Electronic Supplementary Material (ESI) for Green Chemistry.

Supplementary Information 1 (SP1).

European/UK projects oriented to the decarbonization of the lime industry

STRATEGY	AREA	NAME	MAIN GOAL	Period
CARBON DIRECT AVOIDANCE	ENERGY EFFICIENCY	WHEATREC4PG: Waste Heat Recovery for Power Generation Lime: Lhoist	Recovers 4 MW of thermal power from a rotary kiln exhaust gas, and converts it to 0.5 MWe of low carbon electrical power	2012-2013
	ENERGY EFFICIENCY	CHP GENERATION: Combined Heat and Power (CHP) for Limestone Milling Lime: Carmeuse	Energy recovery from drying / heating off gases: Instead using 40% of natural gas' thermal energy for producing electrical power, in the combined heat and power more than 70% of thermal energy is utilized	2014-2017
	RENEWABLE ENERGY SOURCES	ENERGY OPTIMIZATION: Reduced energy consumption through optimized processes and capacity use Lime: Nordkalk	Biogas production from by-products of the food industry slaughterhouses and livestock-breeding as well as wastewater sludge	2011-2016
	RENEWABLE ENERGY SOURCES	ADIREN4LIME: Anaerobic Digestion as Renewable Energy for the Lime Industry Lime: Singleton Birch	Production of biogas from biomass in anaerobic conditions and used as fuel for the lime kiln.	2014-2015
	RENEWABLE ENERGY	HYDROGEN FUEL ENERGY	Use of hydrogen as an alternative fuel	2019-2022

	SOURCES	INNOVATION: Alternatives to natural gas for high calcium lime manufacturing Lime: Mineral Products Association / British Lime Association	for high calcium lime manufacturing.	
	RENEWABLE ENERGY SOURCES	BIOXYSORB: Biomass co-combustion under both air- and oxy-fuel conditions Lime: Lhoist	Emissions of 1st and 2nd generation biomasses, evaluation of sorbents and plant modifications for high thermal share biomass co-combustion	2013-2016
	RENEWABLE ENERGY SOURCES	ENERGY GENERATION: Largest Solar panel farm in Wallonia by a mining company Lime: Carmeuse	13.200 solar panels will supply annually over 3.6 GWh of electricity to power lime production	2014-2017
CARBON DIRECT SEPARATION	KILN TECHNOLOGY DEVELOPMENT	LEILAC1: Low Emissions Intensity Lime and Cement Lime: Lhoist & Tarmac	Calix's Direct Separator Reactor technology is an in-situ CO_2 capture technique that requires no additional chemicals or equipment	2016-2021
	KILN TECHNOLOGY SCALE UP	LEILAC2: Low Emissions Intensity Lime and Cement Lime: Lhoist	X4 scale-up of LEILAC1 and upgrade into dual mode electricity/natural gas potentially balancing services to the grid	2020-2025

	KILN TECHNOLOGY DEVELOPMENT	ZERCAL: Zero-Carbon Lime pilot plant Lime: Singleton Birch	New oxy-fuel flash calcination process able to capture all CO_2 from lime production (lime decomposition and fuel combustion)	2021-2024
	KILN TECHNOLOGY DEVELOPMENT	Butterfly Project Lime: Carmeuse	A new type of kiln designed to effectively capture and concentrate CO_2 released during lime production	2023 -
	KILN TECHNOLOGY DEVELOPMENT	EVEREST project Lime: Lhoist	Improved calcination and carbon capture for the largest lime plant in Europe	2023-
CO2 VALUE CHAIN	CARBON USE	COLUMBUS: Power to Methane Lime: Carmeuse	Transforming CO_2 generated during the lime production process and hydrogen into e-methane, a renewable gas that can be injected into the gas network or used to power vehicles and industry. Pure CO_2 is required.	2022-2025
	CARBON USE	LOWCO_2 Lime: Calcinor	Incorporating CO_2 to alkaline residues (slags of energy plants, slags of steel mills, residues of RCDs construction and demolition and to produce methane/methanol	2019-2022
	CARBON USE	NKL: Neutral Kero Lime Lime: Lhoist	innovative e-Kerosene process using CO_2 from a lime kiln and hydrogen	2022-2026

			produced from green electricity via the Fischer Tropsch process	
	CARBON STORAGE	CSM: Carbon Storage by Mineralization Lime: Nordkalk	A rock composed mainly of magnesium silicate mineral serpentine reacts with the CO_2 to form a stable compound, thus fixing the CO_2 permanently. Direct mineralisation of flue gas instead of separated and compressed CO_2.	2011-2016

Supplementary Information 2 (SP2).

Providers of Energy Source for Electricity Production Germany 2020 and 2050. Based on [11].

	Flow	Amount (kWh)	Description	Provider
2020	electricity, high voltage	9	Biofuels	heat and power co-generation, biogas, gas engine | electricity, high voltage | APOS, S - DE
	electricity, high voltage	4	Wind Offshore	electricity production, wind, 1-3MW turbine, offshore | electricity, high voltage | APOS, S - DE
	electricity, high voltage	4	Hydro	electricity production, hydro, pumped storage | electricity, high voltage | APOS, S - DE
	electricity, high voltage	18	Wind Onshore	electricity production, wind, 1-3MW turbine, onshore | electricity, high voltage | APOS, S - DE
	electricity, high voltage	25	Coal	electricity production, hard coal | electricity, high voltage | APOS, S - DE
	electricity, high voltage	17	Natural gas	electricity production, natural gas, conventional power plant | electricity, high voltage | APOS, S - DE
	electricity, high voltage	11	Nuclear	electricity production, nuclear, pressure water reactor | electricity, high voltage | APOS, S - DE
	electricity, high voltage	1	Oil	electricity production, oil | electricity, high voltage | APOS, S - DE
	electricity, high voltage	9	Solar	electricity production, solar thermal parabolic trough, 50 MW | electricity, high voltage | APOS, S - RoW
	electricity, medium voltage	2	Waste	electricity, from municipal waste incineration to generic market for electricity, medium voltage | electricity, medium voltage | APOS, S - DE
2050	electricity, high voltage	3	Biofuels	heat and power co-generation, biogas, gas engine | electricity, high voltage | APOS, S - DE
	electricity, high voltage	7	Geothermal	electricity production, deep geothermal | electricity, high voltage | APOS, S - DE
	electricity, high voltage	26	Wind Offshore	electricity production, wind, 1-3MW turbine, offshore | electricity, high voltage | APOS, S - DE
	electricity, high voltage	34	Solar	electricity production, solar tower power plant, 20 MW | electricity, high voltage | APOS, S - RoW
	electricity, high voltage	4	Hydro	electricity production, hydro, pumped storage | electricity, high voltage | APOS, S - DE
	electricity, high voltage	26	Wind Onshore	electricity production, wind, 1-3MW turbine, onshore | electricity, high voltage | APOS, S - DE

Providers of Energy Source for Fuel Production Germany 2020 and 2050. Based on [11].

	Flow	Amount (MJ)	Description	Provider
2020	heat, district or industrial, other	2	Biomass	heat production, wood chips from industry, at

	than natural gas			furnace 1000kW | heat, district or industrial, other than natural gas | APOS, S - DE
	heat, district or industrial, other than natural gas	5	Oil	heat production, heavy fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | APOS, S - Europe without Switzerland
	heat, district or industrial, other than natural gas	8	Waste	heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas | heat, district or industrial, other than natural gas | APOS, S - DE
	Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW | Cut-off	34	Natural gas	heat production, natural gas, at industrial furnace >100kW - Europe without Switzerland
	Heat, district or industrial, other than natural gas {Europe without Switzerland}| heat production, at hard coal industri al furnace 1-10MW | Cut-off	51	Fossil Solid Fuels	heat production, at hard coal industrial furnace 1-10MW - Europe without Switzerland
2050	Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW | Cut-off, S - Copied from Ecoinvent	60	Natural gas	heat production, natural gas, at industrial furnace >100kW - Europe without Switzerland
	heat, district or industrial, other than natural gas	32	Biomass	heat production, wood chips from industry, at furnace 1000kW | heat, district or industrial, other than natural gas | APOS, S - DE
	heat, district or industrial, other than natural gas	8	Waste	heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas | heat, district or industrial, other than natural gas | APOS, S - DE

Supplementary Information 3 (SP3).

Life-cycle inventory for the production of the lime-based plaster

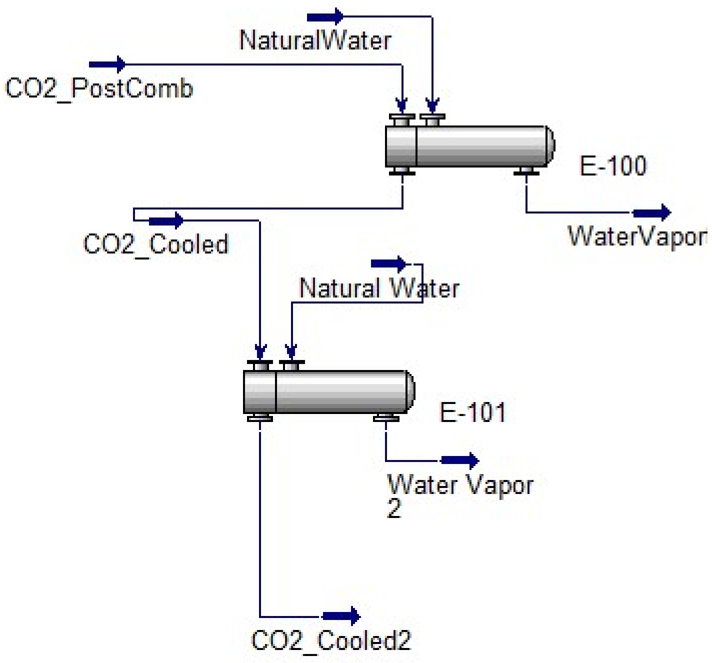
The LCI for the production of the lime-based plaster is shown, based on a previous study carried out by the authors [8]. The following additives are incorporated in the mix (referred to the binder in mass proportions): 2.5% Dispersion Agent, 0.20% Water Retention Agent, 0.02% Air Entrainer, 0.3% Hydrophobic Agent. The average transportation distance per additive is 250 km.

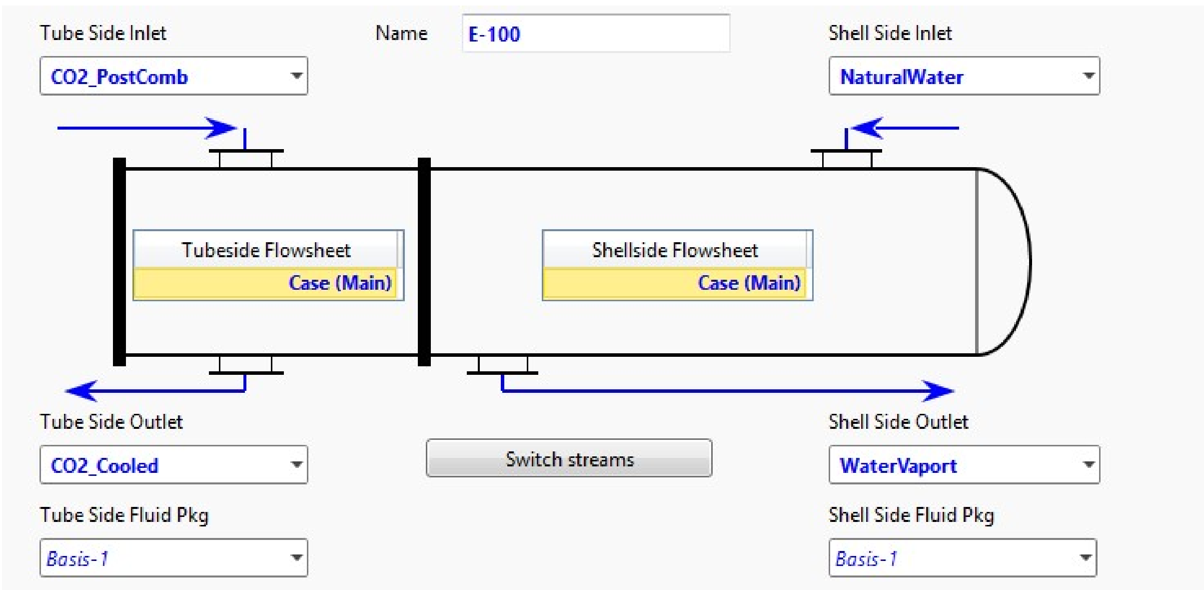
Table 1. Life Cycle Inventory for the production of a lime-based plaster (based on [8])

OPERATION	PROCESS MODELLED	PROCESSED AMOUNT		INVENTORY AMOUNT		SOURCES & NOTES
		AMOUNT	UNIT	AMOUNT	UNIT	
Plaster Manufacturing						
Input	**Fine aggregate**	0.675	t	0.675	t	Laveglia et al, 2023 [5]
	Lightweight aggregate	0.07	t	0.07	t	Modelled by Ecoinvent (pumice quarry operation, GLO)
	Transport	14	t*km	200	km	Modelled by Ecoinvent (transport, lorry 16-32 metric ton, EURO6 | RoW)
	Endless screw conveyor	0.0003	kWh	0.004	kWh / t	Electricity mix (SUBLime designed) [10]
	Artificial lightweight aggregate	0.005	t	0.005	t	Modelled by Ecoinvent (expanded perlite production, GLO)
	Transport	1	t*km	200	km	Modelled by Ecoinvent (transport, lorry 16-32 metric ton, EURO6 | RoW)
	Endless screw conveyor	0.00002	kWh	0.004	kWh / t	Electricity mix (SUBLime designed) [10]
	Hydrated lime (HL)	0.25	t	0.25	t	Laveglia et al, 2022 [10]
	Transport	25	t*km	100	km	Modelled by Ecoinvent (transport, lorry 16-32 metric ton, EURO6| RoW)
	Endless screw conveyor	0.001	kWh	0.004	kWh / t	Electricity mix (SUBLime designed) [10]
	Dry mixer	4	kWh	4	kWh / t	Electricity mix (SUBLime designed) [10]
Output	**Hydrated Lime Plaster (HLP)**	1.00	t	1.00	t	Output of the Plaster Manufacturing

Supplementary Information 4 (SP4).

Design parameters of the carbon capture system (Aspen Hysys Simulation).


NaturalWater
CO2_PostComb
E-100
CO2_Cooled
WaterVapor
Natural Water
E-101
Water Vapor
2
CO2_Cooled2


Tube Side Inlet
Name
E-100
Shell Side Inlet
CO2_PostComb
NaturalWater
Tubeside Flowsheet
Case (Main)
Shellside Flowsheet
Case (Main)
Tube Side Outlet
Shell Side Outlet
CO2_Cooled
Switch streams
WaterVaport
Tube Side Fluid Pkg
Shell Side Fluid Pkg
Basis-1
Basis-1

Configuration

Number of Shell Passes	1
Number of Shells in Series	1
Number of Shells in Parallel	1
Tube Passes per Shell	2
Exchanger Orientation	Horizontal
First Tube Pass Flow Direction	Counter
Elevation (Base)	0,0000

TEMA Type: A E L

Calculated Information

Shell HT Coeff [kJ/h-m2-C]	<empty>
Tube HT Coeff [kJ/h-m2-C]	<empty>
Overall U [kJ/h-m2-C]	24,69
Overall UA [kJ/C-h]	1564
Shell DP [kPa]	2,500e-002
Tube DP [kPa]	3,499e-002
Heat Trans. Area per Shell [m2]	63,33
Tube Volume per Shell [m3]	0,1930
Shell Volume per Shell [m3]	2,241

Overall Performance

Duty	6,163e+005 kJ/h
Heat Leak	0,000e-01 kJ/h
Heat Loss	0,000e-01 kJ/h
UA	1,56e+03 kJ/C-h
Min. Approach	330,000 C
LMTD	394,1 C

Detailed Performance

UA Curvature Error	0,0000 kJ/C-h
Hot Pinch Temp	350,0000 C
Cold Pinch Temp	20,0000 C
Ft Factor	0,823
Uncorrected LMTD	478,887 C

The electricity consumption of the heat exchanger is based on the pumping power required for the shell side. The pump is designed considering the pumping of natural water, at 20°C for 200 kg/h (3.3 L/m). https://www.kawamoto-global.com/web/data/ecatalog_u_pdf/2.pdf

Specification table

50Hz

GE-C/SI/502 E

Suction bore (mm)	Discharge bore (mm)	Ref.	Model	Motor (kW)	Standard specifications: Capacity (m^3/min)	Total head (m)	Capacity (m^3/min)	Total head (m)	Maximum back pressure (MPa)	Vibration isolator application table	
40	32	1	GEI405CE0.75	0.75	0.05	19.8	0.2	14.5	0.77	PBKV-46-404-01	PX-60Z
		2	GEJ405CE1.5	1.5	0.05	31	0.2	24	0.62	PBKV-46-404-02	PX-60Z
		3	GEJ405CE2.2	2.2	0.05	40	0.2	33.5	0.58	PBKV-46-404-02	PX-60Z
50	40	4	GEH505CE0.75	0.75	0.1	15.8	0.32	10.5	0.81	PBKV-46-404-01	PX-60Z
		5	GEI505CE1.5	1.5	0.1	22.5	0.32	17	0.75	PBKV-46-404-01	PX-60Z
		6	GEJ505CE2.2	2.2	0.1	34.5	0.32	24	0.63	PBKV-46-404-02	PX-60Z
		7	GEJ505CE3.7	3.7	0.1	45.5	0.32	36.5	0.53	QRE-01A	PX-60Z
		8	GEK505CE5.5	5.5	0.1	58	0.32	51	0.39	QRE-01A	PX-60Z
65	50	9	GEH655CE1.5	1.5	0.2	15.8	0.63	10.5	0.81	PBKV-46-404-01	PX-60Z
		10	GEI655CE2.2	2.2	0.2	22.8	0.63	15.2	0.75	PBKV-46-404-02	PX-60Z
		11	GEJ655CE3.7	3.7	0.2	32.5	0.63	21	0.65	QRE-01A	PX-60Z
		12	GEK655CE5.5	5.5	0.2	45	0.63	34	0.52	QRE-01A	PX-85Z
		13	GEK655CE7.5	7.5	0.2	54.5	0.63	43.5	0.42	QRE-01A	PX-85Z
80	65	14	GEI805CE3.7	3.7	0.4	23	1.25	12	0.74	QRE-01A	PX-60Z
		15	GEJ805CE5.5	5.5	0.4	30.5	1.25	20	0.66	QRE-01A	PX-85Z
		16	GEJ805CE7.5	7.5	0.4	38.5	1.25	27.5	0.58	QRE-01A	PX-85Z

Supplementary Information 5 (SP5).

Life-cycle cost inventory (based on [8])

Group		Item	Unit of measure	Unit costs
Purchase of Materials	**Binders**	Hydrated Lime	€/kg	0.11
	Aggregates	Sand	€/kg	0.01
		Pumice	€/kg	0.06
		Polystyrene	€/kg	1.29
	Additives	Carboxymethyl celullose	€/kg	0.97
		Alkylbenzene sulfonate	€/kg	0.80
		Polycarboxyllate	€/kg	0.65
		Ethylene vinyl acetate	€/kg	1.12
Others		Carbon tax	€/kg	0.09
Transportation		Truck transportation	€/t.km	0.06
Electricity consumption		Electricity	€/kWh	0.11
End of Life		Sanitary landfilling	€/kg	0.02