

Supporting Information:

Identifying improvement potentials in cement production with life cycle assessment

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S1. LCI of Portland cement and blended cements

Air emissions. All units are kg substance per tonne of cement. 'Plant' includes all emissions at the cement kiln. 'Supply chain' includes emissions for electricity generation, and mining, transport and preparation of resources.

Table S1.1: LCI of clinker and cement production in Europe (rounded to 3 significant digits).

Product / Emissions	Clinker	CEM I (Portland cement)	CEM II (Portland-composite cement)	CEM III (Blastfurnace cement)	CEM IV (Pozzolan cement)	CEM V (Composite cement)
<i>Plant</i>						
CO ₂	846	784	639	277	538	338
NO _x	1.82	1.69	1.38	0.60	1.16	0.73
SO ₂	0.509	0.472	0.385	0.167	0.324	0.203
Dust	0.067	0.062	0.051	0.022	0.043	0.027
CH ₄	0.010	0.009	0.007	0.003	0.006	0.004
NM VOC	0.049	0.046	0.037	0.016	0.031	0.020
PAH	-	-	-	-	-	-
CO	2.56	2.37	1.93	0.84	1.63	1.02
HCl	0.0099	0.0092	0.0075	0.0032	0.0063	0.0040
Hg	4.65E-05	4.31E-05	3.51E-05	1.53E-05	2.96E-05	1.86E-05
Cd	1.37E-05	1.26E-05	1.03E-05	4.48E-06	8.69E-06	5.45E-06
Tl	3.29E-05	3.05E-05	2.48E-05	1.08E-05	2.09E-05	1.31E-05
Sb	1.61E-06	1.49E-06	1.21E-06	5.27E-07	1.02E-06	6.42E-07
As	7.69E-07	7.12E-07	5.81E-07	2.52E-07	4.89E-07	3.07E-07
Pb	2.12E-05	1.97E-05	1.60E-05	6.96E-06	1.35E-05	8.47E-06
Cr	1.14E-05	1.06E-05	8.64E-06	3.75E-06	7.28E-06	4.57E-06
Co	3.23E-06	2.99E-06	2.44E-06	1.06E-06	2.05E-06	1.29E-06
Cu	2.14E-05	1.98E-05	1.61E-05	7.00E-06	1.36E-05	8.52E-06
Mn	1.60E-04	1.49E-04	1.21E-04	5.26E-05	1.02E-04	6.40E-05
Ni	1.69E-05	1.57E-05	1.28E-05	5.54E-06	1.08E-05	6.74E-06
V	8.88E-05	8.22E-05	6.71E-05	2.91E-05	5.65E-05	3.54E-05
Sn	2.61E-06	2.42E-06	1.97E-06	8.55E-07	1.66E-06	1.04E-06
Zn	6.92E-05	6.41E-05	5.22E-05	2.27E-05	4.40E-05	2.76E-05
PCDD/F	3.72E-11	3.45E-11	2.81E-11	1.22E-11	2.37E-11	1.49E-11
<i>Supply chain</i>						
CO ₂	85	103	90	70	79	66
NO _x	0.306	0.333	0.294	0.233	0.271	0.233
SO ₂	0.490	0.542	0.458	0.288	0.391	0.293
Dust	0.407	0.493	0.431	0.214	0.350	0.277
CH ₄	0.463	0.476	0.398	0.226	0.341	0.243
NM VOC	0.101	0.099	0.084	0.050	0.075	0.055
PAH	1.01E-05	1.53E-05	1.39E-05	1.08E-05	1.27E-05	1.09E-05
CO	0.100	0.143	0.130	0.109	0.123	0.110
HCl	0.0044	0.0060	0.0052	0.0040	0.0045	0.0037
Hg	6.28E-06	9.13E-06	8.08E-06	6.45E-06	7.19E-06	6.18E-06
Cd	6.90E-06	1.15E-05	1.03E-05	8.27E-06	9.28E-06	8.07E-06
Tl	1.32E-07	1.27E-07	1.05E-07	5.98E-08	9.01E-08	6.00E-08
Sb	2.00E-06	3.84E-06	3.50E-06	3.00E-06	3.17E-06	2.86E-06
As	1.47E-05	2.88E-05	2.63E-05	2.26E-05	2.38E-05	2.16E-05
Pb	4.96E-05	9.52E-05	8.70E-05	7.49E-05	7.97E-05	7.21E-05
Cr	6.75E-05	7.24E-05	6.12E-05	3.53E-05	5.29E-05	3.83E-05
Co	6.54E-06	7.62E-06	6.50E-06	4.34E-06	5.57E-06	4.31E-06
Cu	5.35E-05	9.97E-05	9.15E-05	8.27E-05	8.53E-05	7.91E-05
Mn	3.09E-05	3.84E-05	3.32E-05	2.22E-05	2.90E-05	2.26E-05
Ni	9.43E-05	1.27E-04	1.11E-04	8.09E-05	9.77E-05	8.01E-05
V	1.43E-04	1.63E-04	1.39E-04	9.22E-05	1.18E-04	9.07E-05
Sn	1.94E-06	4.08E-06	3.75E-06	3.26E-06	3.45E-06	3.15E-06
Zn	6.00E-05	1.15E-04	1.06E-04	9.56E-05	1.00E-04	9.32E-05
PCDD/F	1.87E-11	3.68E-11	3.39E-11	3.00E-11	3.20E-11	2.94E-11
<i>Total</i>						
CO ₂	931	887	729	347	617	404
NO _x	2.13	2.02	1.67	0.83	1.43	0.96
SO ₂	1.000	1.014	0.843	0.455	0.715	0.496
Dust	0.474	0.555	0.481	0.236	0.393	0.303
CH ₄	0.473	0.486	0.406	0.230	0.347	0.247
NM VOC	0.151	0.145	0.122	0.066	0.106	0.075
PAH	1.01E-05	1.53E-05	1.39E-05	1.08E-05	1.27E-05	1.09E-05
CO	2.66	2.51	2.06	0.95	1.75	1.13
HCl	0.0143	0.0152	0.0127	0.0072	0.0108	0.0077
Hg	5.28E-05	5.22E-05	4.32E-05	2.17E-05	3.68E-05	2.47E-05
Cd	2.06E-05	2.41E-05	2.06E-05	1.27E-05	1.80E-05	1.35E-05
Tl	3.30E-05	3.06E-05	2.49E-05	1.08E-05	2.10E-05	1.32E-05
Sb	3.61E-06	5.33E-06	4.71E-06	3.53E-06	4.19E-06	3.50E-06
As	1.55E-05	2.95E-05	2.69E-05	2.29E-05	2.43E-05	2.19E-05
Pb	7.08E-05	1.15E-04	1.03E-04	8.18E-05	9.32E-05	8.06E-05
Cr	7.89E-05	8.30E-05	6.98E-05	3.91E-05	6.02E-05	4.29E-05
Co	9.77E-06	1.06E-05	8.94E-06	5.40E-06	7.62E-06	5.60E-06
Cu	7.49E-05	1.20E-04	1.08E-04	8.97E-05	9.89E-05	8.76E-05
Mn	1.91E-04	1.87E-04	1.54E-04	7.47E-05	1.31E-04	8.67E-05
Ni	1.11E-04	1.43E-04	1.24E-04	8.64E-05	1.08E-04	8.68E-05
V	2.32E-04	2.45E-04	2.06E-04	1.21E-04	1.74E-04	1.26E-04
Sn	4.55E-06	6.50E-06	5.73E-06	4.11E-06	5.11E-06	4.19E-06
Zn	1.29E-04	1.79E-04	1.58E-04	1.18E-04	1.44E-04	1.21E-04
PCDD/F	5.59E-11	7.12E-11	6.20E-11	4.22E-11	5.57E-11	4.42E-11

Table S1.2: LCI of clinker and cement production in the USA (rounded to 3 significant digits).

Product / Emissions	Clinker	PC (Portland cement)	I (SM) (Slag modified Portland cement)	IS (Portland blast furnace slag cement)	S (Slag cement)	I (PM) (Pozzolan modified Portland cement)	IP / P (Portland pozzolan cement)
<i>Plant</i>							
CO ₂	933	842	753	466	132	797	643
NO _x	2.54	2.30	2.05	1.27	0.36	2.17	1.75
SO ₂	1.74	1.57	1.40	0.87	0.25	1.48	1.20
Dust	0.211	0.191	0.171	0.106	0.030	0.180	0.146
CH ₄	0.039	0.036	0.032	0.020	0.006	0.034	0.027
NMVOC	0.005	0.005	0.004	0.003	0.001	0.004	0.004
PAH	-	-	-	-	-	-	-
CO	1.094	0.987	0.883	0.547	0.155	0.934	0.753
HCl	0.0736	0.0664	0.0594	0.0368	0.0105	0.0629	0.0507
Hg	6.56E-05	5.92E-05	5.30E-05	3.28E-05	9.32E-06	5.60E-05	4.52E-05
Cd	1.42E-06	1.28E-06	1.15E-06	7.10E-07	2.02E-07	1.21E-06	9.78E-07
Tl	4.92E-06	4.44E-06	3.97E-06	2.46E-06	6.99E-07	4.20E-06	3.39E-06
Sb	6.07E-07	5.48E-07	4.90E-07	3.04E-07	8.62E-08	5.18E-07	4.18E-07
As	4.34E-07	3.92E-07	3.50E-07	2.17E-07	6.16E-08	3.71E-07	2.99E-07
Pb	9.92E-06	8.95E-06	8.01E-06	4.96E-06	1.41E-06	8.47E-06	6.83E-06
Cr	5.09E-06	4.59E-06	4.11E-06	2.55E-06	7.23E-07	4.35E-06	3.51E-06
Co	1.30E-06	1.17E-06	1.05E-06	6.50E-07	1.85E-07	1.11E-06	8.96E-07
Cu	7.02E-06	6.34E-06	5.67E-06	3.51E-06	9.97E-07	6.00E-06	4.84E-06
Mn	7.32E-05	6.61E-05	5.91E-05	3.66E-05	1.04E-05	6.25E-05	5.04E-05
Ni	5.81E-06	5.24E-06	4.69E-06	2.91E-06	8.25E-07	4.96E-06	4.00E-06
V	2.99E-05	2.70E-05	2.41E-05	1.50E-05	4.25E-06	2.55E-05	2.06E-05
Sn	2.80E-06	2.53E-06	2.26E-06	1.40E-06	3.98E-07	2.39E-06	1.93E-06
Zn	8.51E-05	7.68E-05	6.87E-05	4.26E-05	1.21E-05	7.27E-05	5.86E-05
PCDD/F	1.57E-10	1.41E-10	1.26E-10	7.83E-11	2.22E-11	1.34E-10	1.08E-10
<i>Supply chain</i>							
CO ₂	98	140	138	117	97	135	115
NO _x	0.418	0.491	0.476	0.390	0.299	0.479	0.413
SO ₂	0.570	0.827	0.799	0.655	0.495	0.790	0.659
Dust	0.754	0.538	0.494	0.342	0.168	0.513	0.421
CH ₄	0.579	0.614	0.571	0.415	0.235	0.585	0.483
NMVOC	0.076	0.084	0.079	0.060	0.038	0.081	0.070
PAH	1.93E-05	2.95E-05	2.88E-05	2.47E-05	2.01E-05	2.85E-05	2.47E-05
CO	0.068	0.131	0.131	0.121	0.112	0.130	0.120
HCl	0.0151	0.0225	0.0221	0.0190	0.0157	0.0215	0.0180
Hg	3.14E-06	5.75E-06	5.64E-06	4.89E-06	4.24E-06	5.64E-06	5.00E-06
Cd	6.43E-06	1.20E-05	1.18E-05	1.05E-05	8.91E-06	1.17E-05	1.03E-05
Tl	2.23E-08	2.92E-07	2.63E-07	1.61E-07	5.85E-08	2.80E-07	2.23E-07
Sb	1.94E-06	4.06E-06	4.01E-06	3.64E-06	3.22E-06	3.94E-06	3.52E-06
As	1.89E-05	3.68E-05	3.62E-05	3.25E-05	2.81E-05	3.56E-05	3.15E-05
Pb	5.17E-05	1.05E-04	1.04E-04	9.35E-05	8.19E-05	1.02E-04	9.18E-05
Cr	7.02E-05	7.65E-05	7.10E-05	5.13E-05	2.86E-05	7.31E-05	6.10E-05
Co	5.05E-06	6.72E-06	6.47E-06	5.28E-06	3.92E-06	6.43E-06	5.43E-06
Cu	5.70E-05	1.10E-04	1.09E-04	9.96E-05	8.88E-05	1.08E-04	9.74E-05
Mn	1.52E-05	2.78E-05	2.73E-05	2.41E-05	2.06E-05	2.68E-05	2.34E-05
Ni	6.19E-05	1.00E-04	9.77E-05	8.41E-05	6.85E-05	9.70E-05	8.48E-05
V	8.06E-05	1.01E-04	9.75E-05	7.90E-05	5.79E-05	9.71E-05	8.14E-05
Sn	2.30E-06	4.67E-06	4.58E-06	4.08E-06	3.53E-06	4.54E-06	4.08E-06
Zn	5.63E-05	1.22E-04	1.20E-04	1.08E-04	9.43E-05	1.20E-04	1.10E-04
PCDD/F	7.89E-11	1.16E-10	1.13E-10	9.48E-11	7.47E-11	1.12E-10	9.59E-11
<i>Total</i>							
CO ₂	1030	982	891	584	229	932	758
NO _x	2.96	2.79	2.53	1.66	0.66	2.65	2.17
SO ₂	2.31	2.39	2.20	1.52	0.74	2.27	1.85
Dust	0.966	0.729	0.665	0.448	0.198	0.693	0.567
CH ₄	0.619	0.649	0.603	0.435	0.241	0.618	0.510
NMVOC	0.081	0.089	0.084	0.063	0.038	0.086	0.073
PAH	1.93E-05	2.95E-05	2.88E-05	2.47E-05	2.01E-05	2.85E-05	2.47E-05
CO	1.16	1.12	1.01	0.67	0.27	1.06	0.87
HCl	0.0887	0.0889	0.0815	0.0558	0.0261	0.0844	0.0687
Hg	6.88E-05	6.50E-05	5.86E-05	3.77E-05	1.36E-05	6.17E-05	5.02E-05
Cd	7.85E-06	1.33E-05	1.30E-05	1.12E-05	9.11E-06	1.29E-05	1.13E-05
Tl	4.94E-06	4.73E-06	4.23E-06	2.62E-06	7.57E-07	4.48E-06	3.61E-06
Sb	2.55E-06	4.61E-06	4.50E-06	3.94E-06	3.30E-06	4.46E-06	3.94E-06
As	1.94E-05	3.72E-05	3.66E-05	3.27E-05	2.82E-05	3.60E-05	3.18E-05
Pb	6.16E-05	1.14E-04	1.12E-04	9.85E-05	8.33E-05	1.11E-04	9.87E-05
Cr	7.53E-05	8.11E-05	7.51E-05	5.38E-05	2.93E-05	7.75E-05	6.45E-05
Co	6.35E-06	7.89E-06	7.52E-06	5.93E-06	4.11E-06	7.54E-06	6.32E-06
Cu	6.40E-05	1.16E-04	1.15E-04	1.03E-04	8.98E-05	1.14E-04	1.02E-04
Mn	8.84E-05	9.38E-05	8.64E-05	6.07E-05	3.10E-05	8.94E-05	7.39E-05
Ni	6.77E-05	1.06E-04	1.02E-04	8.70E-05	6.93E-05	1.02E-04	8.88E-05
V	1.11E-04	1.28E-04	1.22E-04	9.40E-05	6.21E-05	1.23E-04	1.02E-04
Sn	5.10E-06	7.19E-06	6.84E-06	5.48E-06	3.92E-06	6.93E-06	6.01E-06
Zn	1.41E-04	1.99E-04	1.89E-04	1.51E-04	1.06E-04	1.93E-04	1.69E-04
PCDD/F	2.36E-10	2.58E-10	2.39E-10	1.73E-10	9.70E-11	2.46E-10	2.04E-10

Plant: CO₂ emissions are calculated based on average energy efficiency and resource mix. NO_x, SO₂, dust, CO, HCl, Hg emissions for Europe and the USA are from (1) and (2), respectively. PCDD/F emissions reported in (2) were divided by a factor of 1000 according to (3). All heavy metals except Hg were calculated with the clinker production model presented in (4) as they are not reported in the data sources. It was assumed that in European production, 14% of VOC (volatile organic carbon) emissions are CH₄ (methane) and 86% unspecified NMVOC (non-methane VOC) (5). PAH emission data at cement kilns are not considered because no data were available.

Supply chain emissions: all emissions are calculated from ecoinvent data (6).

Please note that table 1.1 and 1.2 show CO₂ emissions, while the result category 'climate change' (unit: CO₂-Equivalents) in the following tables takes into account all greenhouse gases.

S2. LCIA results of Portland cement and blended cements

Table S2.1: Life Cycle Impact Assessment (LCIA) results of cement production in Europe (rounded to 3 significant digits).

	Mineral component content ^{a,b}		Climate change (kg CO ₂ -Eq)	CExD, non-renew. (MJ-Eq)	Acidification (kg SO ₂ -Eq)	Eutrophication (kg PO ₄ ³⁻ -Eq)	Human toxicity (kg 1,4-DCB-Eq)
European cement types - main categories							
Portland cement CEM I	Avg.	2.5%	903	6140	2.26	0.294	46.1
	Max.	5.0%	880	5990	2.21	0.287	45.2
	Min.	0.0%	926	6290	2.32	0.302	47.0
Portland composite cement CEM II	Avg.	20.5%	742	5120	1.88	0.244	40.2
	Max.	35.0%	612	4290	1.56	0.203	35.4
	Min.	6.0%	872	5950	2.19	0.285	45.0
Blast furnace cement CEM III	Avg.	65.5%	354	2850	0.98	0.123	28.0
	Max.	95.0%	97	1300	0.37	0.042	19.5
	Min.	36.0%	612	4400	1.58	0.203	36.5
Pozzolanic cement CEM IV	Avg.	33.0%	628	4370	1.60	0.209	35.5
	Max.	55.0%	431	3110	1.12	0.148	27.9
	Min.	11.0%	826	5650	2.08	0.271	43.1
Composite cement CEM V	Avg.	58.0%	412	3080	1.09	0.141	28.5
	Max.	80.0%	217	1860	0.63	0.080	21.5
	Min.	36.0%	607	4300	1.56	0.202	35.5
European cement types - subcategories							
Portland composite cement CEM II / A	Avg.	13.0%	810	5550	2.04	0.265	42.7
	Max.	20.0%	741	5110	1.87	0.244	40.1
	Min.	6.0%	872	5950	2.19	0.285	45.0
Portland composite cement CEM II / B	Avg.	28.0%	675	4690	1.72	0.223	37.7
	Max.	35.0%	612	4290	1.56	0.203	35.4
	Min.	21.0%	742	5120	1.88	0.244	40.2
Blast furnace cement CEM III / A	Avg.	50.5%	524	4910	1.42	0.334	47.5
	Max.	65.0%	354	2840	0.97	0.123	27.9
	Min.	36.0%	612	4400	1.58	0.203	36.5
Blast furnace cement CEM III / B	Avg.	73.0%	289	2460	0.82	0.102	25.8
	Max.	80.0%	223	2060	0.67	0.082	23.6
	Min.	66.0%	354	2850	0.98	0.123	28.0
Blast furnace cement CEM III / C	Avg.	88.0%	158	1660	0.52	0.061	21.5
	Max.	95.0%	97	1300	0.37	0.042	19.5
	Min.	81.0%	223	2060	0.67	0.082	23.6
Pozzolanic cement CEM IV / A	Avg.	23.0%	718	4950	1.81	0.237	39.0
	Max.	35.0%	610	4250	1.55	0.203	34.8
	Min.	11.0%	826	5650	2.08	0.271	43.1
Pozzolanic cement CEM IV / B	Avg.	45.5%	517	3650	1.33	0.174	31.2
	Max.	55.0%	430	3090	1.12	0.147	27.8
	Min.	36.0%	602	4190	1.53	0.199	34.3
Composite cement CEM V / A	Avg.	48.0%	500	3640	1.30	0.169	31.7
	Max.	60.0%	412	3090	1.09	0.142	28.5
	Min.	36.0%	607	4300	1.56	0.202	35.5
Composite cement CEM V / B	Avg.	61.0%	386	2920	1.03	0.133	27.5
	Max.	80.0%	217	1860	0.63	0.080	21.5
	Min.	42.0%	554	3970	1.43	0.185	33.6

^a Mineral component content is in addition to clinker

^b The average mineral component contents show the midpoints of the allowable ranges, not the average contents of the respective produced cements.

In this study, a gypsum content of 5% relative to the weight of contained clinker is assumed for all cements. The range of mineral component contents is reported in the European cement standard EN-197-1. The average blended cement minerals composition of CEM II is calculated from the market shares of the different CEM II types (7) (of CEM I, III-V only one type exists).

Table S2.2: Life Cycle Impact Assessment (LCIA) results of cement production in the USA (rounded to 3 significant digits).

	Mineral component content ^{a,b}		Climate change (kg CO ₂ -Eq)	CExD, non-renew. (MJ-Eq)	Acidification (kg SO ₂ -Eq)	Eutrophication (kg PO ₄ ³⁻ -Eq)	Human toxicity (kg 1,4-DCB-Eq)
U.S. cement types - main categories							
Portland cement	Avg.	5.0%	1000	6440	4.39	0.388	58.7
	Max.	10.0%	949	6140	4.17	0.368	56.6
	Min.	0.0%	1050	6750	4.60	0.408	61.0
Slag modified portland cement I(SM)	Avg.	15.0%	907	5970	4.02	0.353	56.6
	Max.	25.0%	811	5450	3.62	0.316	53.6
	Min.	5.0%	1000	6490	4.41	0.390	59.5
Portland blast-furnace slag cement IS	Avg.	47.5%	596	4280	2.74	0.234	47.0
	Max.	70.0%	380	3100	1.85	0.152	40.3
	Min.	25.0%	811	5450	3.62	0.316	53.6
Slag cement S	Avg.	85.0%	237	2320	1.26	0.097	35.8
	Max.	100.0%	92.8	1530	0.67	0.042	31.4
	Min.	70.0%	380	3100	1.85	0.152	40.3
Pozzolan-modified portland cement I(PM)	Avg.	10.0%	949	6140	4.17	0.370	56.5
	Max.	15.0%	898	5830	3.95	0.350	54.2
	Min.	5.0%	1000	6440	4.39	0.389	58.7
Portland pozzolan cement IP / P	Avg.	27.5%	772	5060	3.40	0.303	48.5
	Max.	40.0%	645	4290	2.86	0.255	42.8
	Min.	15.0%	898	5830	3.95	0.350	54.2

^a Mineral component content is in addition to clinker

^b The average mineral component contents show the midpoints of the allowable ranges, not the average contents of the respective produced cements.

In this study, a gypsum content of 5% relative to the weight of contained clinker is assumed for all cements. The minimal content of mineral components in the U.S. cement types 'I (SM) and I (PM)' is not specified in the ASTM C595 standard and assumed 5% in this study.

S3. Fuels and wastes mixes

The fuel mix for Europe and the USA is from (8, 9) and (10), respectively. The waste mix for Europe used in this study (18% waste fuels) (8) is taken from (9) (reported for the year 2001 with 12% waste fuels).

Table S3.1: Fuel mix for clinker production in Europe

	% heat	kg CO ₂ / GJ	% biogenic
<i>Traditional fuels</i>			
Hard coal	24%	96	0%
Brown coal	5%	101	0%
Petcoke	48%	92.8	0%
Natural gas	1%	56.1	0%
Oil	4%	74	0%
<i>Wastes</i>			
Tires	3%	85	27%
Waste oil	3%	74	0%
Solvents	1%	74	0%
Other ^a	3%	83	30%
Animal meal, fat	3%	89	100%
Paper, cardboard, wood	1%	110	100%
Plastics	1%	75	0%
Impregnated saw dust	<1%	75	80%
Other (hazardous waste)	3%	75	0%

^aOther: biogenic content of 30% assumed.

Table S3.2: Fuel mix for clinker production in the USA

	% heat	kg CO ₂ / GJ	% biogenic
<i>Traditional fuels</i>			
Hard coal	65%	96.0	0%
Petcoke	21%	92.8	0%
Natural gas	3%	56.1	0%
Oil	1%	74	0%
<i>Wastes</i>			
Tires	4%	85	0%
Liquid wastes (mostly oils and solvents)	5%	74	0%
Other ^a	2%	83	30%

^aOther: biogenic content of 30% assumed.

S4. Resource characteristics

Fuels (traditional fuels and waste)

Table S4.1: Fuel characteristics

		Hard coal	Brown coal	Petcoke	Heavy oil	Natural gas	Tires	Waste oil	Solvents	Others (non-hazardous)	Animal meal	Paper, cardboard, wood	Plastics	Impregnated saw dust	Other hazardous	Sewage sludge
Unit		kg	kg	kg	kg	Nm3	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg
<i>Heating value</i>																
NCV (Net calorific value)	MJ	26.62	21.69	31.44	41.00	33.50	30.83	32.93	22.46	17.87	21.45	14.78	27.94	12.21	29.82	9.00
CO2 emission factor	kg / GJ	96.0	101.0	92.6	77.3	56.1	85.0	74.0	74.0	83.0	89.0	110.0	75.0	75.0	75.0	110.0
<i>Elemental analysis</i>																
H2O (as fired)	%	1.00	1.00	1.00	1.00	0.00	1.00	15.10	17.50	16.30	3.00	15.00	16.82	28.31	11.60	8.00
C org (TOC)	%	69.75	59.80	79.45	86.50	51.30	71.50	66.50	45.35	40.50	52.10	44.38	57.20	25.00	61.00	27.03
S	%	0.60	0.93	5.43	1.78	0.00	1.44	0.60	0.00	0.68	0.36	0.23	0.27	0.52	1.00	0.41
N	%	1.60	0.85	2.00	0.46	14.33	0.50	0.00	1.04	0.20	7.62	0.10	1.44	0.59	0.59	3.54
Cl	%	0.10	0.10	0.00	0.10	0.00	0.08	0.26	0.00	0.10	0.00	0.18	0.15	0.33	0.51	0.04
F	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H	%	3.82	13.03	6.40	6.82	17.07	7.17	10.05	8.15	5.00	6.94	5.02	5.25	5.50	5.50	4.00
O	%	9.01	17.30	5.00	3.33	17.30	7.90	1.70	19.34	17.67	10.04	34.49	8.30	16.28	14.50	12.64
Ash	%	12.86	4.74	0.50	0.00	0.00	9.08	5.22	8.50	16.70	19.79	0.60	10.23	19.72	4.79	38.00
Calcination CO2	%	1.23	2.23	0.09	0.00	0.00	0.18	0.53	0.00	2.72	0.00	0.00	0.30	3.45	0.38	6.11
<i>Trace elements</i>																
Cd	ppm	0.28	1.00	0.00	0.00	0.00	12.38	3.32	3.12	1.54	1.38	0.25	0.95	4.00	1.83	1.57
Hg	ppm	0.16	0.10	0.02	0.01	0.00	0.27	0.42	0.82	0.40	2.27	0.02	0.02	1.00	18.28	0.89
Tl	ppm	0.88	3.00	0.00	0.00	0.00	7.29	2.11	3.73	3.30	3.70	10.00	1.09	3.00	4.00	0.23
Sb	ppm	0.99	2.00	0.00	0.00	0.00	0.86	5.51	13.45	0.00	4.56	5.00	1.84	18.00	2.53	5.00
As	ppm	4.85	10.00	0.34	0.80	0.00	6.91	2.56	3.63	6.20	4.36	37.00	0.83	4.00	5.60	5.30
Pb	ppm	20.92	20.00	2.18	9.00	0.00	21.38	25.28	145.15	125.00	17.90	7.00	37.91	403.00	40.22	70.33
Cr	ppm	19.00	20.00	4.68	0.30	0.00	28.88	12.91	82.85	80.00	6.21	42.00	8.30	159.00	8.23	71.00
Co	ppm	5.84	10.00	0.00	2.00	0.00	17.73	4.72	9.54	19.50	1.52	1.00	9.38	22.00	5.96	7.33
Cu	ppm	13.62	20.00	0.00	1.00	0.00	70.03	70.95	197.28	268.60	8.49	44.00	102.79	372.00	47.55	358.33
Mn	ppm	92.08	40.00	0.00	0.00	0.00	166.07	15.38	13.05	268.00	12.50	40.00	43.23	259.00	9.50	321.00
Ni	ppm	17.00	20.00	300.00	30.00	0.00	5.80	16.91	44.33	36.70	4.21	2.50	3.65	109.00	4.96	33.67
V	ppm	31.38	40.00	1000.00	60.00	0.00	3.79	1.83	25.31	0.00	3.39	5.00	0.50	25.00	2.79	23.67
Sn	ppm	13.13	8.00	0.00	0.00	0.00	7.21	12.87	36.78	0.00	14.00	0.00	142.50	59.00	133.25	460.00
Zn	ppm	35.31	50.00	0.00	3.50	0.00	11258.00	289.89	629.84	543.00	70.35	91.00	214.69	1562.00	973.91	867.70
<i>Ash composition</i>																
SiO2	%	49.15	8.14	8.18	0.00	0.00	8.01	36.34	0.00	28.78	3.48	49.30	0.00	35.74	60.32	26.53
Al2O3	%	26.85	5.12	3.38	0.00	0.00	2.03	26.21	0.00	16.38	0.23	13.59	14.55	7.91	7.50	18.59
Fe2O3	%	4.55	4.88	6.89	0.00	0.00	78.62	6.28	0.00	16.11	0.53	13.87	45.37	16.33	2.25	16.04
CaO	%	8.99	37.79	22.28	0.00	0.00	0.81	13.00	0.00	15.47	52.44	7.25	2.82	19.05	7.44	17.24
MgO	%	2.33	15.93	0.67	0.00	0.00	1.20	0.00	0.00	3.77	1.36	2.63	0.62	2.32	1.92	2.34
SO3	%	5.92	22.79	57.25	0.00	0.00	7.19	18.17	0.00	16.60	1.02	5.44	0.00	6.55	10.93	1.98
K2O	%	0.42	0.70	1.16	0.00	0.00	0.14	0.00	0.00	1.02	1.59	2.69	7.59	1.76	1.68	1.41
Na2O	%	0.63	4.19	0.06	0.00	0.00	1.75	0.00	0.00	1.84	4.22	4.37	29.05	6.25	7.95	0.74
P2O5	%	1.16	0.47	0.13	0.00	0.00	0.25	0.00	0.00	0.03	35.14	0.86	0.00	4.08	0.00	15.13
<i>Characteristics</i>																
Biogenic C / Total C	%	0%	0%	0%	0%	0%	27%	0%	0%	30%	100%	100%	0%	80%	0%	100%

Chemical composition of traditional fuels and waste fuels is from (11). Heavy metals contents of traditional fuels are from (6). Data for N, H, O was not reported and is based on (6, 12-16). CO₂ emission factors applied in this study are CSI/IPCC defaults (17). The elemental compositions shown in this table are exemplary. In reality, large variations occur for all elements.

Raw materials

Table S4.2: Raw material characteristics

		Raw meal Europe (base)	Raw meal US (base)	Limestone	Clay	Iron ore	Slag	Fly ash	Waste limestone	Contaminated soil
	Unit	kg	kg	kg	kg	kg	kg	kg	kg	kg
<i>Main elements</i>										
H ₂ O (in kiln feed)	%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
TOC (C org)	%	0.23	0.23	0.20	0.40	0.20	0.20	4.50	2.00	5.00
Cl	%	0.01	0.01	0.01	0.02	0.05	0.02	0.03	0.11	0.05
SiO ₂	%	13.90	13.64	6.90	61.00	1.28	37.19	41.41	0.97	62.06
Al ₂ O ₃	%	3.34	3.28	1.63	14.62	2.45	12.95	22.34	1.30	5.78
Fe ₂ O ₃	%	2.47	2.45	0.73	6.55	77.21	0.80	10.52	1.33	2.55
CaO	%	42.75	42.97	48.97	5.40	8.59	39.39	8.94	46.03	9.17
MgO	%	0.68	0.68	0.66	0.86	0.08	5.94	1.76	1.48	2.49
SO ₃	%	0.61	0.60	0.33	2.44	0.42	0.09	1.38	0.25	0.26
K ₂ O	%	0.51	0.50	0.29	1.90	0.88	0.61	1.86	0.02	1.16
Na ₂ O	%	0.17	0.17	0.10	0.57	0.72	0.48	0.87	8.74	0.57
P ₂ O ₅	%	0.00	0.00	0.00	0.00	0.07	0.00	4.83	0.04	0.14
Calcination CO ₂	%	34.17	34.33	38.97	5.36	6.82	0.00	0.00	37.74	9.92
<i>Trace elements</i>										
Cd	ppm	0.45	0.45	0.10	0.37	25.00	0.00	1.74	2.00	4.00
Hg	ppm	0.01	0.01	0.01	0.02	0.25	0.00	0.01	0.01	3.00
Tl	ppm	0.13	0.13	0.14	0.09	0.10	0.00	7.80	3.00	4.00
Sb	ppm	1.18	1.18	1.00	0.80	17.00	0.00	0.43	0.50	5.00
As	ppm	0.82	0.82	0.70	0.70	10.00	80.00	68.90	1.00	7.00
Pb	ppm	10.45	10.42	0.20	10.00	700.00	50.00	136.50	60.00	36.00
Cr	ppm	25.55	25.28	14.80	71.00	280.00	28.40	11.73	2.00	19.00
Co	ppm	3.92	3.83	1.00	21.00	25.00	8.42	0.00	0.00	5.00
Cu	ppm	2.30	2.23	0.50	14.00	3.20	42.00	43.80	0.00	28.00
Mn	ppm	254.49	253.51	204.00	414.00	2000.00	0.00	16.00	112.00	0.00
Ni	ppm	5.66	5.50	1.00	33.70	31.00	24.27	18.32	0.50	13.00
V	ppm	16.88	16.32	1.10	116.00	60.00	22.56	85.00	0.00	23.00
Sn	ppm	1.41	1.39	1.00	4.20	0.00	6.90	0.00	0.00	4.00
Zn	ppm	27.45	27.10	15.00	87.70	244.70	5.84	147.40	130.00	87.00

Chemical composition of the raw meal is calculated to obtain clinker of adequate quality from the raw materials limestone and clay and iron ore (Fe-corrective) from (11). The four alternative raw materials slag, fly ash, waste limestone and contaminated soil replace these traditional raw materials in the improvement scenarios (See Supporting Information S6). Chemical composition of raw materials is from (11). Mineral composition has been amended that total mass sums up to 100%. Data for TOC was not reported and is based on (18, 19). The elemental compositions shown in this table are exemplary. In reality, large variations occur for all elements.

The current raw material mix in Europe (20) and the USA (2) is shown in the table S4.3.

Table S4.3: Raw material mix for clinker production in Europe and the USA

Europe	USA	Raw material type
93.5%	92.0%	Total traditional raw materials (limestone, marl, clay, shale)
6.5%	8.0%	Total alternative raw materials (listed below)
0.7%	2.7%	Si-source (e.g. sand, foundry sand)
1.1%	0.0%	Ca-source (e.g. waste limestone, spent lime)
1.5%	2.1%	Fe-source (e.g. iron ore, mill scale, pyrite ash)
0.3%	0.0%	Al-source (e.g. spent pot liner, ind. sludge)
1.8%	1.5%	Si-Al-Ca-Fe source (e.g. fly ash, slag, bottom ash)
0.3%	0.0%	Soil (e.g. contaminated soil)
0.8%	1.7%	Others

S5. Preparation of resources

Production supply chain of traditional resources is from the LCI database ecoinvent (6). Average transportation of wastes is assumed 100 km by lorry. Electricity and heat consumption is from (4) and (11).

Table S5.1: Preparation of resources

<i>Clinker production</i>	Preparation	
Unit	kWh_{el} / t	MJ heat / t
<i>Traditonal fuels</i>		
Hard coal	0 ^a	0 ^b
Brown coal	0 ^a	0 ^b
Petcoke	0 ^a	0 ^b
Natural gas	0 ^a	-
Oil	0 ^a	200 ^b
<i>Waste fuels</i>		
Tires	0 / 40 ^c	-
Waste oil	-	-
Solvents	-	-
Other (non-hazardous)	35 / 80 ^d	-
Animal meal	-	-
Plastics	35 / 80 ^d	-
Paper, cardboard, wood	25	-
Impregnated saw dust	40	250
Other (hazardous)	40	250
Sewage sludge (dry)	243	6265
<i>Raw materials</i>		
All raw materials	0 ^a	-

<i>Cement blending and grinding</i>	Preparation		Grinding electricity relative to Portland cement (%)^g
Unit	kWh_{el} / t	MJ heat / t	
Portland cement ^e	-	-	100%
Limestone	-	-	70%
Pozzolana	-	-	90%
Flyash	-	-	40%
Slag	-	600 ^f	160%

^a Preparation of traditional fuels and of traditional and alternative raw materials occurs at the cement plant. The respective electricity consumption is included in the total electricity requirement of the plant. Preparation of waste fuels is assumed to be carried out at external waste preparation facilities. Energy consumption is added to the consumption at the plant.

^b The respective fuels are dried with waste heat from the kiln system. Oil requires heating due to its viscosity.

^c Tires can be fed to the kiln as whole pieces (no preparation) or shredded (40 kWh/t). In this study, 80% and 60% whole tires are assumed in Europe and the USA, respectively (11).

^d One or two stage shredding (35 kWh/t and 80 kWh/t, respectively) required for waste preparation. 50% one stage shredding and 50% two stage shredding is assumed in this study.

^e Grinding of Portland cement with 95% clinker and 5% gypsum.

^f Waste heat or heat from diesel-fuelled hot gas generator. 100% process waste heat is assumed in this study.

^g Electricity requirement for grinding cement components (21). Average electricity consumption for grinding cement is assumed to be 38 kWh/t in Europe and 57 kWh/t in the USA in this study (22, 23). Specific electricity consumption for cement grinding depends primarily on grinding technology, fineness, and cement components.

Depending on the process and resource characteristics, the numbers in these tables may vary. The sensitivity analysis S7 assesses the impact of varying heat and electricity requirements for clinker and cement production.

S6. Improved clinker and cement production scenarios

Fuel mix in improved clinker production assumed in this study

Table S6.1: Fuel and raw material substitution in the improved production scenario

<i>Fuel substitution</i>			
	% heat	kg CO ₂ / GJ	% biogenic
Traditional fossil fuel mix (Europe/U.S.)	50%	93.1 / 93.8 ^a	0%
Tires	8%	85	27%
Plastics	8%	75	0%
Solvents	8%	74	0%
Waste oil	8%	74	0%
Animal meal	7%	89	100%
Sewage sludge	7%	110	100%
Paper, cardboard, wood	4%	110	100%
<i>Raw material substitution</i>			
Slag		+1%	
Fly ash		+1%	
Waste limestone		+1%	
Contaminated soil		+1%	

^a Mix of fossil fuels used in actual production in Europe and the USA, extrapolated to 50% heat input.

LCIA results of improved clinker and cement production for Europe and the USA.

Scenario 1 analyzes improved energy efficiency

Scenario 2 analyzes 50% waste fuel substitution

Scenario 3 analyzes substitution of 4% alternative raw materials for traditional raw materials

Table S6.2: Life Cycle Impact Assessment (LCIA) results of improved production scenario for Europe (rounded to 3 significant digits).

Europe	Scenario #	Climate change (kg CO ₂ -Eq)	CExD, non-renew. (MJ-Eq)	Acidification (kg SO ₂ -Eq)	Eutrophication (kg PO ₄ ³⁻ -Eq)	Human toxicity (kg 1,4-DCB-Eq)
<i>Clinker (production of 1 tonne clinker)</i>						
Current average production	-	946	6050	2.29	0.307	35.6
Increased energy efficiency	1	913	5590	2.18	0.285	34.2
50% fuel substitution	2	889	4490	2.18	0.296	33.5
4% raw material substitution	3	944	6040	2.29	0.307	36.4
Improved production scenario	1-3	861	4200	2.08	0.276	33.5
<i>Cement (production of 1 tonne Portland cement)</i>						
Current average production	-	903	6140	2.26	0.294	46.1
Increased energy efficiency	1	872	5710	2.16	0.274	44.7
50% fuel substitution	2	850	4700	2.15	0.285	44.1
4% raw material substitution	3	901	6130	2.26	0.294	46.8
Improved production scenario	1-3	822	4380	2.05	0.265	43.6
<i>Cement types</i>						
CEM I	1-3	822	4380	2.05	0.265	43.6
CEM II	1-3	675	3680	1.70	0.220	38.1
CEM III	1-3	323	2180	0.89	0.112	26.6
CEM IV	1-3	572	3160	1.45	0.189	33.7
CEM V	1-3	375	2300	0.99	0.128	27.1

Table S6.3: Life Cycle Impact Assessment (LCIA) results of improved production scenario for the USA (rounded to 3 significant digits).

USA	Scenario #	Climate change (kg CO ₂ -Eq)	CExD, non-renew. (MJ-Eq)	Acidification (kg SO ₂ -Eq)	Eutrophication (kg PO ₄ ³⁻ -Eq)	Human toxicity (kg 1,4-DCB-Eq)
<i>Clinker (production of 1 tonne clinker)</i>						
Current average production	-	1050	6180	4.37	0.401	40.8
Increased energy efficiency	1	928	4860	4.00	0.327	36.1
50% fuel substitution	2	985	4770	4.47	0.409	44.1
4% raw material substitution	3	1050	6210	4.29	0.410	41.9
Improved production scenario	1-3	878	3600	3.98	0.326	35.4
<i>Cement (production of 1 tonne Portland cement)</i>						
Current average production	-	1000	6440	4.39	0.388	58.7
Increased energy efficiency	1	884	5140	3.96	0.309	45.7
50% fuel substitution	2	936	5070	4.39	0.384	52.9
4% raw material substitution	3	993	6370	4.23	0.384	50.8
Improved production scenario	1-3	820	3700	3.80	0.303	39.7
<i>Cement types</i>						
Portland cement	1-3	820	3700	3.80	0.303	39.7
Slag modified portland cement - I(SM)	1-3	744	3480	3.47	0.276	38.1
Portland blast-furnace slag cement - IS	1-3	489	2630	2.35	0.183	31.1
Slag cement - S	1-3	178	1380	0.94	0.072	18.5
Pozzolan modified portland cement - I(PM)	1-3	779	3540	3.61	0.289	38.0
Portland pozzolan cement - IP / P	1-3	635	2970	2.96	0.237	32.2

Detailed LCIA results for Climate change and Cumulative Exergy Demand, non-renewable

Table S6.4: Detailed Life Cycle Impact Assessment (LCIA) results for the methods Climate change and nonrenewable Cumulative Exergy Demand (rounded to 3 significant digits).

Climate change (kg CO₂-Eq. / tonne)

	Current production			Improved production scenario		
	Raw material calcination	Fuel combustion	Supply chain	Raw material calcination	Fuel combustion	Supply chain
<i>European cements</i>						
CEM I	486	297	120	485	220	116
CEM II	396	242	104	396	180	100
CEM III	172	105	77	172	78	74
CEM IV	334	204	91	333	151	88
CEM V	209	128	75	209	95	71
<i>U.S. cements</i>						
Portland cement	476	367	157	474	224	123
I (SM)	425	328	153	424	200	120
IS	264	203	129	263	124	102
S	75	58	104	75	35	68
I (PM)	450	347	152	448	212	119
IP / P	363	280	129	362	171	102

CExD, non-renewable (MJ_{ex}-Eq. / tonne)

	Current production			Improved production scenario		
	Fossil	Nuclear	Minerals + Metals	Fossil	Nuclear	Minerals + Metals
<i>European cements</i>						
CEM I	5380	582	176	3630	574	174
CEM II	4470	507	147	3030	498	146
CEM III	2370	409	73	1720	387	73
CEM IV	3820	429	125	2610	421	124
CEM V	2630	367	86	1860	353	84
<i>U.S. cements</i>						
Portland cement	5750	545	151	3160	414	125
I (SM)	5300	536	137	2960	408	113
IS	3720	464	92	2190	362	73
S	1900	382	40	1120	239	26
I (PM)	5470	521	144	3030	397	119
IP / P	4500	439	119	2530	341	97

S7. Sensitivity analysis

The sensitivity analysis is carried out regarding resource characteristics and supply chain of wastes used in clinker production, heat requirement in clinker production, and mineral components used in cement production.

Scenarios Se1-Se9 analyze the impact of varying heavy metals concentrations in resources, preparation efforts and transport distances of wastes, and different waste mixes. The scenario Se8 with 40% biogenic waste represents current maximum biomass use in Europe (24). Scenario Se9 represents an AFR co-processing rate presented in the reference document on best available technology (1).

Scenarios Se10-Se12 analyze the effect of different heat requirement assumption for best available technology (BAT). The heat requirement is calculated from the minimum of 2900 and the maximum of 3300 MJ/ t without waste co-processing (1) and adjusted to the current waste co-processing rate of 18%.

Scenarios Se13-Se19 analyze the impact of impact of different transport distances and preparation efforts of mineral components. Slag modified Portland cement in the USA has been selected for the analysis because in the USA, some granulated slag is imported from Europe and Japan.

Scenario Se20 analyzes the impact of different electricity consumption for cement grinding.

The scenarios Se1, Se6, Se10, Se13, Se14 (base case) refer to production described in Supporting Information S1-S6.

Table S7.1: LCIA results of sensitivity analysis (rounded to 3 significant digits).

	Scenario # (Sensitivity)	Climate change (kg CO ₂ -Eq)	CExD, non-renew. (MJ-Eq)	Acidification (kg SO ₂ -Eq)	Eutrophication (kg PO ₄ ³⁻ -Eq)	Human toxicity (kg 1,4-DCB-Eq)	Description of scenario
<i>Sensitivity analysis: waste co-processing in clinker production</i>							
Clinker	Se1	946	6050	2.29	0.307	35.6	Clinker production in Europe (base case)
Clinker	Se2	946	6050	2.29	0.307	36.0	Heavy metals in wastes x2
Clinker	Se3	946	6050	2.29	0.307	36.2	Heavy metals in traditional fuels x2
Clinker	Se4	946	6050	2.29	0.307	38.2	Heavy metals in raw meal x2
Clinker	Se5	948	6080	2.30	0.308	35.9	Preparation of wastes x2, Transport of waste x2
Clinker	Se6	889	4490	2.18	0.296	33.5	Clinker Europe, 50% wastes, 20% biogenic (base case)
Clinker	Se7	890	4500	2.18	0.296	35.1	Clinker Europe, 50% wastes with heavy metals x2
Clinker	Se8	834	4500	2.21	0.304	33.8	Clinker Europe, 50% waste, 40% biogenic
Clinker	Se9	841	2200	1.89	0.264	28.1	Clinker Europe, 83% waste, 19% biogenic
Clinker	Se10	913	5590	2.18	0.285	34.2	Clinker Europe, heat requirement: 3260 (base case)
Clinker	Se11	884	5190	2.08	0.266	32.9	Clinker Europe, heat requirement: 2950 MJ / t
Clinker	Se12	924	5740	2.22	0.293	34.7	Clinker Europe, heat requirement: 3360 MJ / t
<i>Sensitivity analysis: Transport distances and preparation of mineral components</i>							
Portland cement	Se13	1000	6440	4.39	0.388	58.7	Portland cement production in USA (base case)
Slag modified Portland cement (15% slag)	Se14	907	5970	4.02	0.353	56.6	Slag modified Portland cement (base case)
Slag modified Portland cement (15% slag)	Se15	915	6100	4.05	0.362	57.8	Transport distance slag x5 (lorry)
Slag modified Portland cement (15% slag)	Se16	924	6260	4.11	0.373	59.3	Transport distance slag x10 (lorry)
Slag modified Portland cement (15% slag)	Se17	918	6150	4.26	0.374	63.0	Transport distance slag x1 (lorry) + 7000 km by freighter
Slag modified Portland cement (15% slag)	Se18	926	6280	4.30	0.383	64.2	Transport distance slag x5 (lorry) + 7000 km by freighter
Slag modified Portland cement (15% slag)	Se19	915	6090	4.03	0.354	57.0	Heat source for slag drying: diesel-fueled hot gas generator instead of process waste heat
Slag modified Portland cement (15% slag)	Se20	933	6390	4.21	0.361	63.8	Electricity requirement for cement grinding + 50%

Predicted heavy metals emissions in clinker production options from the sensitivity analysis production scenarios Se1-Se12. Please note that the sensitivity analyses and the respective predicted emissions are calculated only for the scenarios Se1-Se12 described above. Further variations between individual plants as well as in fuel and raw materials characteristics (e.g. heavy metal contents) can be large but are not assessed.

Table S7.2: Predicted heavy metals emissions and heavy metal contents in clinker from the sensitivity analysis (kg / t clinker) (see table S7.1).

Scenario # (Sensitivity)	Se1	Se2	Se3	Se4	Se5	Se6	Se7	Se8	Se9	Se10	Se11	Se12
<i>Heavy metal emissions at plant</i>												
Hg	4.65E-05	8.23E-05	4.97E-05	5.42E-05	4.65E-05	4.03E-05	7.10E-05	5.72E-05	3.33E-05	4.30E-05	3.96E-05	4.41E-05
Cd	1.37E-05	1.51E-05	1.39E-05	2.56E-05	1.37E-05	1.64E-05	2.08E-05	1.52E-05	2.04E-05	1.35E-05	1.34E-05	1.35E-05
Tl	3.29E-05	4.31E-05	3.75E-05	5.09E-05	3.29E-05	4.64E-05	7.19E-05	5.00E-05	8.33E-05	3.15E-05	3.02E-05	3.19E-05
Sb	1.78E-06	1.87E-06	1.83E-06	3.44E-06	1.78E-06	2.12E-06	2.56E-06	2.15E-06	2.59E-06	1.77E-06	1.76E-06	1.78E-06
As	8.53E-07	9.56E-07	9.80E-07	1.48E-06	8.53E-07	1.04E-06	1.38E-06	1.25E-06	1.44E-06	8.33E-07	8.12E-07	8.39E-07
Pb	2.36E-05	2.55E-05	2.48E-05	4.40E-05	2.36E-05	2.73E-05	3.35E-05	2.74E-05	3.32E-05	2.33E-05	2.30E-05	2.34E-05
Cr	1.27E-05	1.30E-05	1.30E-05	2.48E-05	1.27E-05	1.34E-05	1.46E-05	1.35E-05	1.44E-05	1.27E-05	1.26E-05	1.27E-05
Co	3.58E-06	3.72E-06	3.73E-06	6.87E-06	3.58E-06	3.68E-06	4.04E-06	3.53E-06	4.00E-06	3.56E-06	3.54E-06	3.56E-06
Cu	2.37E-05	3.35E-05	2.57E-05	3.56E-05	2.37E-05	6.43E-05	1.16E-04	8.65E-05	6.75E-05	2.27E-05	2.17E-05	2.30E-05
Mn	1.78E-04	1.79E-04	1.79E-04	3.53E-04	1.78E-04	1.80E-04	1.85E-04	1.81E-04	1.80E-04	1.78E-04	1.78E-04	1.78E-04
Ni	1.88E-05	1.91E-05	3.10E-05	2.50E-05	1.88E-05	1.49E-05	1.62E-05	1.43E-05	1.09E-05	1.76E-05	1.66E-05	1.80E-05
V	9.86E-05	9.87E-05	1.66E-04	1.30E-04	9.86E-05	7.32E-05	7.45E-05	6.87E-05	4.76E-05	9.25E-05	8.69E-05	9.44E-05
Sn	2.61E-06	3.24E-06	2.97E-06	4.23E-06	2.61E-06	1.30E-05	2.42E-05	2.13E-05	5.28E-06	2.52E-06	2.44E-06	2.55E-06
Zn	6.92E-05	1.06E-04	7.04E-05	1.01E-04	6.92E-05	1.39E-04	2.46E-04	1.00E-04	2.57E-04	6.58E-05	6.27E-05	6.67E-05
<i>Heavy metals in clinker</i>												
Hg	6.23E-05	1.10E-04	6.65E-05	7.26E-05	6.23E-05	5.39E-05	9.51E-05	7.62E-05	4.46E-05	5.75E-05	5.30E-05	5.91E-05
Cd	8.09E-04	8.93E-04	8.26E-04	1.52E-03	8.09E-04	9.73E-04	1.23E-03	8.84E-04	1.21E-03	8.00E-04	7.92E-04	8.03E-04
Tl	3.73E-04	4.89E-04	4.26E-04	5.78E-04	3.73E-04	5.26E-04	8.16E-04	7.05E-04	9.45E-04	3.58E-04	3.43E-04	3.62E-04
Sb	1.98E-03	2.07E-03	2.03E-03	3.82E-03	1.98E-03	2.35E-03	2.84E-03	2.36E-03	2.87E-03	1.97E-03	1.96E-03	1.97E-03
As	1.75E-03	1.96E-03	2.01E-03	3.03E-03	1.75E-03	2.13E-03	2.84E-03	2.86E-03	2.95E-03	1.71E-03	1.67E-03	1.72E-03
Pb	1.88E-02	2.03E-02	1.98E-02	3.51E-02	1.88E-02	2.18E-02	2.67E-02	2.04E-02	2.65E-02	1.86E-02	1.84E-02	1.86E-02
Cr	4.18E-02	4.28E-02	4.29E-02	8.17E-02	4.18E-02	4.41E-02	4.81E-02	4.38E-02	4.75E-02	4.17E-02	4.16E-02	4.17E-02
Co	6.65E-03	6.91E-03	6.93E-03	1.28E-02	6.65E-03	6.85E-03	7.51E-03	6.61E-03	7.43E-03	6.62E-03	6.58E-03	6.63E-03
Cu	7.12E-03	1.00E-02	7.73E-03	1.07E-02	7.12E-03	1.93E-02	3.47E-02	1.71E-02	2.03E-02	6.80E-03	6.50E-03	6.89E-03
Mn	4.03E-01	4.05E-01	4.06E-01	8.00E-01	4.03E-01	4.07E-01	4.19E-01	4.05E-01	4.08E-01	4.03E-01	4.03E-01	4.03E-01
Ni	2.65E-02	2.69E-02	4.37E-02	3.53E-02	2.65E-02	2.10E-02	2.29E-02	2.06E-02	1.54E-02	2.49E-02	2.34E-02	2.54E-02
V	8.27E-02	8.28E-02	1.39E-01	1.09E-01	8.27E-02	6.14E-02	6.25E-02	6.13E-02	3.99E-02	7.76E-02	7.29E-02	7.92E-02
Sn	3.53E-03	4.37E-03	4.02E-03	5.72E-03	3.53E-03	1.76E-02	3.28E-02	1.65E-02	7.13E-03	3.41E-03	3.30E-03	3.44E-03
Zn	9.34E-02	1.42E-01	9.50E-02	1.36E-01	9.34E-02	1.88E-01	3.32E-01	1.19E-01	3.48E-01	8.89E-02	8.46E-02	9.00E-02

Analysis of heavy metal inputs by input category

Table S7.3: Analysis of heavy metal inputs from the sensitivity analysis (see table S7.1)

Scenario # (Sensitivity)	Se1			Se2			Se3			Se4			Se5			Se6		
	Traditional fuels	Raw materials	Waste fuels	Traditional fuels	Raw materials	Waste fuels	Traditional fuels	Raw materials	Waste fuels	Traditional fuels	Raw materials	Waste fuels	Traditional fuels	Raw materials	Waste fuels	Traditional fuels	Raw materials	Waste fuels
Hg	7%	16%	77%	4%	9%	87%	13%	15%	72%	6%	28%	66%	7%	16%	77%	5%	19%	76%
Cd	2%	87%	10%	2%	79%	19%	4%	86%	10%	1%	93%	6%	2%	87%	10%	1%	72%	26%
Tl	14%	55%	31%	11%	42%	47%	25%	48%	27%	9%	71%	20%	14%	55%	31%	6%	39%	55%
Sb	2%	93%	5%	2%	89%	9%	5%	91%	5%	1%	96%	2%	2%	93%	5%	1%	78%	21%
As	15%	73%	12%	13%	65%	22%	26%	64%	10%	9%	84%	7%	15%	73%	12%	8%	59%	33%
Pb	5%	87%	8%	5%	80%	15%	10%	82%	8%	3%	93%	4%	5%	87%	8%	3%	75%	23%
Cr	2%	95%	2%	2%	93%	4%	5%	93%	2%	1%	98%	1%	2%	95%	2%	1%	89%	9%
Co	4%	92%	4%	4%	89%	7%	8%	88%	4%	2%	96%	2%	4%	92%	4%	3%	88%	10%
Cu	9%	50%	41%	6%	36%	58%	16%	46%	38%	6%	67%	27%	9%	50%	41%	2%	18%	80%
Mn	1%	99%	1%	1%	98%	1%	2%	98%	1%	0%	99%	0%	1%	99%	1%	1%	97%	3%
Ni	65%	33%	2%	64%	33%	3%	79%	20%	1%	49%	50%	1%	65%	33%	2%	50%	41%	9%
V	68%	32%	0%	68%	32%	0%	81%	19%	0%	52%	48%	0%	68%	32%	0%	56%	42%	2%
Sn	14%	62%	24%	11%	50%	39%	24%	55%	21%	9%	77%	15%	14%	62%	24%	2%	12%	86%
Zn	2%	46%	53%	1%	30%	69%	3%	45%	52%	1%	63%	36%	2%	46%	53%	1%	23%	77%

Scenario # (Sensitivity)	Se7			Se8			Se9			Se10			Se11			Se12		
	Traditional fuels	Raw materials	Waste fuels	Traditional fuels	Raw materials	Waste fuels	Traditional fuels	Raw materials	Waste fuels	Traditional fuels	Raw materials	Waste fuels	Traditional fuels	Raw materials	Waste fuels	Traditional fuels	Raw materials	Waste fuels
Hg	3%	11%	87%	3%	13%	83%	2%	23%	75%	7%	18%	76%	6%	19%	74%	7%	17%	76%
Cd	1%	57%	42%	1%	80%	19%	0%	59%	41%	2%	88%	10%	2%	89%	9%	2%	88%	10%
Tl	4%	25%	71%	5%	29%	67%	1%	22%	77%	13%	57%	29%	13%	60%	28%	14%	57%	30%
Sb	1%	64%	35%	1%	77%	22%	0%	64%	35%	2%	93%	4%	2%	94%	4%	2%	93%	4%
As	6%	45%	50%	6%	44%	50%	2%	44%	55%	14%	75%	11%	13%	77%	10%	14%	74%	11%
Pb	2%	61%	37%	3%	80%	17%	1%	62%	38%	5%	88%	7%	4%	89%	7%	5%	87%	8%
Cr	1%	82%	17%	1%	90%	9%	0%	85%	15%	2%	96%	2%	2%	96%	2%	2%	96%	2%
Co	2%	80%	18%	3%	91%	7%	1%	83%	16%	4%	93%	4%	3%	93%	3%	4%	92%	4%
Cu	1%	10%	89%	2%	21%	77%	1%	18%	81%	8%	53%	39%	8%	55%	37%	8%	52%	40%
Mn	0%	94%	6%	1%	97%	3%	0%	98%	2%	1%	99%	1%	1%	99%	1%	1%	99%	1%
Ni	46%	38%	16%	51%	42%	7%	23%	58%	19%	63%	36%	2%	61%	38%	2%	64%	35%	2%
V	55%	41%	4%	56%	42%	2%	29%	67%	4%	66%	34%	0%	64%	36%	0%	67%	33%	0%
Sn	1%	7%	92%	2%	13%	85%	1%	31%	68%	13%	64%	23%	12%	67%	21%	13%	64%	23%
Zn	0%	13%	87%	1%	36%	64%	0%	12%	87%	2%	48%	50%	2%	51%	48%	2%	48%	51%

Characterization factors of different human toxicity Life Cycle Impact Assessment (LCIA) methods

Table S7.4: Characterization factors of different human toxicity Life Cycle Impact Assessment (LCIA) methods, normalized to dioxins emissions

<i>Substance</i>	CML 2001 human toxicity HTP 100a GLO	TRACI human health carcinogenics US	TRACI human health non-carcinogenics US	EDIP environmental impact human toxicity, via air GLO	eco-indicator 99, (H,A) human health carcinogenics RER
Dioxins	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00
PAH	3.0E-04	-	-	-	9.5E-07
CO	-	-	-	2.9E-08	-
NO _x	6.2E-10	-	-	3.0E-07	-
SO ₂	5.0E-11	-	-	4.5E-08	-
HCl	2.6E-10	-	6.1E-13	-	-
Cd	7.5E-05	8.0E-08	1.1E-06	4.0E-03	7.5E-04
Hg	1.4E-07	-	2.9E-07	2.3E-04	-
Tl	8.3E-06	-	5.5E-06	1.8E-05	-
Sb	1.3E-07	-	8.1E-06	7.0E-07	-
As	1.8E-04	2.7E-05	1.4E-06	1.8E-04	1.4E-04
Pb	1.5E-08	1.9E-07	6.3E-06	3.5E-03	-
Cr	-	2.2E-07	1.7E-07	3.5E-05	-
Co	8.9E-06	-	8.4E-08	3.3E-07	-
Cu	2.2E-06	-	3.8E-08	2.0E-08	-
Mn	-	-	1.8E-08	8.8E-05	-
Ni	1.8E-05	4.8E-09	2.1E-07	2.3E-06	2.4E-07
V	1.4E-07	-	4.0E-07	2.8E-06	-
Sn	7.2E-11	-	6.0E-10	-	-
Zn	5.0E-08	-	3.0E-08	2.8E-06	-

S8. Comparison of existing LCI of cement

Comparison to Life Cycle Inventories (LCI) from a meta-analysis on available cement LCI in Europe (25). For background information and references of the cements presented in the table S8.1 please refer to the meta-analysis study. The dataset 'European LCA database' in the table S8.1 refers to the European LCA database by the European Commission Joint Research Centre (26).

Table S8.1: Comparison of existing LCI of cement

Emissions / Product	CO ₂	NO _x	SO ₂	Dust	Product name in meta-analysis study
CEM I					
CEM I	355	0.96	0.43	10.00	Cement Portland I
CEM I	810	2.00	0.60	0.30	Cement CH
CEM I	813	2.09	0.67	0.18	Cement N
CEM I	853	2.58	0.09	7.50	Portland cement NL 1
CEM I	805	1.94	0.45	0.16	Cement S
CEM I	780	3.70	0.63	0.39	Cement SF 1
CEM I	812	2.95	1.33	0.32	Cement SF2
European LCA database	885	1.78	1.05	0.31	
This study	887	2.02	1.01	0.55	
CEM II					
CEM II / A	918	3.11	1.16	0.24	Portland Cement
CEM II / A	586	1.57	0.12	0.27	Portland cement A
CEM II / A	807	2.95	0.09	0.29	Portland cement NL2
CEM II / B	289	0.71	0.98	79.60	Portland cement NL3
European LCA database	n.a.	n.a.	n.a.	n.a.	-
This study (CEM II avg)	729	1.67	0.84	0.48	
CEM III					
CEM III / B	222	0.51	0.51	10.00	Blastfurnace slag cement
CEM III / B	334	1.11	0.58	0.01	Cement Hoogoven I
CEM III / B	212	0.85	0.03	0.14	Blastfurnace slag cement NL1
CEM III / B	134	0.40	0.43	88.60	Blastfurnace slag cement NL2
European LCA database	n.a.	n.a.	n.a.	n.a.	-
This study (CEM III avg)	347	0.83	0.46	0.24	
CEM IV					
CEM IV / B	693	2.33	0.90	0.18	Portland Ash cement
European LCA database	n.a.	n.a.	n.a.	n.a.	
This study (CEM IV avg)	617	1.43	0.71	0.39	

Comparison to the LCI of the European (26) and U.S. (27) LCA database. Direct comparability between the data from the European and U.S. databases is not possible due to different system boundaries. The European database provides aggregated cradle-to-gate emissions. The U.S. database does not include the production of fuels and electricity. Both databases do not provide data on blended cements.

The differences in emissions between this study and the European database may be due to different data sources to model clinker production and supply chain emissions. The European database does not provide disaggregated information on production or on emissions. The differences in U.S. production are because the U.S. LCA database assumes Portland cement with 95.1% clinker and 4.9% gypsum, while this study assumes 90.3% clinker, 4.7% gypsum and 5% minor additional constituents (i.e. inorganic process addition, limestone). Carbon dioxide emissions in this study are calculated with the clinker production model (4) and not taken from the report. A different approach is applied for the calculation of calcination CO₂ emissions. The report assumes that all CaCO₃ in the raw meal is being calcined in the kiln system. In contrast, the model applied in this study assumes that CaCO₃ in cement kiln dust (CKD) was not calcined in precalciner/suspension preheater kilns and 50% calcined in long wet, long dry, and grate preheater (Lepol) kilns (4). PCDD/F emissions in the U.S. LCA database report are wrong and were therefore adjusted by a factor 1000 according to (3).

Table S8.2: Comparison of LCI from this study to the European and the U.S. LCA databases.

Product / Emissions	European Portland cement (this study)	European Portland cement (European LCA database)	difference (%)	U.S. Portland cement (this study)	U.S. Portland cement (U.S. LCA database)	difference (%)
Total (cradle-to-gate)				Plant (gate-to-gate)		
CO ₂	887	885	0.2%	842	918	-8.3%
NO _x	2.02	1.78	13.6%	2.30	2.42	-5.1%
SO ₂	1.01	1.05	-3.5%	1.57	1.65	-5.1%
Dust	0.555	0.310	78.8%	0.191	0.201	-5.1%
CH ₄	0.486	0.580	-16.3%	0.036	0.038	-5.1%
NM VOC	0.145	0.226	-35.7%	0.005	-	-
PAH	1.53E-05	1.30E-04	-88.2%	n.a.	n.a.	-
CO	2.51	2.14	17.4%	0.987	1.040	-5.1%
HCl	0.0152	0.0198	-23.5%	0.066	0.070	-5.1%
Hg	5.22E-05	2.81E-05	85.8%	5.92E-05	6.24E-05	-5.1%
Cd	2.41E-05	7.19E-06	235.4%	1.28E-06	n.a.	-
Tl	3.06E-05	5.73E-06	433.6%	4.44E-06	n.a.	-
Sb	5.33E-06	5.24E-06	1.8%	5.48E-07	n.a.	-
As	2.95E-05	1.26E-05	134.4%	3.92E-07	n.a.	-
Pb	1.15E-04	4.90E-06	2244.7%	8.95E-06	n.a.	-
Cr	8.30E-05	2.95E-05	181.5%	4.59E-06	n.a.	-
Co	1.06E-05	1.06E-05	0.0%	1.17E-06	n.a.	-
Cu	1.20E-04	2.06E-05	480.2%	6.34E-06	n.a.	-
Mn	1.87E-04	5.56E-05	236.3%	6.61E-05	n.a.	-
Ni	1.43E-04	5.69E-06	2409.1%	5.24E-06	n.a.	-
V	2.45E-04	1.50E-04	63.6%	2.70E-05	n.a.	-
Sn	6.50E-06	1.82E-05	-64.3%	2.53E-06	n.a.	-
Zn	1.79E-04	5.16E-05	246.8%	7.68E-05	n.a.	-
PCDD/F	7.12E-11	4.26E-11	67.2%	1.41E-10	1.49E-07	-99.9%

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