. The four blended PC designs are: 100 wt% OPC; 90 wt% OPC with 10 wt% $CaCO_3$; 85 wt% OPC with 15 wt% $CaCO_3$; 65 wt% OPC with 5 wt% $CaCO_3$ and 30 wt% SiO_2.

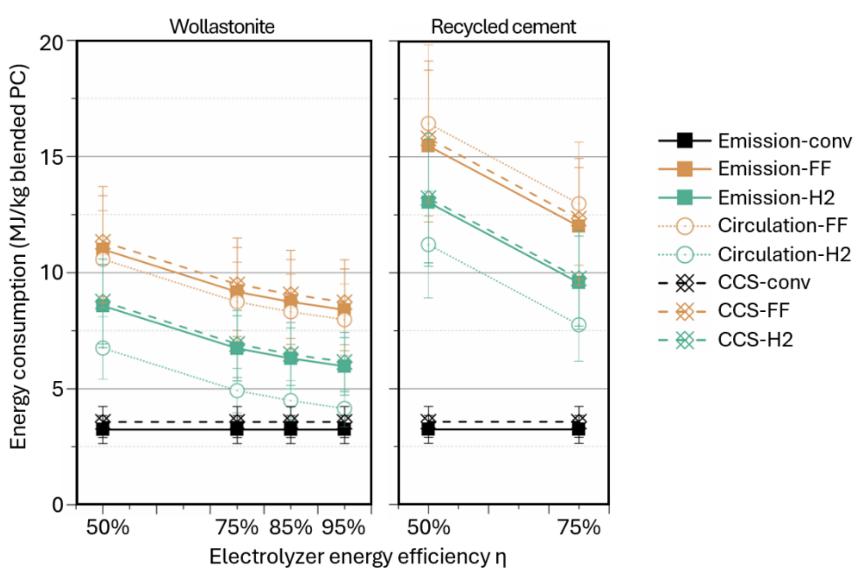

Figure S22. Sensitivity analysis of electrolyzer energy efficiency on total energy consumption for eight scenarios. The error bar provides the varying range of energy consumption due to varying blended PC design (100 wt% OPC; 90 wt% OPC with 10 wt% $CaCO_3$; 85 wt% OPC with 15 wt% $CaCO_3$; 65 wt% OPC with 5 wt% $CaCO_3$ and 30 wt% SiO_2).

Table S9. Sensitivity analysis – GWP (kg CO_2-eq./kg blended PC produced): $CaSiO_3$ at low renewable electricity (RE) emission and high electrolyzer efficiency.

Emission-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
TOTAL	9.31E-01	8.38E-01	7.91E-01	6.14E-01

Emission-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	7.14E-03	6.42E-03	6.07E-03	4.64E-03
electrolyzer operation	1.36E-02	1.22E-02	1.16E-02	8.84E-03
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	4.56E-01	3.69E-01	3.25E-01	2.76E-01

Emission-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	7.14E-03	6.42E-03	6.07E-03	4.64E-03
electrolyzer operation	1.36E-02	1.22E-02	1.16E-02	8.84E-03
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with green H2	5.13E-01	4.62E-01	4.36E-01	3.34E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	6.88E-02	2.07E-02	-3.31E-03	2.42E-02

Circulation-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
electrolyzer operation	1.36E-02	1.22E-02	1.16E-02	8.84E-03
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation (pumping)	5.28E-03	5.21E-03	5.17E-03	3.66E-03
capture of excess flue gas CO2	4.74E-04	4.26E-04	4.03E-04	3.08E-04
transport & storage excess flue gas CO2	3.87E-02	3.48E-02	3.29E-02	2.52E-02
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	1.06E-01	5.46E-02	2.89E-02	4.86E-02

Circulation-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
electrolyzer operation	1.36E-02	1.22E-02	1.16E-02	8.84E-03
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	1.56E-04	1.40E-04	1.33E-04	1.01E-04
pyroprocessing with green H2	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation & supplemental DAC	2.02E-04	8.11E-04	1.12E-03	4.46E-04
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	6.18E-02	1.51E-02	-8.29E-03	2.00E-02

CCS-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	1.10E-03	9.91E-04	9.36E-04	7.16E-04
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
TOTAL	1.22E-01	1.10E-01	1.04E-01	8.75E-02

CCS-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	7.14E-03	6.42E-03	6.07E-03	4.64E-03
electrolyzer operation	1.36E-02	1.22E-02	1.16E-02	8.84E-03
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	1.10E-03	9.91E-04	9.36E-04	7.16E-04
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-3.53E-01	-3.59E-01	-3.62E-01	-2.50E-01

CCS-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	7.14E-03	6.42E-03	6.07E-03	4.64E-03
electrolyzer operation	1.36E-02	1.22E-02	1.16E-02	8.84E-03
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	1.56E-04	1.40E-04	1.33E-04	1.01E-04
pyroprocessing with green H2	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	6.28E-04	5.65E-04	5.34E-04	4.08E-04
flue gas CO2 transport & storage	5.13E-02	4.62E-02	4.36E-02	3.33E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-3.92E-01	-3.95E-01	-3.95E-01	-2.75E-01

Table S10. Sensitivity analysis – GWP (kg CO_2-eq./kg blended PC produced): $CaSiO_3$ at medium RE emission and high electrolyzer efficiency.

Emission-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
TOTAL	9.31E-01	8.38E-01	7.91E-01	6.14E-01

Emission-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	2.80E-02	2.52E-02	2.38E-02	1.82E-02
electrolyzer operation	5.34E-02	4.80E-02	4.54E-02	3.47E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	5.17E-01	4.23E-01	3.77E-01	3.15E-01

Emission-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	2.80E-02	2.52E-02	2.38E-02	1.82E-02
electrolyzer operation	5.34E-02	4.80E-02	4.54E-02	3.47E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with green H2	5.14E-01	4.62E-01	4.37E-01	3.34E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	1.30E-01	7.56E-02	4.86E-02	6.39E-02

Circulation-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
electrolyzer operation	5.34E-02	4.80E-02	4.54E-02	3.47E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation (pumping)	2.07E-02	2.04E-02	2.03E-02	1.44E-02
capture of excess flue gas CO2	1.86E-03	1.67E-03	1.58E-03	1.21E-03
transport & storage excess flue gas CO2	3.87E-02	3.48E-02	3.29E-02	2.52E-02
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	1.63E-01	1.07E-01	7.90E-02	8.60E-02

Circulation-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
electrolyzer operation	5.34E-02	4.80E-02	4.54E-02	3.47E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	6.12E-04	5.50E-04	5.20E-04	3.97E-04
pyroprocessing with green H2	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation & supplemental DAC	7.93E-04	3.18E-03	4.38E-03	1.75E-03
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	1.03E-01	5.36E-02	2.92E-02	4.75E-02

CCS-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	4.32E-03	3.89E-03	3.67E-03	2.81E-03
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
TOTAL	1.25E-01	1.12E-01	1.07E-01	8.96E-02

CCS-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	2.80E-02	2.52E-02	2.38E-02	1.82E-02
electrolyzer operation	5.34E-02	4.80E-02	4.54E-02	3.47E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	4.32E-03	3.89E-03	3.67E-03	2.81E-03
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-2.89E-01	-3.02E-01	-3.08E-01	-2.08E-01

CCS-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	2.80E-02	2.52E-02	2.38E-02	1.82E-02
electrolyzer operation	5.34E-02	4.80E-02	4.54E-02	3.47E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	6.12E-04	5.50E-04	5.20E-04	3.97E-04
pyroprocessing with green H2	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	2.46E-03	2.22E-03	2.09E-03	1.60E-03
flue gas CO2 transport & storage	5.13E-02	4.62E-02	4.36E-02	3.33E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-3.29E-01	-3.38E-01	-3.42E-01	-2.34E-01

Table S11. Sensitivity analysis – GWP (kg CO_2-eq./kg blended PC produced): $CaSiO_3$ at high RE emission and high electrolyzer efficiency.

Emission-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
TOTAL	9.31E-01	8.38E-01	7.91E-01	6.14E-01

Emission-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	8.02E-02	7.22E-02	6.82E-02	5.21E-02
electrolyzer operation	1.53E-01	1.38E-01	1.30E-01	9.94E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	6.68E-01	5.60E-01	5.06E-01	4.14E-01

Emission-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	8.02E-02	7.22E-02	6.82E-02	5.21E-02
electrolyzer operation	1.53E-01	1.38E-01	1.30E-01	9.94E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with green H2	5.15E-01	4.63E-01	4.38E-01	3.35E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	2.83E-01	2.13E-01	1.78E-01	1.64E-01

Circulation-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
electrolyzer operation	1.53E-01	1.38E-01	1.30E-01	9.94E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation (pumping)	5.94E-02	5.85E-02	5.81E-02	4.11E-02
capture of excess flue gas CO2	5.32E-03	4.79E-03	4.53E-03	3.46E-03
transport & storage excess flue gas CO2	3.87E-02	3.48E-02	3.29E-02	2.52E-02
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	3.05E-01	2.37E-01	2.04E-01	1.80E-01

Circulation-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
electrolyzer operation	1.53E-01	1.38E-01	1.30E-01	9.94E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	1.75E-03	1.58E-03	1.49E-03	1.14E-03
pyroprocessing with green H2	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation & supplemental DAC	2.27E-03	9.12E-03	1.25E-02	5.02E-03
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	2.05E-01	1.50E-01	1.23E-01	1.17E-01

CCS-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	1.24E-02	1.11E-02	1.05E-02	8.05E-03
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
TOTAL	1.33E-01	1.20E-01	1.13E-01	9.49E-02

CCS-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	8.02E-02	7.22E-02	6.82E-02	5.21E-02
electrolyzer operation	1.53E-01	1.38E-01	1.30E-01	9.94E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	1.24E-02	1.11E-02	1.05E-02	8.05E-03
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-1.29E-01	-1.58E-01	-1.72E-01	-1.04E-01

CCS-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	8.02E-02	7.22E-02	6.82E-02	5.21E-02
electrolyzer operation	1.53E-01	1.38E-01	1.30E-01	9.94E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	1.75E-03	1.58E-03	1.49E-03	1.14E-03
pyroprocessing with green H2	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	7.06E-03	6.35E-03	6.00E-03	4.59E-03
flue gas CO2 transport & storage	5.13E-02	4.62E-02	4.36E-02	3.33E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-1.71E-01	-1.96E-01	-2.08E-01	-1.32E-01

Table S12. Sensitivity analysis – GWP (kg CO_2-eq./kg blended PC produced): $CaSiO_3$ at low RE emission and low electrolyzer efficiency.

Emission-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
TOTAL	9.31E-01	8.38E-01	7.91E-01	6.14E-01

Emission-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	7.14E-03	6.42E-03	6.07E-03	4.64E-03
electrolyzer operation	2.04E-02	1.84E-02	1.73E-02	1.33E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	4.63E-01	3.75E-01	3.31E-01	2.80E-01

Emission-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	7.14E-03	6.42E-03	6.07E-03	4.64E-03
electrolyzer operation	2.04E-02	1.84E-02	1.73E-02	1.33E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with green H2	5.13E-01	4.62E-01	4.36E-01	3.34E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	7.56E-02	2.68E-02	2.47E-03	2.86E-02

Circulation-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
electrolyzer operation	2.04E-02	1.84E-02	1.73E-02	1.33E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation (pumping)	5.28E-03	5.21E-03	5.17E-03	3.66E-03
capture of excess flue gas CO2	4.74E-04	4.26E-04	4.03E-04	3.08E-04
transport & storage excess flue gas CO2	3.87E-02	3.48E-02	3.29E-02	2.52E-02
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	1.13E-01	6.07E-02	3.47E-02	5.30E-02

Circulation-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
electrolyzer operation	2.04E-02	1.84E-02	1.73E-02	1.33E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	1.56E-04	1.40E-04	1.33E-04	1.01E-04
pyroprocessing with green H2	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation & supplemental DAC	2.02E-04	8.11E-04	1.12E-03	4.46E-04
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	6.86E-02	2.12E-02	-2.48E-03	2.45E-02

CCS-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	1.10E-03	9.91E-04	9.36E-04	7.16E-04
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
TOTAL	1.22E-01	1.10E-01	1.04E-01	8.75E-02

CCS-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	7.14E-03	6.42E-03	6.07E-03	4.64E-03
electrolyzer operation	2.04E-02	1.84E-02	1.73E-02	1.33E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	1.10E-03	9.91E-04	9.36E-04	7.16E-04
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-3.46E-01	-3.53E-01	-3.57E-01	-2.45E-01

CCS-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	7.14E-03	6.42E-03	6.07E-03	4.64E-03
electrolyzer operation	2.04E-02	1.84E-02	1.73E-02	1.33E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	1.56E-04	1.40E-04	1.33E-04	1.01E-04
pyroprocessing with green H2	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	6.28E-04	5.65E-04	5.34E-04	4.08E-04
flue gas CO2 transport & storage	5.13E-02	4.62E-02	4.36E-02	3.33E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-3.85E-01	-3.88E-01	-3.90E-01	-2.71E-01

Table S13. Sensitivity analysis – GWP (kg CO_2-eq./kg blended PC produced): $CaSiO_3$ at medium RE emission and low electrolyzer efficiency.

Emission-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
TOTAL	9.31E-01	8.38E-01	7.91E-01	6.14E-01

Emission-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	2.80E-02	2.52E-02	2.38E-02	1.82E-02
electrolyzer operation	8.00E-02	7.20E-02	6.80E-02	5.20E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	5.43E-01	4.47E-01	3.99E-01	3.33E-01

Emission-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	2.80E-02	2.52E-02	2.38E-02	1.82E-02
electrolyzer operation	8.00E-02	7.20E-02	6.80E-02	5.20E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with green H2	5.14E-01	4.62E-01	4.37E-01	3.34E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	1.57E-01	9.96E-02	7.12E-02	8.12E-02

Circulation-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
electrolyzer operation	8.00E-02	7.20E-02	6.80E-02	5.20E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation (pumping)	2.07E-02	2.04E-02	2.03E-02	1.44E-02
capture of excess flue gas CO2	1.86E-03	1.67E-03	1.58E-03	1.21E-03
transport & storage excess flue gas CO2	3.87E-02	3.48E-02	3.29E-02	2.52E-02
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	1.90E-01	1.31E-01	1.02E-01	1.04E-01

Circulation-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
electrolyzer operation	8.00E-02	7.20E-02	6.80E-02	5.20E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	6.12E-04	5.50E-04	5.20E-04	3.97E-04
pyroprocessing with green H2	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation & supplemental DAC	7.93E-04	3.18E-03	4.38E-03	1.75E-03
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	1.30E-01	7.76E-02	5.18E-02	6.48E-02

CCS-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	4.32E-03	3.89E-03	3.67E-03	2.81E-03
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
TOTAL	1.25E-01	1.12E-01	1.07E-01	8.96E-02

CCS-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	2.80E-02	2.52E-02	2.38E-02	1.82E-02
electrolyzer operation	8.00E-02	7.20E-02	6.80E-02	5.20E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	4.32E-03	3.89E-03	3.67E-03	2.81E-03
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-2.62E-01	-2.78E-01	-2.85E-01	-1.91E-01

CCS-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	2.80E-02	2.52E-02	2.38E-02	1.82E-02
electrolyzer operation	8.00E-02	7.20E-02	6.80E-02	5.20E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	6.12E-04	5.50E-04	5.20E-04	3.97E-04
pyroprocessing with green H2	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	2.46E-03	2.22E-03	2.09E-03	1.60E-03
flue gas CO2 transport & storage	5.13E-02	4.62E-02	4.36E-02	3.33E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-3.02E-01	-3.14E-01	-3.19E-01	-2.17E-01

Table S14. Sensitivity analysis – GWP (kg CO_2-eq./kg blended PC produced): $CaSiO_3$ at high RE emission and low electrolyzer efficiency.

Emission-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
TOTAL	9.31E-01	8.38E-01	7.91E-01	6.14E-01

Emission-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	8.02E-02	7.22E-02	6.82E-02	5.21E-02
electrolyzer operation	2.29E-01	2.06E-01	1.95E-01	1.49E-01
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	7.45E-01	6.29E-01	5.71E-01	4.64E-01

Emission-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	8.02E-02	7.22E-02	6.82E-02	5.21E-02
electrolyzer operation	2.29E-01	2.06E-01	1.95E-01	1.49E-01
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with green H2	5.15E-01	4.63E-01	4.38E-01	3.35E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	3.60E-01	2.82E-01	2.43E-01	2.13E-01

Circulation-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
electrolyzer operation	2.29E-01	2.06E-01	1.95E-01	1.49E-01
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation (pumping)	5.94E-02	5.85E-02	5.81E-02	4.11E-02
capture of excess flue gas CO2	5.32E-03	4.79E-03	4.53E-03	3.46E-03
transport & storage excess flue gas CO2	3.87E-02	3.48E-02	3.29E-02	2.52E-02
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	3.81E-01	3.06E-01	2.69E-01	2.30E-01

Circulation-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
electrolyzer operation	2.29E-01	2.06E-01	1.95E-01	1.49E-01
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	1.75E-03	1.58E-03	1.49E-03	1.14E-03
pyroprocessing with green H2	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation & supplemental DAC	2.27E-03	9.12E-03	1.25E-02	5.02E-03
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	2.82E-01	2.19E-01	1.88E-01	1.66E-01

CCS-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	1.24E-02	1.11E-02	1.05E-02	8.05E-03
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
TOTAL	1.33E-01	1.20E-01	1.13E-01	9.49E-02

CCS-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	8.02E-02	7.22E-02	6.82E-02	5.21E-02
electrolyzer operation	2.29E-01	2.06E-01	1.95E-01	1.49E-01
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	1.24E-02	1.11E-02	1.05E-02	8.05E-03
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-5.31E-02	-8.90E-02	-1.07E-01	-5.50E-02

CCS-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	1.22E-02	1.18E-02	1.17E-02	8.36E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
raw materials grinding	9.02E-03	8.89E-03	8.83E-03	6.25E-03
DAC	8.02E-02	7.22E-02	6.82E-02	5.21E-02
electrolyzer operation	2.29E-01	2.06E-01	1.95E-01	1.49E-01
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	1.75E-03	1.58E-03	1.49E-03	1.14E-03
pyroprocessing with green H2	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	7.06E-03	6.35E-03	6.00E-03	4.59E-03
flue gas CO2 transport & storage	5.13E-02	4.62E-02	4.36E-02	3.33E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-9.54E-02	-1.27E-01	-1.43E-01	-8.25E-02

Table S15. Sensitivity analysis – GWP (kg CO_2-eq./kg blended PC produced): recycled cement at low RE emission and high electrolyzer efficiency.

Emission-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
TOTAL	9.31E-01	8.38E-01	7.91E-01	6.14E-01

Emission-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
DAC	7.14E-03	6.42E-03	6.07E-03	4.64E-03
electrolyzer operation	2.57E-02	2.31E-02	2.18E-02	1.67E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	4.49E-01	3.61E-01	3.17E-01	2.71E-01

Emission-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
DAC	7.14E-03	6.42E-03	6.07E-03	4.64E-03
electrolyzer operation	2.57E-02	2.31E-02	2.18E-02	1.67E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with green H2	5.13E-01	4.62E-01	4.36E-01	3.34E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	6.19E-02	1.28E-02	-1.16E-02	1.89E-02

Circulation-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03

raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
electrolyzer operation	2.57E-02	2.31E-02	2.18E-02	1.67E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation (pumping)	9.97E-03	9.83E-03	9.76E-03	6.91E-03
capture of excess flue gas CO2	4.74E-04	4.26E-04	4.03E-04	3.08E-04
transport & storage excess flue gas CO2	3.87E-02	3.48E-02	3.29E-02	2.52E-02
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	1.04E-01	5.14E-02	2.52E-02	4.66E-02

Circulation-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
electrolyzer operation	2.57E-02	2.31E-02	2.18E-02	1.67E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	1.56E-04	1.40E-04	1.33E-04	1.01E-04
pyroprocessing with green H2	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation & supplemental DAC	2.02E-04	8.11E-04	1.12E-03	4.46E-04
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	5.49E-02	7.27E-03	-1.66E-02	1.47E-02

CCS-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	1.10E-03	9.91E-04	9.36E-04	7.16E-04
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
TOTAL	1.22E-01	1.10E-01	1.04E-01	8.75E-02

CCS-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03

DAC	7.14E-03	6.42E-03	6.07E-03	4.64E-03
electrolyzer operation	2.57E-02	2.31E-02	2.18E-02	1.67E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	1.10E-03	9.91E-04	9.36E-04	7.16E-04
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-3.60E-01	-3.67E-01	-3.71E-01	-2.55E-01

CCS-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
DAC	7.14E-03	6.42E-03	6.07E-03	4.64E-03
electrolyzer operation	2.57E-02	2.31E-02	2.18E-02	1.67E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	1.56E-04	1.40E-04	1.33E-04	1.01E-04
pyroprocessing with green H2	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	6.28E-04	5.65E-04	5.34E-04	4.08E-04
flue gas CO2 transport & storage	5.13E-02	4.62E-02	4.36E-02	3.33E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-3.99E-01	-4.02E-01	-4.04E-01	-2.80E-01

Table S16. Sensitivity analysis – GWP (kg CO_2-eq./kg blended PC produced): recycled cement paste at medium RE emission and high electrolyzer efficiency.

Emission-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
TOTAL	9.31E-01	8.38E-01	7.91E-01	6.14E-01

Emission-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
DAC	2.80E-02	2.52E-02	2.38E-02	1.82E-02
electrolyzer operation	1.01E-01	9.07E-02	8.56E-02	6.55E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	5.45E-01	4.47E-01	3.98E-01	3.33E-01

Emission-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
DAC	2.80E-02	2.52E-02	2.38E-02	1.82E-02
electrolyzer operation	1.01E-01	9.07E-02	8.56E-02	6.55E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with green H2	5.14E-01	4.62E-01	4.37E-01	3.34E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	1.59E-01	9.96E-02	7.03E-02	8.16E-02

Circulation-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03

raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
electrolyzer operation	1.01E-01	9.07E-02	8.56E-02	6.55E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation (pumping)	3.91E-02	3.86E-02	3.83E-02	2.71E-02
capture of excess flue gas CO2	1.86E-03	1.67E-03	1.58E-03	1.21E-03
transport & storage excess flue gas CO2	3.87E-02	3.48E-02	3.29E-02	2.52E-02
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	2.10E-01	1.49E-01	1.19E-01	1.17E-01

Circulation-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
electrolyzer operation	1.01E-01	9.07E-02	8.56E-02	6.55E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	6.12E-04	5.50E-04	5.20E-04	3.97E-04
pyroprocessing with green H2	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation & supplemental DAC	7.93E-04	3.18E-03	4.38E-03	1.75E-03
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	1.31E-01	7.76E-02	5.09E-02	6.51E-02

CCS-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	4.32E-03	3.89E-03	3.67E-03	2.81E-03
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
TOTAL	1.25E-01	1.12E-01	1.07E-01	8.96E-02

CCS-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03

DAC	2.80E-02	2.52E-02	2.38E-02	1.82E-02
electrolyzer operation	1.01E-01	9.07E-02	8.56E-02	6.55E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	4.32E-03	3.89E-03	3.67E-03	2.81E-03
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-2.61E-01	-2.78E-01	-2.86E-01	-1.91E-01

CCS-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
DAC	2.80E-02	2.52E-02	2.38E-02	1.82E-02
electrolyzer operation	1.01E-01	9.07E-02	8.56E-02	6.55E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	6.12E-04	5.50E-04	5.20E-04	3.97E-04
pyroprocessing with green H2	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	2.46E-03	2.22E-03	2.09E-03	1.60E-03
flue gas CO2 transport & storage	5.13E-02	4.62E-02	4.36E-02	3.33E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-3.01E-01	-3.14E-01	-3.20E-01	-2.17E-01

Table S17. Sensitivity analysis – GWP (kg CO_2-eq./kg blended PC produced): recycled cement paste at high RE emission and high electrolyzer efficiency.

Emission-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
TOTAL	9.31E-01	8.38E-01	7.91E-01	6.14E-01

Emission-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
DAC	8.02E-02	7.22E-02	6.82E-02	5.21E-02
electrolyzer operation	2.89E-01	2.60E-01	2.45E-01	1.88E-01
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	7.85E-01	6.63E-01	6.03E-01	4.89E-01

Emission-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
DAC	8.02E-02	7.22E-02	6.82E-02	5.21E-02
electrolyzer operation	2.89E-01	2.60E-01	2.45E-01	1.88E-01
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with green H2	5.15E-01	4.63E-01	4.38E-01	3.35E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	4.00E-01	3.17E-01	2.75E-01	2.39E-01

Circulation-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
electrolyzer operation	2.89E-01	2.60E-01	2.45E-01	1.88E-01
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation (pumping)	1.12E-01	1.11E-01	1.10E-01	7.77E-02
capture of excess flue gas CO2	5.32E-03	4.79E-03	4.53E-03	3.46E-03
transport & storage excess flue gas CO2	3.87E-02	3.48E-02	3.29E-02	2.52E-02
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	4.74E-01	3.93E-01	3.53E-01	2.92E-01

Circulation-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
electrolyzer operation	2.89E-01	2.60E-01	2.45E-01	1.88E-01
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	1.75E-03	1.58E-03	1.49E-03	1.14E-03
pyroprocessing with green H2	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation & supplemental DAC	2.27E-03	9.12E-03	1.25E-02	5.02E-03
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	3.22E-01	2.53E-01	2.20E-01	1.92E-01

CCS-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	1.24E-02	1.11E-02	1.05E-02	8.05E-03
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
TOTAL	1.33E-01	1.20E-01	1.13E-01	9.49E-02

CCS-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
DAC	8.02E-02	7.22E-02	6.82E-02	5.21E-02
electrolyzer operation	2.89E-01	2.60E-01	2.45E-01	1.88E-01
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	1.24E-02	1.11E-02	1.05E-02	8.05E-03
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-1.27E-02	-5.43E-02	-7.50E-02	-2.96E-02

CCS-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
DAC	8.02E-02	7.22E-02	6.82E-02	5.21E-02
electrolyzer operation	2.89E-01	2.60E-01	2.45E-01	1.88E-01
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	1.75E-03	1.58E-03	1.49E-03	1.14E-03
pyroprocessing with green H2	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	7.06E-03	6.35E-03	6.00E-03	4.59E-03
flue gas CO2 transport & storage	5.13E-02	4.62E-02	4.36E-02	3.33E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-5.50E-02	-9.24E-02	-1.11E-01	-5.70E-02

Table S18. Sensitivity analysis – GWP (kg CO_2-eq./kg blended PC produced): recycled cement paste at low RE emission and low electrolyzer efficiency.

Emission-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
TOTAL	9.31E-01	8.38E-01	7.91E-01	6.14E-01

Emission-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
DAC	7.14E-03	6.42E-03	6.07E-03	4.64E-03
electrolyzer operation	3.85E-02	3.47E-02	3.28E-02	2.50E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	4.62E-01	3.72E-01	3.28E-01	2.79E-01

Emission-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
DAC	7.14E-03	6.42E-03	6.07E-03	4.64E-03
electrolyzer operation	3.85E-02	3.47E-02	3.28E-02	2.50E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with green H2	5.13E-01	4.62E-01	4.36E-01	3.34E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	7.47E-02	2.44E-02	-7.01E-04	2.73E-02

Circulation-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03

raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
electrolyzer operation	3.85E-02	3.47E-02	3.28E-02	2.50E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation (pumping)	9.97E-03	9.83E-03	9.76E-03	6.91E-03
capture of excess flue gas CO2	4.74E-04	4.26E-04	4.03E-04	3.08E-04
transport & storage excess flue gas CO2	3.87E-02	3.48E-02	3.29E-02	2.52E-02
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	1.17E-01	6.29E-02	3.61E-02	5.49E-02

Circulation-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
electrolyzer operation	3.85E-02	3.47E-02	3.28E-02	2.50E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	1.56E-04	1.40E-04	1.33E-04	1.01E-04
pyroprocessing with green H2	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation & supplemental DAC	2.02E-04	8.11E-04	1.12E-03	4.46E-04
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	6.78E-02	1.88E-02	-5.65E-03	2.31E-02

CCS-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	1.10E-03	9.91E-04	9.36E-04	7.16E-04
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
TOTAL	1.22E-01	1.10E-01	1.04E-01	8.75E-02

CCS-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03

DAC	7.14E-03	6.42E-03	6.07E-03	4.64E-03
electrolyzer operation	3.85E-02	3.47E-02	3.28E-02	2.50E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	1.10E-03	9.91E-04	9.36E-04	7.16E-04
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-3.47E-01	-3.56E-01	-3.60E-01	-2.47E-01

CCS-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
DAC	7.14E-03	6.42E-03	6.07E-03	4.64E-03
electrolyzer operation	3.85E-02	3.47E-02	3.28E-02	2.50E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	1.56E-04	1.40E-04	1.33E-04	1.01E-04
pyroprocessing with green H2	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	6.28E-04	5.65E-04	5.34E-04	4.08E-04
flue gas CO2 transport & storage	5.13E-02	4.62E-02	4.36E-02	3.33E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-3.86E-01	-3.91E-01	-3.93E-01	-2.72E-01

Table S19. Sensitivity analysis – GWP (kg CO_2-eq./kg blended PC produced): recycled cement paste at medium RE emission and low electrolyzer efficiency.

Emission-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
TOTAL	9.31E-01	8.38E-01	7.91E-01	6.14E-01

Emission-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
DAC	2.80E-02	2.52E-02	2.38E-02	1.82E-02
electrolyzer operation	1.51E-01	1.36E-01	1.28E-01	9.82E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	5.95E-01	4.92E-01	4.41E-01	3.66E-01

Emission-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
DAC	2.80E-02	2.52E-02	2.38E-02	1.82E-02
electrolyzer operation	1.51E-01	1.36E-01	1.28E-01	9.82E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with green H2	5.14E-01	4.62E-01	4.37E-01	3.34E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	2.09E-01	1.45E-01	1.13E-01	1.15E-01

Circulation-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03

raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
electrolyzer operation	1.51E-01	1.36E-01	1.28E-01	9.82E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation (pumping)	3.91E-02	3.86E-02	3.83E-02	2.71E-02
capture of excess flue gas CO2	1.86E-03	1.67E-03	1.58E-03	1.21E-03
transport & storage excess flue gas CO2	3.87E-02	3.48E-02	3.29E-02	2.52E-02
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	2.60E-01	1.94E-01	1.61E-01	1.49E-01

Circulation-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
electrolyzer operation	1.51E-01	1.36E-01	1.28E-01	9.82E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	6.12E-04	5.50E-04	5.20E-04	3.97E-04
pyroprocessing with green H2	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation & supplemental DAC	7.93E-04	3.18E-03	4.38E-03	1.75E-03
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	1.82E-01	1.23E-01	9.37E-02	9.79E-02

CCS-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	4.32E-03	3.89E-03	3.67E-03	2.81E-03
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
TOTAL	1.25E-01	1.12E-01	1.07E-01	8.96E-02

CCS-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03

DAC	2.80E-02	2.52E-02	2.38E-02	1.82E-02
electrolyzer operation	1.51E-01	1.36E-01	1.28E-01	9.82E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	4.32E-03	3.89E-03	3.67E-03	2.81E-03
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-2.10E-01	-2.33E-01	-2.44E-01	-1.58E-01

CCS-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
DAC	2.80E-02	2.52E-02	2.38E-02	1.82E-02
electrolyzer operation	1.51E-01	1.36E-01	1.28E-01	9.82E-02
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	6.12E-04	5.50E-04	5.20E-04	3.97E-04
pyroprocessing with green H2	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	2.46E-03	2.22E-03	2.09E-03	1.60E-03
flue gas CO2 transport & storage	5.13E-02	4.62E-02	4.36E-02	3.33E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	-2.50E-01	-2.69E-01	-2.77E-01	-1.84E-01

Table S20. Sensitivity analysis – GWP (kg CO_2-eq./kg blended PC produced): recycled cement paste at high RE emission and low electrolyzer efficiency.

Emission-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
TOTAL	9.31E-01	8.38E-01	7.91E-01	6.14E-01

Emission-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
DAC	8.02E-02	7.22E-02	6.82E-02	5.21E-02
electrolyzer operation	4.33E-01	3.90E-01	3.68E-01	2.82E-01
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	9.00E-01	8.10E-01	7.65E-01	5.85E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	9.30E-01	7.93E-01	7.25E-01	5.83E-01

Emission-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
DAC	8.02E-02	7.22E-02	6.82E-02	5.21E-02
electrolyzer operation	4.33E-01	3.90E-01	3.68E-01	2.82E-01
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with green H2	5.15E-01	4.63E-01	4.38E-01	3.35E-01
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	5.44E-01	4.46E-01	3.98E-01	3.33E-01

Circulation-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03

raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
electrolyzer operation	4.33E-01	3.90E-01	3.68E-01	2.82E-01
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation (pumping)	1.12E-01	1.11E-01	1.10E-01	7.77E-02
capture of excess flue gas CO2	5.32E-03	4.79E-03	4.53E-03	3.46E-03
transport & storage excess flue gas CO2	3.87E-02	3.48E-02	3.29E-02	2.52E-02
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	6.19E-01	5.23E-01	4.75E-01	3.86E-01

Circulation-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
electrolyzer operation	4.33E-01	3.90E-01	3.68E-01	2.82E-01
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	1.75E-03	1.58E-03	1.49E-03	1.14E-03
pyroprocessing with green H2	0.00E+00			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 circulation & supplemental DAC	2.27E-03	9.12E-03	1.25E-02	5.02E-03
electrochemical CO2 intake (net)	0.00E+00	-4.40E-02	-6.60E-02	-2.20E-02
TOTAL	4.66E-01	3.83E-01	3.42E-01	2.86E-01

CCS-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	9.29E-03	8.37E-03	7.89E-03	6.04E-03
raw materials transport to cement plant	1.43E-03	1.28E-03	1.21E-03	9.27E-04
raw materials grinding	7.04E-03	6.33E-03	5.98E-03	4.57E-03
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	7.25E-03
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	9.60E-04
in-cement plant convey	8.03E-05	7.23E-05	6.83E-05	5.22E-05
limestone as supplementary cementitious materials	0.00E+00	4.33E-04	6.49E-04	2.16E-04
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	1.24E-02	1.11E-02	1.05E-02	8.05E-03
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
TOTAL	1.33E-01	1.20E-01	1.13E-01	9.49E-02

CCS-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03

DAC	8.02E-02	7.22E-02	6.82E-02	5.21E-02
electrolyzer operation	4.33E-01	3.90E-01	3.68E-01	2.82E-01
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
pyroprocessing with fossil fuel	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	1.24E-02	1.11E-02	1.05E-02	8.05E-03
flue gas CO2 transport & storage	9.00E-02	8.10E-02	7.65E-02	5.85E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	1.32E-01	7.56E-02	4.77E-02	6.43E-02

CCS-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.25E-03	2.03E-03	1.91E-03	1.46E-03
raw materials transport to cement plant	3.37E-03	3.29E-03	3.25E-03	2.31E-03
DAC	8.02E-02	7.22E-02	6.82E-02	5.21E-02
electrolyzer operation	4.33E-01	3.90E-01	3.68E-01	2.82E-01
filtering	1.06E-02	1.04E-02	1.03E-02	7.32E-03
in-cement plant convey	8.03E-05	8.03E-05	8.03E-05	8.03E-05
H2 pumping to cement kiln	1.75E-03	1.58E-03	1.49E-03	1.14E-03
pyroprocessing with green H2	0 (CCS)			
finishing milling & grinding	1.24E-02	1.11E-02	1.05E-02	8.03E-03
blending	2.66E-04	2.66E-04	2.66E-04	2.66E-04
flue gas CO2 capture	7.06E-03	6.35E-03	6.00E-03	4.59E-03
flue gas CO2 transport & storage	5.13E-02	4.62E-02	4.36E-02	3.33E-02
electrochemical CO2 intake	-5.13E-01	-5.06E-01	-5.02E-01	-3.55E-01
TOTAL	8.94E-02	3.76E-02	1.18E-02	3.68E-02

Table S21. Sensitivity analysis – energy consumptions (MJ/kg blended PC produced): $CaSiO_3$ at high electrolyzer efficiency.

Emission-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.01E-01	1.81E-01	1.70E-01	1.30E-01
raw materials transport to cement plant	8.45E-03	7.60E-03	7.18E-03	5.49E-03
raw materials grinding	2.24E-01	2.01E-01	1.90E-01	1.45E-01
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	1.35E-01
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	5.70E-03
in-cement plant convey	2.55E-03	2.30E-03	2.17E-03	1.66E-03
limestone as supplementary cementitious materials	0.00E+00	9.07E-03	1.36E-02	4.53E-03
pyroprocessing with fossil fuel	3.00E+00	2.70E+00	2.55E+00	1.95E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
TOTAL	3.84E+00	3.47E+00	3.27E+00	2.64E+00

Emission-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.63E-01	2.55E-01	2.51E-01	1.81E-01
raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
raw materials grinding	2.87E-01	2.83E-01	1.99E-01	1.99E-01
DAC	2.33E+00	2.10E+00	1.98E+00	1.52E+00
electrolyzer operation	4.45E+00	4.00E+00	3.78E+00	2.89E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
pyroprocessing with fossil fuel	3.00E+00	2.70E+00	2.55E+00	1.95E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
TOTAL	1.11E+01	1.00E+01	9.45E+00	7.24E+00

Emission-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.63E-01	2.55E-01	2.51E-01	1.81E-01
raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
raw materials grinding	2.87E-01	2.83E-01	2.81E-01	1.99E-01
DAC	2.33E+00	2.10E+00	1.98E+00	1.52E+00
electrolyzer operation	4.45E+00	4.00E+00	3.78E+00	2.89E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
pyroprocessing with green H2	5.10E-02	4.59E-02	4.33E-02	3.31E-02
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
TOTAL	8.14E+00	7.40E+00	7.03E+00	5.33E+00

Circulation-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	5.83E-02	2.55E-01	2.51E-01	1.81E-01
raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
raw materials grinding	2.87E-01	2.83E-01	2.81E-01	1.99E-01
electrolyzer operation	4.45E+00	4.00E+00	3.78E+00	2.89E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
pyroprocessing with fossil fuel	3.00E+00	2.70E+00	2.55E+00	1.95E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
flue gas CO2 circulation (pumping)	1.73E+00	1.70E+00	1.69E+00	1.20E+00
capture of excess flue gas CO2	1.55E-01	1.39E-01	1.32E-01	1.01E-01
transport & storage excess flue gas CO2	1.67E-02	1.50E-02	1.42E-02	1.09E-02
TOTAL	1.05E+01	9.81E+00	9.39E+00	7.04E+00

Circulation-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.63E-01	2.55E-01	2.51E-01	1.81E-01
raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
raw materials grinding	2.87E-01	2.83E-01	2.81E-01	1.99E-01
electrolyzer operation	4.45E+00	4.00E+00	3.78E+00	2.89E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
H2 pumping to cement kiln	5.10E-02	4.59E-02	4.33E-02	3.31E-02
pyroprocessing with green H2	0.00E+00	0.00E+00	0.00E+00	0.00E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
flue gas CO2 circulation & supplemental DAC	6.61E-02	2.65E-01	3.65E-01	1.46E-01
electrochemical CO2 intake (net)	5.82E+00	5.52E+00	5.37E+00	3.93E+00
TOTAL	5.87E+00	5.57E+00	5.41E+00	3.96E+00

CCS-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.01E-01	1.81E-01	1.70E-01	1.30E-01
raw materials transport to cement plant	8.45E-03	7.60E-03	7.18E-03	5.49E-03
raw materials grinding	2.24E-01	2.01E-01	1.90E-01	1.45E-01
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	1.35E-01
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	5.70E-03
in-cement plant convey	2.55E-03	2.30E-03	2.17E-03	1.66E-03
limestone as supplementary cementitious materials	0.00E+00	9.07E-03	1.36E-02	4.53E-03
pyroprocessing with fossil fuel	3.00E+00	2.70E+00	2.55E+00	1.95E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
flue gas CO2 capture	3.60E-01	3.24E-01	3.06E-01	2.34E-01
flue gas CO2 transport & storage	3.89E-02	3.50E-02	3.30E-02	2.53E-02
TOTAL	4.23E+00	3.83E+00	3.61E+00	2.90E+00

CCS-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.63E-01	2.55E-01	2.51E-01	1.81E-01
raw materials transport to cement plant	1.99E-02	2.85E-01	1.92E-02	1.37E-02
raw materials grinding	2.87E-01	2.83E-01	2.81E-01	1.99E-01
DAC	2.33E+00	2.10E+00	1.98E+00	1.52E+00
electrolyzer operation	4.45E+00	4.00E+00	3.78E+00	2.89E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
pyroprocessing with fossil fuel	3.00E+00	2.70E+00	2.55E+00	1.95E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
flue gas CO2 capture	3.60E-01	3.24E-01	3.06E-01	2.34E-01
flue gas CO2 transport & storage	3.89E-02	3.50E-02	3.30E-02	2.53E-02
TOTAL	1.15E+01	4.55E-02	4.30E-02	3.29E-02

CCS-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.63E-01	2.55E-01	2.51E-01	1.81E-01
raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
raw materials grinding	2.87E-01	2.83E-01	2.81E-01	1.99E-01
DAC	2.33E+00	2.10E+00	1.98E+00	1.52E+00
electrolyzer operation	4.45E+00	4.00E+00	3.78E+00	2.89E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
H2 pumping to cement kiln	5.10E-02	4.59E-02	4.33E-02	3.31E-02
pyroprocessing with green H2	0.00E+00	0.00E+00	0.00E+00	0.00E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
flue gas CO2 capture	2.05E-01	1.85E-01	1.74E-01	1.33E-01
flue gas CO2 transport & storage	2.22E-02	1.99E-02	1.88E-02	1.44E-02
TOTAL	8.37E+00	7.61E+00	7.22E+00	5.48E+00

Table S22. Sensitivity analysis – energy consumptions (MJ/kg blended PC produced): wollastonite at low electrolyzer efficiency.

Emission-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.01E-01	1.81E-01	1.70E-01	1.30E-01
raw materials transport to cement plant	8.45E-03	7.60E-03	7.18E-03	5.49E-03
raw materials grinding	2.24E-01	2.01E-01	1.90E-01	1.45E-01
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	1.35E-01
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	5.70E-03
in-cement plant convey	2.55E-03	2.30E-03	2.17E-03	1.66E-03
limestone as supplementary cementitious materials	0.00E+00	9.07E-03	1.36E-02	4.53E-03
pyroprocessing with fossil fuel	3.00E+00	2.70E+00	2.55E+00	1.95E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
TOTAL	3.84E+00	3.47E+00	3.27E+00	2.64E+00

Emission-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.63E-01	2.55E-01	2.51E-01	1.81E-01
raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
raw materials grinding	2.87E-01	2.83E-01	1.99E-01	1.99E-01
DAC	2.33E+00	2.10E+00	1.98E+00	1.52E+00
electrolyzer operation	6.67E+00	6.00E+00	5.67E+00	4.33E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
pyroprocessing with fossil fuel	3.00E+00	2.70E+00	2.55E+00	1.95E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
TOTAL	1.34E+01	1.20E+01	1.13E+01	8.69E+00

Emission-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.63E-01	2.55E-01	2.51E-01	1.81E-01
raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
raw materials grinding	2.87E-01	2.83E-01	2.81E-01	1.99E-01
DAC	2.33E+00	2.10E+00	1.98E+00	1.52E+00
electrolyzer operation	6.67E+00	6.00E+00	5.67E+00	4.33E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
pyroprocessing with green H2	5.10E-02	4.59E-02	4.33E-02	3.31E-02
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
TOTAL	1.04E+01	9.40E+00	8.92E+00	6.77E+00

Circulation-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	5.83E-02	2.55E-01	2.51E-01	1.81E-01
raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
raw materials grinding	2.87E-01	2.83E-01	2.81E-01	1.99E-01
electrolyzer operation	6.67E+00	6.00E+00	5.67E+00	4.33E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
pyroprocessing with fossil fuel	3.00E+00	2.70E+00	2.55E+00	1.95E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
flue gas CO2 circulation (pumping)	1.73E+00	1.70E+00	1.69E+00	1.20E+00
capture of excess flue gas CO2	1.55E-01	1.39E-01	1.32E-01	1.01E-01
transport & storage excess flue gas CO2	1.67E-02	1.50E-02	1.42E-02	1.09E-02
TOTAL	1.27E+01	1.18E+01	1.12E+01	8.48E+00

Circulation-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.63E-01	2.55E-01	2.51E-01	1.81E-01
raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
raw materials grinding	2.87E-01	2.83E-01	2.81E-01	1.99E-01
electrolyzer operation	6.67E+00	6.00E+00	5.67E+00	4.33E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
H2 pumping to cement kiln	5.10E-02	4.59E-02	4.33E-02	3.31E-02
pyroprocessing with green H2	0.00E+00	0.00E+00	0.00E+00	0.00E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
flue gas CO2 circulation & supplemental DAC	6.61E-02	2.65E-01	3.65E-01	1.46E-01
electrochemical CO2 intake (net)	8.05E+00	7.52E+00	7.26E+00	5.37E+00
TOTAL	8.10E+00	7.57E+00	7.30E+00	5.40E+00

CCS-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.01E-01	1.81E-01	1.70E-01	1.30E-01
raw materials transport to cement plant	8.45E-03	7.60E-03	7.18E-03	5.49E-03
raw materials grinding	2.24E-01	2.01E-01	1.90E-01	1.45E-01
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	1.35E-01
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	5.70E-03
in-cement plant convey	2.55E-03	2.30E-03	2.17E-03	1.66E-03
limestone as supplementary cementitious materials	0.00E+00	9.07E-03	1.36E-02	4.53E-03
pyroprocessing with fossil fuel	3.00E+00	2.70E+00	2.55E+00	1.95E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
flue gas CO2 capture	3.60E-01	3.24E-01	3.06E-01	2.34E-01
flue gas CO2 transport & storage	3.89E-02	3.50E-02	3.30E-02	2.53E-02
TOTAL	4.23E+00	3.83E+00	3.61E+00	2.90E+00

CCS-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.63E-01	2.55E-01	2.51E-01	1.81E-01
raw materials transport to cement plant	1.99E-02	2.85E-01	1.92E-02	1.37E-02
raw materials grinding	2.87E-01	2.83E-01	2.81E-01	1.99E-01
DAC	2.33E+00	2.10E+00	1.98E+00	1.52E+00
electrolyzer operation	6.67E+00	6.00E+00	5.67E+00	4.33E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
pyroprocessing with fossil fuel	3.00E+00	2.70E+00	2.55E+00	1.95E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
flue gas CO2 capture	3.60E-01	3.24E-01	3.06E-01	2.34E-01
flue gas CO2 transport & storage	3.89E-02	3.50E-02	3.30E-02	2.53E-02
TOTAL	1.38E+01	4.55E-02	4.30E-02	3.29E-02

CCS-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.63E-01	2.55E-01	2.51E-01	1.81E-01
raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
raw materials grinding	2.87E-01	2.83E-01	2.81E-01	1.99E-01
DAC	2.33E+00	2.10E+00	1.98E+00	1.52E+00
electrolyzer operation	6.67E+00	6.00E+00	5.67E+00	4.33E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
H2 pumping to cement kiln	5.10E-02	4.59E-02	4.33E-02	3.31E-02
pyroprocessing with green H2	0.00E+00	0.00E+00	0.00E+00	0.00E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
flue gas CO2 capture	2.05E-01	1.85E-01	1.74E-01	1.33E-01
flue gas CO2 transport & storage	2.22E-02	1.99E-02	1.88E-02	1.44E-02
TOTAL	1.06E+01	9.61E+00	9.11E+00	6.92E+00

Table S23. Sensitivity analysis – energy consumptions (MJ/kg blended PC produced): recycled cement paste at high electrolyzer efficiency.

Emission-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.01E-01	1.81E-01	1.70E-01	1.30E-01
raw materials transport to cement plant	8.45E-03	7.60E-03	7.18E-03	5.49E-03
raw materials grinding	2.24E-01	2.01E-01	1.90E-01	1.45E-01
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	1.35E-01
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	5.70E-03
in-cement plant convey	2.55E-03	2.30E-03	2.17E-03	1.66E-03
limestone as supplementary cementitious materials	0.00E+00	9.07E-03	1.36E-02	4.53E-03
pyroprocessing with fossil fuel	3.00E+00	2.70E+00	2.55E+00	1.95E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
TOTAL	3.84E+00	3.47E+00	3.27E+00	2.64E+00

Emission-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	4.86E-02	4.37E-02	4.13E-02	3.16E-02
raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
DAC	2.33E+00	2.10E+00	1.98E+00	1.52E+00
electrolyzer operation	8.39E+00	7.56E+00	7.14E+00	5.46E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
pyroprocessing with fossil fuel	3.00E+00	2.70E+00	2.55E+00	1.95E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
TOTAL	1.46E+01	1.31E+01	1.24E+01	9.46E+00

Emission-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	4.86E-02	4.37E-02	4.13E-02	3.16E-02
raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
DAC	2.33E+00	2.10E+00	1.98E+00	1.52E+00
electrolyzer operation	8.39E+00	7.56E+00	7.14E+00	5.46E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
pyroprocessing with green H2	5.10E-02	4.59E-02	4.33E-02	3.31E-02
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
TOTAL	1.16E+01	1.04E+01	9.89E+00	7.55E+00

Circulation-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2

raw materials quarrying	4.86E-02	4.37E-02	4.13E-02	3.16E-02
raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
electrolyzer operation	8.39E+00	7.56E+00	7.14E+00	5.46E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
pyroprocessing with fossil fuel	3.00E+00	2.70E+00	2.55E+00	1.95E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
flue gas CO2 circulation (pumping)	3.26E+00	3.21E+00	3.19E+00	2.26E+00
capture of excess flue gas CO2	1.55E-01	1.39E-01	1.32E-01	1.01E-01
transport & storage excess flue gas CO2	1.67E-02	1.50E-02	1.42E-02	1.09E-02
TOTAL	1.57E+01	1.43E+01	1.37E+01	1.03E+01

Circulation-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	4.86E-02	4.37E-02	4.13E-02	3.16E-02
raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
electrolyzer operation	8.39E+00	7.56E+00	7.14E+00	5.46E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
H2 pumping to cement kiln	5.10E-02	4.59E-02	4.33E-02	3.31E-02
pyroprocessing with green H2	0.00E+00	0.00E+00	0.00E+00	0.00E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
flue gas CO2 circulation & supplemental DAC	6.61E-02	2.65E-01	3.65E-01	1.46E-01
TOTAL	9.32E+00	8.63E+00	8.27E+00	6.18E+00

CCS-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.01E-01	1.81E-01	1.70E-01	1.30E-01
raw materials transport to cement plant	8.45E-03	7.60E-03	7.18E-03	5.49E-03
raw materials grinding	2.24E-01	2.01E-01	1.90E-01	1.45E-01
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	1.35E-01
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	5.70E-03
in-cement plant convey	2.55E-03	2.30E-03	2.17E-03	1.66E-03
limestone as supplementary cementitious materials	0.00E+00	9.07E-03	1.36E-02	4.53E-03
pyroprocessing with fossil fuel	3.00E+00	2.70E+00	2.55E+00	1.95E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
flue gas CO2 capture	3.60E-01	3.24E-01	3.06E-01	2.34E-01
flue gas CO2 transport & storage	3.89E-02	3.50E-02	3.30E-02	2.53E-02
TOTAL	4.23E+00	3.83E+00	3.61E+00	2.90E+00

CCS-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	4.86E-02	4.37E-02	4.13E-02	3.16E-02

raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
DAC	2.33E+00	2.10E+00	1.98E+00	1.52E+00
electrolyzer operation	8.39E+00	7.56E+00	7.14E+00	5.46E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
pyroprocessing with fossil fuel	3.00E+00	2.70E+00	2.55E+00	1.95E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
flue gas CO2 capture	3.60E-01	3.24E-01	3.06E-01	2.34E-01
flue gas CO2 transport & storage	3.89E-02	3.50E-02	3.30E-02	2.53E-02
TOTAL	1.50E+01	1.34E+01	1.27E+01	9.72E+00

CCS-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	4.86E-02	4.37E-02	4.13E-02	3.16E-02
raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
DAC	2.33E+00	2.10E+00	1.98E+00	1.52E+00
electrolyzer operation	8.39E+00	7.56E+00	7.14E+00	5.46E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
H2 pumping to cement kiln	5.10E-02	4.59E-02	4.33E-02	3.31E-02
pyroprocessing with green H2	0.00E+00	0.00E+00	0.00E+00	0.00E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
flue gas CO2 capture	2.05E-01	1.85E-01	1.74E-01	1.33E-01
flue gas CO2 transport & storage	2.22E-02	1.99E-02	1.88E-02	1.44E-02
TOTAL	1.19E+01	1.06E+01	1.00E+01	7.69E+00

Table S24. Sensitivity analysis – energy consumptions (MJ/kg blended PC produced): recycled cement paste at low electrolyzer efficiency.

Emission-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.01E-01	1.81E-01	1.70E-01	1.30E-01
raw materials transport to cement plant	8.45E-03	7.60E-03	7.18E-03	5.49E-03
raw materials grinding	2.24E-01	2.01E-01	1.90E-01	1.45E-01
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	1.35E-01
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	5.70E-03
in-cement plant convey	2.55E-03	2.30E-03	2.17E-03	1.66E-03
limestone as supplementary cementitious materials	0.00E+00	9.07E-03	1.36E-02	4.53E-03
pyroprocessing with fossil fuel	3.00E+00	2.70E+00	2.55E+00	1.95E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
TOTAL	3.84E+00	3.47E+00	3.27E+00	2.64E+00

Emission-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	4.86E-02	4.37E-02	4.13E-02	3.16E-02

raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
DAC	2.33E+00	2.10E+00	1.98E+00	1.52E+00
electrolyzer operation	1.26E+01	1.13E+01	1.07E+01	8.18E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
pyroprocessing with fossil fuel	3.00E+00	2.70E+00	2.55E+00	1.95E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
TOTAL	1.88E+01	1.68E+01	1.59E+01	1.22E+01

Emission-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	4.86E-02	4.37E-02	4.13E-02	3.16E-02
raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
DAC	2.33E+00	2.10E+00	1.98E+00	1.52E+00
electrolyzer operation	1.26E+01	1.13E+01	1.07E+01	8.18E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
pyroprocessing with green H2	5.10E-02	4.59E-02	4.33E-02	3.31E-02
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
TOTAL	1.58E+01	1.42E+01	1.34E+01	1.02E+01

Circulation-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	4.86E-02	4.37E-02	4.13E-02	3.16E-02
raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
electrolyzer operation	1.26E+01	1.13E+01	1.07E+01	8.18E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
pyroprocessing with fossil fuel	3.00E+00	2.70E+00	2.55E+00	1.95E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
flue gas CO2 circulation (pumping)	3.26E+00	3.21E+00	3.19E+00	2.26E+00
capture of excess flue gas CO2	1.55E-01	1.39E-01	1.32E-01	1.01E-01
transport & storage excess flue gas CO2	1.67E-02	1.50E-02	1.42E-02	1.09E-02
TOTAL	1.99E+01	1.81E+01	1.73E+01	1.30E+01

Circulation-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	4.86E-02	4.37E-02	4.13E-02	3.16E-02
raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
electrolyzer operation	1.26E+01	1.13E+01	1.07E+01	8.18E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
H2 pumping to cement kiln	5.10E-02	4.59E-02	4.33E-02	3.31E-02

pyroprocessing with green H2	0.00E+00	0.00E+00	0.00E+00	0.00E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
flue gas CO2 circulation & supplemental DAC	6.61E-02	2.65E-01	3.65E-01	1.46E-01
TOTAL	1.36E+01	1.24E+01	1.18E+01	8.91E+00

CCS-conv

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	2.01E-01	1.81E-01	1.70E-01	1.30E-01
raw materials transport to cement plant	8.45E-03	7.60E-03	7.18E-03	5.49E-03
raw materials grinding	2.24E-01	2.01E-01	1.90E-01	1.45E-01
fly ash acquisition & processing	0.00E+00	0.00E+00	0.00E+00	1.35E-01
fly ash transport to cement plant	0.00E+00	0.00E+00	0.00E+00	5.70E-03
in-cement plant convey	2.55E-03	2.30E-03	2.17E-03	1.66E-03
limestone as supplementary cementitious materials	0.00E+00	9.07E-03	1.36E-02	4.53E-03
pyroprocessing with fossil fuel	3.00E+00	2.70E+00	2.55E+00	1.95E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
flue gas CO2 capture	3.60E-01	3.24E-01	3.06E-01	2.34E-01
flue gas CO2 transport & storage	3.89E-02	3.50E-02	3.30E-02	2.53E-02
TOTAL	4.23E+00	3.83E+00	3.61E+00	2.90E+00

CCS-FF

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	4.86E-02	4.37E-02	4.13E-02	3.16E-02
raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
DAC	2.33E+00	2.10E+00	1.98E+00	1.52E+00
electrolyzer operation	1.26E+01	1.13E+01	1.07E+01	8.18E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
pyroprocessing with fossil fuel	3.00E+00	2.70E+00	2.55E+00	1.95E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
flue gas CO2 capture	3.60E-01	3.24E-01	3.06E-01	2.34E-01
flue gas CO2 transport & storage	3.89E-02	3.50E-02	3.30E-02	2.53E-02
TOTAL	1.92E+01	1.72E+01	1.63E+01	1.24E+01

CCS-H2

GWP	OPC	10% $CaCO_3$	15% $CaCO_3$	5% $CaCO_3$ + 30% SiO_2
raw materials quarrying	4.86E-02	4.37E-02	4.13E-02	3.16E-02
raw materials transport to cement plant	1.99E-02	1.95E-02	1.92E-02	1.37E-02
DAC	2.33E+00	2.10E+00	1.98E+00	1.52E+00
electrolyzer operation	1.26E+01	1.13E+01	1.07E+01	8.18E+00
filtering	3.36E-01	3.31E-01	3.29E-01	2.33E-01
in-cement plant convey	2.55E-03	2.55E-03	2.55E-03	2.55E-03
H2 pumping to cement kiln	5.10E-02	4.59E-02	4.33E-02	3.31E-02

pyroprocessing with green H2	0.00E+00	0.00E+00	0.00E+00	0.00E+00
finishing milling & grinding	3.93E-01	3.54E-01	3.34E-01	2.55E-01
blending	8.47E-03	8.47E-03	8.47E-03	8.47E-03
flue gas CO2 capture	2.05E-01	1.85E-01	1.74E-01	1.33E-01
flue gas CO2 transport & storage	2.22E-02	1.99E-02	1.88E-02	1.44E-02
TOTAL	1.61E+01	1.44E+01	1.36E+01	1.04E+01

SI References

1. J. Li, W. Zhang, C. Li and P. J. M. Monteiro, *Journal of Cleaner Production*, 2020, **261**.
2. J. K. Soeherman, A. J. Jones and P. J. Dauenhauer, *ACS Engineering Au*, 2023, **3**, 114-127.
3. K. Z. House, A. C. Baclig, M. Ranjan, E. A. van Nierop, J. Wilcox and H. J. Herzog, *Proceedings of the National Academy of Sciences*, 2011, **108**, 20428-20433.
4. L. D. Ellis, A. F. Badel, M. L. Chiang, R. J. Park and Y. M. Chiang, *Proc Natl Acad Sci U S A*, 2020, **117**, 12584-12591.
5. S. A. Miller and R. J. Myers, *Environ Sci Technol*, 2020, **54**, 677-686.
6. C150/C150M – 22 Standard Specification for Portland Cement, 2022, DOI: 10.1520/C0150_C0150M-22.
7. A. P. Gursel, Green Concrete LCA Web Tool, (https://greenconcrete.berkeley.edu/, 2024).
8. A. P. Gursel, H. Maryman and C. Ostertag, *Journal of Cleaner Production*, 2016, **112**, 823-836.
9. *ISO 14040:2006 - Environmental management -- Life cycle assessment -- Principles and framework*, International Organization for Standardization, 2006.
10. L. Riboldi and O. Bolland, *Energy Procedia*, 2017, **114**, 2390-2400.
11. T. Terlouw, K. Treyer, C. Bauer and M. Mazzotti, *Environ Sci Technol*, 2021, **55**, 11397-11411.
12. D.-A. Chisalita, L. Petrescu, P. Cobden, H. A. J. van Dijk, A.-M. Cormos and C.-C. Cormos, *Journal of Cleaner Production*, 2019, **211**, 1015-1025.
13. A. P. Gursel, 2014. *Life-cycle assessment of concrete: decision-support tool and case study application*. University of California, Berkeley.
14. J. Bare, D. Young and M. Hopton, *Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI)*, Sustainable Technology Division, National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, 2012.
15. T. J. Skone, M. Mutchek, M. Krynock, S. Moni, R. Srijana, J. Chou, C. D. R., M. Jamieson, G. Cooney, E. Dale and A. K. Claros, *Carbon Dioxide Utilization Life Cycle Analysis Guidance for the U.S. DOE Office of Fossil Energy and Carbon Management, Version 2.0*, U.S. Department of Energy/Natinal Energy Technology Laboratory, 2022.
16. *Land-Based Wind Market Report - 2024 Edition*, Lawrence Berkeley National Laboratory, 2024.
17. J. Li, W. Zhang, K. Xu and P. J. M. Monteiro, *Cement Concrete Res*, 2020, **137**, 106195.
18. T. H. Mehedi, E. Gemechu and A. Kumar, *Applied Energy*, 2022, **314**, 118918.
19. A. Kumar, F. Du and J. H. V. Lienhard, *ACS Energy Letters*, 2021, **6**, 3563-3566.
20. DOE, Technical Targets for Proton Exchange Membrane Electrolysis, https://www.energy.gov/eere/fuelcells/technical-targets-proton-exchange-membrane-electrolysis, (accessed 9/24/2024).
21. M. Fasihi, O. Efimova and C. Breyer, *Journal of Cleaner Production*, 2019, **224**, 957-980.
22. IEA, *Global Hydrogen Review 2021*, International Energy Agency, Paris, 2021.
23. Coal explained - Coal prices and outlook, https://www.eia.gov/energyexplained/coal/prices-and-outlook.php, 2024).
24. J. Vickers, D. Peterson and K. Randolph, *Cost of Electrolytic Hydrogen Production with Existing Technology*, U.S. Department of Energy, 2020.
25. G. H. Rau, S. A. Carroll, W. L. Bourcier, M. J. Singleton, M. M. Smith and R. D. Aines, *Proceedings of the National Academy of Sciences*, 2013, **110**, 10095-10100.
26. Crushed Stone Statistics and Information, https://www.usgs.gov/centers/national-minerals-information-center/crushed-stone-statistics-and-information).
27. Data and Information Used by WaterSense, https://www.epa.gov/watersense/data-and-information-used-watersense#Cost%20of%20Water, 2024).
28. Cement Statistics and Information, https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information, 2024).
29. H. E. Holmes, R. P. Lively and M. J. Realff, *JACS Au*, 2021, **1**, 795-806.
30. W. J. Schmelz, G. Hochman and K. G. Miller, *Interface Focus*, 2020, **10**, 20190065.

31. G. H. Rau, *Environ Sci Technol*, 2008, **42**, 8935-8940.
32. P. Badjatya, A. H. Akca, D. V. Fraga Alvarez, B. Chang, S. Ma, X. Pang, E. Wang, Q. van Hinsberg, D. V. Esposito and S. Kawashima, *Proc Natl Acad Sci U S A*, 2022, **119**, e2114680119.
33. Z. Zhang, B. A. W. Mowbray, C. T. E. Parkyn, C. Waizenegger, A. S. R. Williams, E. W. Lees, S. Ren, Y. Kim, R. P. Jansonius and C. P. Berlinguette, *Energy & Environmental Science*, 2022, **15**, 5129-5136.
34. B. A. W. Mowbray, Z. B. Zhang, C. T. E. Parkyn and C. P. Berlinguette, *ACS Energy Letters*, 2023, **8**, 1772-1778.
35. R. K. Miao, N. Wang, S.-F. Hung, W.-Y. Huang, J. Zhang, Y. Zhao, P. Ou, S. Wang, J. P. Edwards, C. Tian, J. Han, Y. Xu, M. Fan, J. E. Huang, Y. C. Xiao, A. H. Ip, H. Liang, E. H. Sargent and D. Sinton, *ACS Energy Letters*, 2023, **8**, 4694-4701.
36. M. De La Pierre, R. Demichelis, U. Wehrmeister, D. E. Jacob, P. Raiteri, J. D. Gale and R. Orlando, *The Journal of Physical Chemistry C*, 2014, **118**, 27493-27501.
37. S. Ortaboy, J. Li, G. Geng, R. J. Myers, P. J. M. Monteiro, R. Maboudian and C. Carraro, *RSC Advances*, 2017, **7**, 48925-48933.