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Scoping cost and abatement metrics for biomass with carbon capture and storage — the example of bioCCS in cement

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ABSTRACT

Negative emission technologies such as biomass with carbon capture and storage (bioCCS) may become an important instrument to limit global warming. Currently, estimates of CO_2 avoidance cost for bioCCS vary widely. Using a case study of a cement plant, this paper illustrates how this variance is partially attributable to the system boundary choices made by modellers. The estimated avoidance cost for the bioCCS-in-cement plant ranged from 48-321€$_{2017}$/t CO_2(eq) and the net CO_2(eq) from -660 to 16 kg CO_2(eq)/t cement, without any change in the technological model, equipment and input costs, or lifecycle emissions, but by changing the system boundaries used for cost and emission accounting, reflecting the different boundaries seen in bioCCS literature. To allow for more comparable bioCCS cost estimates, studies should always account for costs and emissions of both biomass production and the full chain of carbon capture, transport, and permanent storage, as both are fundamental to the role of bioCCS as a potential "negative emission technology". We also advocate for clear decomposition of metrics, separation of "avoided emissions" from physical flows of greenhouse gases; and explicit consideration of the temporality of the bioCCS system. With these guidelines, the range of avoidance cost of the bioCCS-in-cement plant shrinks to 157-193€$_{2017}$/t CO_2(eq) for near-term estimates and to 89-107€$_{2017}$/t CO_2(eq) for longer-term estimates.

1. Introduction

The Glasgow Climate Pact reaffirmed a global commitment to limiting global warming to "well below 2°C" (3.6°F), a commitment that requires reducing our annual net emissions of carbon dioxide to zero—or less—within the next few decades (IPCC, 2018). To do so, and thus avoid the most catastrophic outcomes from the ongoing climate crisis will likely require the deployment of massive scale "negative emission technologies" that permanently remove greenhouse gases such as carbon dioxide from the atmosphere (IPCC, 2018).

Biomass with carbon capture and storage (bioCCS) is a potential negative emission technology where biomass is used as an energy carrier or feedstock and the resulting biogenic CO_2 is captured and permanently stored, such as in a geologic formation. While large models primarily allocate bioCCS to the power sector or biofuel production (IPCC, 2018; Rogelj et al., 2018), it also has the potential to compensate for residual emissions from difficult to decarbonise industrial sectors, where carbon is a necessary element of feedstocks, catalysts, or products. (Tanzer et al., 2021b). However, bioCCS combines the complexities of large-scale sustainable biomass use, the high energy demand of CO_2 capture, and the infrastructure demands of transporting and storing captured CO_2.

To understand whether bioCCS can be a viable option for CO_2-neutral industrial production a fundamental question is how much does bioCCS cost? Cost estimates for industrial bioCCS in recent literature are limited and vary widely, ranging from 13-388 €$_{2020}$/t CO_2 abated (Tanzer et al., 2021b), similar to that seen for bioCCS in general (IPCC, 2018). This variance is commonly discussed in terms of technological differences in the system or parametrical assumptions for cost estimates (Fuss et al., 2018; Tanzer et al., 2021b). In particular, whether the CO_2 is

Table of abbreviations: bioCCS, biomass with carbon capture and storage; CCS, carbon capture and storage; CO_2eq, carbon dioxide equivalent; FOAK, first of a kind; GHG, greenhouse gases; Gt, gigatonne; kg, kilogram; kt, kilotonne; kWh, kilowatt hour; MEA, monoethanolamine; MPa, megapascal; Mt, megatonne; NOAK, Nth of a kind; t, tonne; Tj, terajoule.

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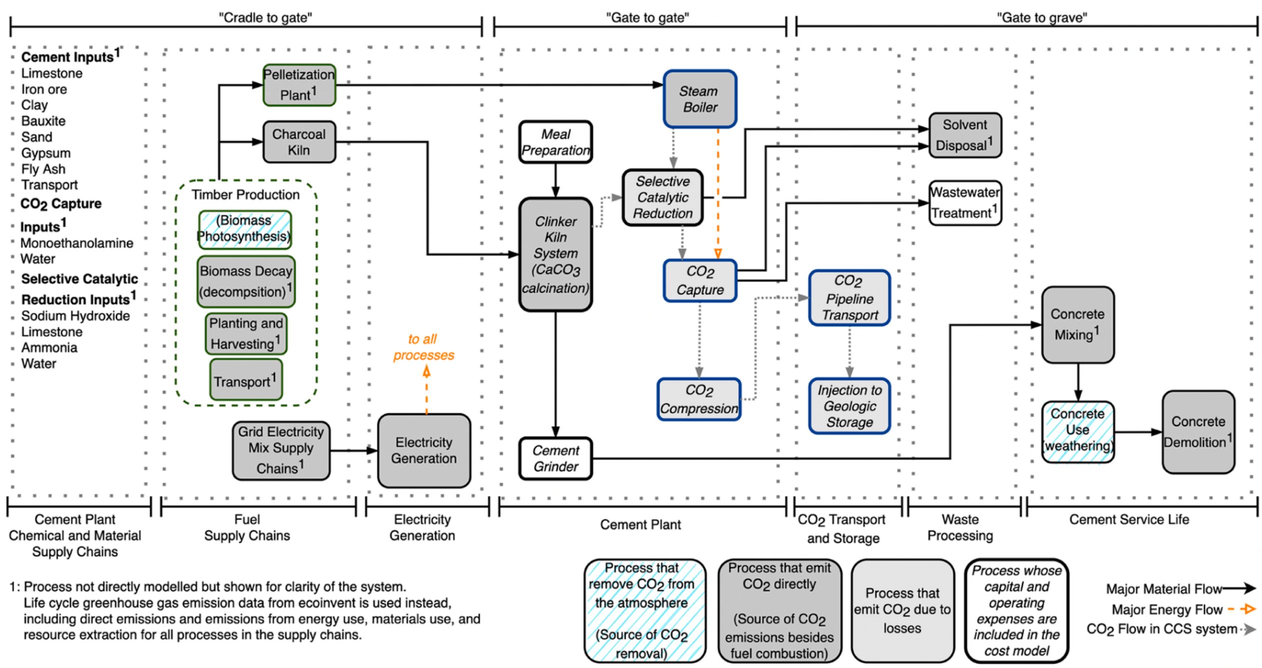

Fig. 1. Model overview. For clarity, many material flows are not explicitly connected. Full model parameters are available in the appendix.

diluted or concentrated and the distance between where the CO_2 is captured and where it is stored are major factors in cost estimates.

However, variation in bioCCS abatement cost estimates is also due to variation of scope . Cost estimates from a literature review on bioCCS in industry (Tanzer et al 2021b) were presented as: per tonne of CO_2 captured (14-126 €$_{2017}$/t, n=3); per tonne of CO_2 stored (-78-726 €$_{2017}$/t, n=13); or per tonne of CO_2 "avoided" (-88-135 €$_{2017}$/t, n=6), which considers the reduction in emissions from an unabated case.

Adding further ambiguity, all of these may be referred to as cost of "CO_2 avoided" in literature (e.g., Berghout et al., 2019; Lozano et al., 2020; Mandova et al., 2019; Onarheim et al., 2017; Restrepo-Valencia and Walter, 2019; Yang et al., 2021). The large range of cost of CCS is due primarily to differences in CO_2 transport distance between studies. Negative values result from the assumption of a credit or subsidy for stored CO_2 or the sale of CO_2, e.g., for enhanced oil recovery. Furthermore, estimates of CO_2 avoidance potential of bioCCS—including those independent of cost estimates—also embody a wide range of system boundaries, and may or may not include CO_2 emissions from supply chains of biomass production, energy use, or chemicals and materials, and/or may or may not include emissions from (by)product use or CO_2 transport and storage (Tanzer et al 2021b). Many studies combined estimates of physical emissions and removals of greenhouse gases with estimates of "avoided emissions", assumed reductions in emissions occurring in other systems from e.g., the sale of co-generated electricity. Therefore, a relative avoidance > 100% does not necessarily indicate negative emissions (i.e., physical net removal of greenhouse gases from the atmosphere). High estimates of relative avoidance resulted when the unabated system was itself biogenic and the study assumed "carbon neutral" biomass, or included "avoided emissions", leading to an unabated system with a low or negative net CO_2(eq) estimate. In an extreme case, bioCCS in the paper industry was assumed to lead to abatement of over 2500% (Yang et al., 2021). Additionally, in estimates of avoidance cost, the system represented by the cost estimate may not be the same as that represented by the emission abatement estimate, such as assuming that the captured CO_2 is permanently stored in the abatement estimate, but excluding capital costs or emissions associated with transport and storage (Mandova et al., 2019; Onarheim et al., 2017; Santos et al., 2021).

If bioCCS is to be a lynchpin technology in reaching net-zero in the coming decades, it is critical that there are transparent and comprehensive estimates of both cost and emissions available. Overestimation of avoidance, or underestimation of cost, can lead to miscalculations in investment and policy or misassessment of the possible role of bioCCS. This paper explores the influence of system boundary choices found in bioCCS studies on estimates of technological cost, potential abatement, and CO_2 avoidance cost.

Instead of assuming a static set of system boundaries and exploring the influence of the assumed configuration of technology, input costs, or geography, this paper holds the configuration static and explores the influence of system boundaries on the avoidance cost. By this, we explore the relative influence of these choices on avoidance cost and propose guidelines for bioCCS avoidance cost estimates (Fig. 1). The boundaries considered are based on those found in other bioCCS literature (Tanzer et al., 2021b) and, for cost, include operational and capital expenses of capture, transport, and storage, as well as the type of cost-scaling estimation used. For avoidance, system boundary options include direct emissions from the industrial production site, electricity generation, energy supply chains, material and chemical supply chains, CO_2 transport and storage, and product use. Another boundary option includes a global warming factor for biogenic CO_2. Finally, the inclusion of non-CO_2 greenhouse gas emissions is considered, including CH_4, N2O, as well as additional GHGs included in the database used for background process data.

To explore the impact of system boundaries on avoidance costs, this paper considers the case of a bioCCS retrofit of a cement plant. Cement is the second largest industrial emitter of CO_2, after iron and steel, with 2.4 Gt of CO_2 emissions in 2019 (IEA, 2020), of which approximately 60% were from calcination of limestone ($CaCO_3 \rightarrow CaO + CO_2$), and thus cannot be decarbonised by a fossil-free energy mix (CEMBUREAU, 2019). The cement industry itself perceives the need for a decarbonisation approach that requires both CCS and the increased use of biogenic fuels (CEMBUREAU, 2019; MPA UK Concrete, 2020). In 2019, co-fired biomass represented 18% of European cement kiln fuel (Global Cement and Concrete Association, 2020), primarily in the form of biowastes, and the first full-scale retrofit of CO_2 capture into cement production is currently under construction in Brevik, Norway (IEA, 2021).

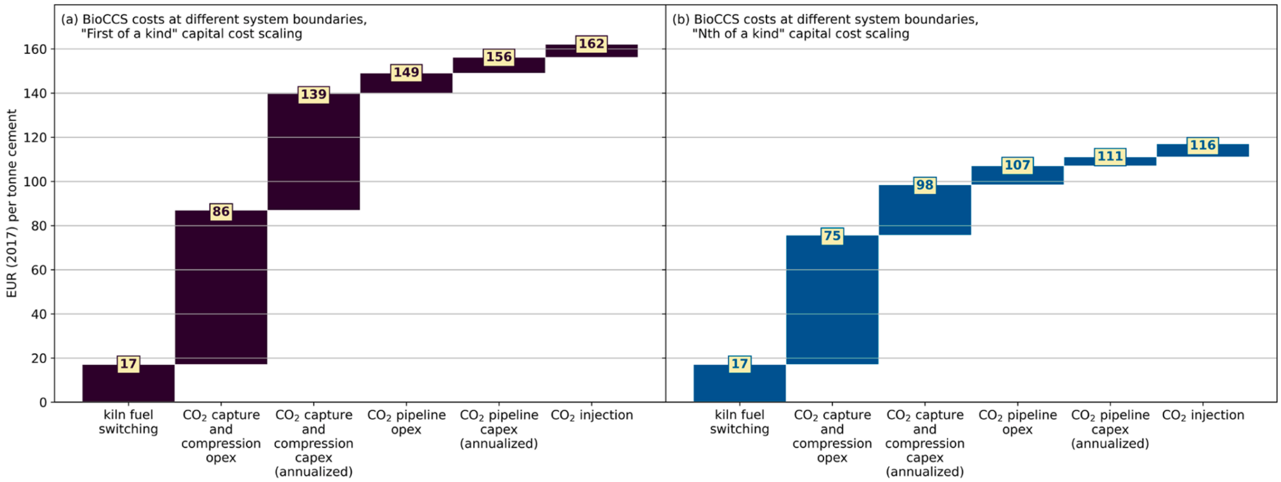

Fig. 2. Cost of bioCCS, separated by system component. These costs are in addition to the baseline costs of cement product (33€$_{2017}$/t cement, model results for production without biomass or CCS based primarily on Gardarsdottir et al., 2019).

However, the existing literature on bioCCS-in-cement is sparse (Obrist et al., 2021; Schakel et al., 2018; Tanzer et al., 2021a; Yang et al., 2021) and as of 2021, there exists, to our knowledge, no dedicated study on the CO_2 avoidance costs of bioCCS-in-cement.

2. Methods

The results of this paper are based on an *ex-ante* model of the use of biomass and CCS (bioCCS) in cement. It consists of a process model of cement production with and without biomass use and CO_2 capture, transport and storage; a life cycle accounting of greenhouse gas emissions; and an economic assessment of cement production costs. Fig. 2 summarises the boundaries of the complete system that was modelled. As our baseline, a state-of-the-art coal-fired[1] cement plant in northwest Europe was modelled based on IEAGHG (2013a); Voldsund et al. (2019), in line with the EU Best Available Technology guidelines (European Commission, 2013). To align with the reference models, it has a design capacity of 1.36 Mt/year of CEMII cement (73% clinker), with an average energy consumption of 2.4 GJ and 104 kWh per tonne of cement. The cement is assumed to be used in the production of an exterior concrete wall with a 50-year lifespan.

2.1. Process Model

The process model consisted of connected fixed-ratio black box models for each unit process and was constructed following the methodology described in Tanzer et al. (2021a), using the open-source python black box modelling library blackblox.py (Tanzer, 2021), which is designed specifically for comparison of multiple process configurations and model parameter sets. The main model parameters are summarised in Table 1 and are provided in full in the appendix. For the use case model, the cement was assumed to be used in 25 Mpa concrete, requiring 200 kg cement/m^3 of concrete (Wernet et al., 2016).

Cement is produced by heating ground limestone and aluminosilicate minerals such as clay or bauxite, which are then heated to 800-1450°C, allowing the limestone to calcinate ($CaCO_3$ + heat → CaO + CO_2) and amalgamate with the other mineral constituents into clinker, the primary component of cement. The clinker is then blended with additives such as gypsum, fly ash, and/or steel slag and pulverised into cement powder. To produce concrete, the cement is hydrated, mixed with aggregates (sand and gravel), and poured into form, where it hardens.

The CCS model included the retrofit of post-combustion CO_2 capture using monoethanolamine (MEA) to separate CO_2 from the clinker kiln flue gases. MEA-based capture was selected as it is a commercially available technology and provides a conservative assumption for the energy demand of capture. Based on a literature review of MEA-based CO_2 capture, a capture rate of 90% with a reboiler duty of 3.2 MJ/kg CO_2 separated was assumed (Tanzer et al., 2021a). It was assumed that no waste heat from the kiln was available for use in the CO_2 capture system. Instead, steam was provided from a dedicated boiler. Flue gases from the steam boiler were also assumed to be sent to CO_2 capture. Captured CO_2 was then compressed to 11 Mpa, transported by pipeline (100 km onshore and 10 km offshore), and injected into a legacy gas reservoir.

In the bioCCS case, charcoal was assumed to replace coal 1:1 as clinker kiln fuel on an energy basis and the steam boiler was assumed to be fired with wood pellets. Charcoal was assumed for the kiln as it has a sufficient energy density to theoretically reach the required temperatures for clinker production (Abreu et al., 2015; Cheng et al., 2016). The use of charcoal is a simplification to ensure that biofuel emissions can be fully internalized into the model, as the complexities of accounting for the emissions embodied in mixed fossil waste and biowastes (often assumed to be zero)—a more likely cement kiln fuel mix based on current practices (European Commission, 2013; Global Cement and Concrete Association, 2020)—is outside the scope of this study. In all cases, electricity was assumed to be provided by the Dutch electricity grid mix with a direct generation intensity of 390 g CO_2/kWh (European Environment Agency, 2020). Table 2 provides the emission factors and energy contents of fuels used in this model.

2.2. Life Cycle Assessment

The estimates of net greenhouse gas emissions included cement production, biomass production and use, and CCS. For the emission estimates of upstream supply chains of material and energy carriers, downstream supply chains of waste disposal, and supply chains of transport and building and equipment construction, data from the life cycle inventory database ecoinvent 3.7.1 (Wernet et al., 2016) was used. These include estimates of greenhouse gas emissions as a result of resource extraction, material production, energy use, and transport throughout the supply chains—and the supply chains of the supply chains. The exact database processes used are provided in the appendix

[1] Commonly, European cement kilns use a mix of fuels that include fossil and biogenic waste products alongside coal. For the clarity of this case study, the simplification of a single-fuel kiln was used for both the unabated and bioCCS cases.

Table 1
Main Model Parameters.

Parameter	Qty	Unit	Source
Cement Production			
Clinker content of cement	737	kg/t cement	Gardarsdottir et al. (2019)
Limestone Content of meal	745	kg/t meal	Schakel et al. (2018)
Clinker kiln thermal energy demand	3.3	GJ/t clinker	European Commission (2013)
Electricity demand	104	kWh/t cement	Worrell et al. (2007)
Transport of raw materials, by train	200	km	Assumed
CO_2 Capture and Compression			
Capture efficiency	90	% of CO_2 in	Assumed
Reboiler duty	3.2	GJ/t CO_2 captured	Tanzer et al, 2021a, based on literature review of MEA capture
Monoethanolamine makeup	1	kg/t CO_2 captured	Assumed, based on literature review of MEA capture
Electricity demand, capture	38	kWh/t CO_2 captured	(Gardarsdottir et al., 2019; IEAGHG, 2013b)
Electricity demand, compression to 110 bar	106	kWh/t CO_2 compressed	Gardarsdottir et al. (2019)
Steam Boiler			
Efficiency	90	%	Assumed
Electricity demand	5	kWh/GJ steam	(Tanzer et al., 2020)
CO_2 transport by pipeline and injection to geologic storage			
Transport distance, onshore	100	km	Assumed
Transport distance, offshore	10	km	Assumed
Electricity demand, transport	3	kWh/t CO_2 transported	Knoope et al. (2014)
Electricity demand, injection	7	kWh/t CO_2 stored	Khoo and Tan (2006)
Charcoal Production - Missouri-style kiln			
Carbon efficiency	69	% of C in wood in charcoal	Pennise et al. (2001)
CO_2 emissions	540	kg CO_2/t charcoal	Pennise et al. (2001)
CH_4 emissions	1022	kg CO_2eq/t charcoal	Pennise et al. (2001)
Concrete weathering			
Service Life	50	years	Assumed
Uptake of CO_2, service life	12%	% of CO_2 removed during calcination	European Committee for Standardization (2017), Annex BB.1
Uptake of CO_2, demolition	3%	% of CO_2 removed during calcination	European Committee for Standardization (2017)

Table 2
Fuel energy contents and emission factors (IPCC, 2019; Pennise et al., 2001).

	Energy Content (GJ/t)	CO_2	CH_4	N_2O	Unit
coal	25.8	96.1	<0.001	<0.001	kg CO_2eq/GJ
natural gas	48.0	56.1	<0.001	<0.001	kg CO_2eq/GJ
charcoal	31.5	112	0.005	0.001	kg CO_2eq/GJ
wood pellets (dry)	19.1	112	0	0.002	kg CO_2eq/GJ

(Fig. S1). Emissions of greenhouse gases other than carbon dioxide are characterised in their 100-year "CO_2 equivalent" (CO_2eq) global warming potential using the IPCC characterisation factors (Myhre et al., 2013).

The model of life cycle emissions, like the process model itself, relies on generic literature data, and is not meant to represent a specific installation of bioCCS-in-cement, nor determine an optimal system of production, but rather to provide a representative example based on currently available data.

Emissions of CO_2, CH_4, and N_2O from the production of cement, concrete, and biofuels, as well as from steam production, electricity generation, and CO_2 capture, transport, and storage, were also estimated. For N_2O emissions at the cement plant, selective catalytic reduction was assumed to abate 90% of produced N_2O (IEAGHG, 2008).

The wood used for charcoal and pellets was assumed to be from sustainable European forestry with a 100-year rotation period, such as for boreal forestry species of Scots pine or Norwegian spruce (Bauhus et al., 2010), after which the total carbon removed and stored in the timber is equal the total carbon embodied in the initial amount of biomass used. The biomass was assumed to be harvested and replanted in the same year of cement production.

Concrete also absorbs CO_2 over time as the free lime recarbonates into limestone. CO_2 uptake by concrete was modelled for CEMII concrete, assuming that the concrete was used as a 20 n-cm exterior wall with a 50year lifetime using the calculatio method in (European Committee for Standardization, 2017). At end of life, the concrete was assumed to be reused as a road sublayer or other application where it is no longer exposed to air. In total, recarbonation during concrete use and demolition was assumed to result in the uptake of the equivalent of 15% of the CO_2 released during limestone calcination.

2.2.1. System Boundaries Considered

This paper considers the net emissions—total emissions of greenhouse gases to the atmosphere minus total removals of CO_2 from the atmosphere—for nine different system boundaries seen in bioCCS literature, listed in Table 3. Between the different boundary options, configuration and parameters of the model itself do not change, only what elements are included in the estimation of net emissions according to each boundary.

2.3. Economic Model

The economic model estimated the cost of cement production with and without bioCCS, building on the results of the process model. The cement plant was assumed to be located in the Netherlands and operate at 91.3% of its design capacity, as was assumed in the main cost model reference (Gardarsdottir et al., 2019). The infrastructure of CO_2 capture and compression were assumed to be retrofitted into an existing cement plant, while the CO_2 pipeline was assumed to be built on unused land. The cost model in this paper followed the guidelines for CCS cost estimation in Roussanaly et al. (2021).

All costs are presented in 2017 Euros, using EPCCI to scale capital costs (IHS Markit, 2018) and historical inflation rates to scale operational costs (Alioth Finance, 2021).

2.3.1. Capital Expenses

The capital cost models used equipment scales derived from the material and energy flow estimates in the process models. For CO_2 capture, compression, and steam production, equipment costs were scaled using Eq. (1). The CO_2 capture system also included 500 m of stainless steel ducting for flue gas transport within the cement plant, using cost estimates from Roussanaly et al. (2021). The size of the CO_2 transport pipeline was calculated assuming an inlet pressure of 11 Mpa, outlet pressure of 8 Mpa, and a pressure drop of 50 m/second, using the method presented in Knoope et al. (2014). Table 4 presents the estimated equipment scales, costs, and data sources used.

$$Cost_{scaled,2017} = Cost_{base} \times \left(\frac{Capacity_{scaled}}{Capacity_{base}}\right)^{0.7} \times \left(\frac{Cost\ Index_{2017}}{Cost\ Index_{base}}\right) \quad (1)$$

Table 3
System boundaries considered in this paper.

	Gate-to-gate CO_2	Gate-to-gate CO_2 assuming "CO_2 neutral" biomass	Gate-to-gate CO_2 and electricity	Cradle-to-gate CO_2, energy supply chains only	Cradle-to-gate CO_2	Cradle-to-grave CO_2, excluding use	Cradle-to-grave CO_2, including use	Cradle-to-grave CO_2eq, including biogenic CO_2 GWP	Cradle-to-grave CO_2eq, all GHGs and biogenic CO_2 GWP	data source
CO_2 emitted at cement plant from cement kiln	X	X	X	X	X	X	X	X	X	(Gardarsdottir et al., 2019; IEAGHG, 2013b; IPCC, 2019)
CO_2 emitted at cement plant, from CO_2 capture system	X	X	X	X	X	X	X	X	X	(Gardarsdottir et al., 2019; IEAGHG, 2013b)
CO_2 emitted at by fuel combustion at electricity generation site			X	X	X	X	X	X	X	European Environment Agency (2020)
CO_2 emitted in supply chains of coal, charcoal, wood pellets, and electricity				X	X	X	X	X	X	Wernet et al. (2016)
CO_2 emitted in supply chains of non-energy material and chemical inputs					X	X	X	X	X	Wernet et al. (2016)
CO_2 emitted in supply chains of cement and CO_2 capture infrastructure						X	X	X	X	Wernet et al. (2016)
CO_2 emitted by CO_2 transport and storage and its energy and infrastructure supply chains						X	X	X	X	(IPCC, 2005; Wernet et al., 2016)
CO_2 emitted by the disposal of wastewater and waste solvents						X	X	X	X	Wernet et al. (2016)
CO_2 emitted by the production, use and demolition of concrete and their supply chains							X	X	X	Wernet et al. (2016)
GWP of biogenic CO_2 emitted, based on biomass rotation period								X	X	Guest et al. (2013)
CH_4 and N_2O emitted during the production charcoal and cement									X	(IPCC, 2019; Pennise et al., 2001)
CH_4, N_2O, CFCs, and other greenhouse gases emitted in upstream supply chains									X	Wernet et al. (2016)
CO_2 removed by biomass photosynthesis		X	X	X	X	X	X	X	X	equal to biogenic CO_2 produced
CO_2 removed by concrete weathering							X	X	X	European Committee for Standardization (2017)

Starting from equipment costs, scaling factors were used to determine the costs of installation, labour, land and buildings, construction contingencies, financing, insurance, and taxes. As, CO_2 capture is not yet a commercialised technology for cement production, with the first full-scale installation currently under development (IEA, 2021), capital expenses were estimated using factors for a "first of a kind" cost escalation that assumes the need for redundant equipment and substantially larger factors for contingency and supplementary funds to account for the need for "on the job" technological learning and a higher likelihood of unexpected costs and delays. However, as many economic models for

Table 4
Equipment costs, installation costs plus maintenance factor.

Equipment	Equipment Cost		Base Scale	Scale unit	Installation Factor	Process Contingency	Maintenance	Source
CO_2 Absorption (MEA)	7.901	M €$_{2014}$	765	kt CO_2 captured/year	1.76	18%	7%	Gardarsdottir et al. (2019)
CO_2 Desorption (MEA)	7.024	M €$_{2014}$	765	kt CO_2 captured/year	2.04	18%	7%	Gardarsdottir et al. (2019)
CO_2 Compression	14.857	M €$_{2014}$	765	kt CO_2 captured/year	1.24	23%	7%	Gardarsdottir et al. (2019)
CO_2 Dehydration (TEG)	0.228	M €$_{2014}$	765	kt CO_2 captured/year	4.07	23%	7%	Gardarsdottir et al. (2019)
CO_2 Dehydration (TEG)	0.228	M €$_{2014}$	765	kt CO_2 captured/year	4.07	23%	7%	Gardarsdottir et al. (2019)
Flue Gas Cleaning Unit (additional capacity)	1.1	M €$_{2013}$ (direct cost)	765	kt CO_2 captured/year	n.a.	n.a.	3.5%	Gardarsdottir et al. (2019)
Steam Boiler	34	M €$_{2013}$	4730	TJ/year	2.08	10%	3.5%	IEAGHG (2013b)
CO_2 Injection	19	M €$_{2010}$ (direct costs)	1000	kt CO_2 stored/year	n.a.	n.a.	included in storage variable costs	European Technology Platform for Zero Emission Fossil Fuel Power Plants (2011)

Table 5
Cost Model Scaling Factor.

Cost Factor	Includes		"First of a kind"	"Nth of a kind"
Installed Costs (IC)	Equipment Costs (EC) +	installation costs	as in Table 4	as in Table 4
Direct Costs (DC)	IC +	process contingencies	as in Table 4	as in Table 4
		Equipment redundancies (for CO_2 capture and compression equipment)	equipment scaled to 3 × 50% of capacity	no redundancies
Total Plant Costs (TPC)	DC +	Owner Costs	7% of DC	7% of DC
		Indirect Costs	14% of DC	14% of DC
		System Contingencies	10% of DC	n.a.
		Project Contingency	50% of DC	30% of DC
		Supplementary Funds	50% of DC	25% of DC

bioCCS-in-industry follow the convention of "Nth of a kind" cost estimation, which assumes that all technology components are available and usable as if they were commercialised technologies Tanzer et al. (2021b), an "Nth of a kind" estimate was also calculated. The cost escalation factors for both methods are presented in Table 5.

2.3.2. Capital Charge

The capital expenses of the CCS system were annualised into a capital charge assuming a 25-year lifetime (n) and an 8% discount rate (i) using equation 2. The capital charge also includes the costs of a three-month shutdown of cement production to retrofit the CO_2 capture system during which time the fixed costs of cement production still occur (Roussanaly et al., 2021).

Table 6
Variable Costs.

Variable Costs	Cost	Unit	Source
Energy Costs			
electricity	0.06	€$_{2017}$/kWh	European Commission (2020)
coal	3	€$_{2017}$/GJ	IEA (2020)
charcoal	10	€$_{2017}$/GJ	Ukrainian Biofuel Portal (2021)
wood pellets	11	€$_{2017}$/GJ	Ukrainian Biofuel Portal (2021)
Utility Costs			
water	1	€$_{2017}$/t water	Netherlands regional market average
Cement Production Costs			
raw meal	5.1	€$_{2017}$/t clinker	Gardarsdottir et al. (2019)
other materials	1.1	€$_{2017}$/t clinker	Gardarsdottir et al. (2019)
CCS costs			
MEA	1476	€$_{2017}$/t MEA	Gardarsdottir et al. (2019)
ammonia	132	€$_{2017}$/t NH_3	AMIS (2021)
sodium hydroxide	377	€$_{2017}$/t NaOH	Gardarsdottir et al. (2019)
CO_2 injection, offshore	6.5	€$_{2017}$/t CO_2 stored	European Technology Platform for Zero Emission Fossil Fuel Power Plants (2011)

$$\text{Capital Charge}_{annual} = (\text{Total Plant Costs of CCS} + \text{Fixed Costs during Retrofit}) \times \frac{i \times (i+1)^n}{(i+1)^n - 1} \tag{2}$$

The cement plant was assumed to be extant and paid off and its component capital costs were not estimated and no capital charge was considered. For the purposes of estimating taxes, insurance, and maintenance, a total capital cost of 150.7 M €$_{2017}$ for the cement plant was assumed (Gardarsdottir et al., 2019).

2.3.3. Operating Expenses

The operating cost model includes the variable costs of material inputs and utilities and the fixed costs of labour, maintenance, insurance and taxes.

Table 7
Cost Model System Boundaries Considered.

	without CCS	with marginal cost of CO_2 capture	with full cost of CO_2 capture	with full cost of CO_2 capture and marginal cost of CO_2 transport and storage	with full cost of CO_2 capture, transport, and storage	data sources
cement production materials	x	x	x	x	x	Gardarsdottir et al. (2019)
cement production fuel and electricity (including kiln fuel switching from coal to charcoal)	x	x	x	x	x	(European Commission, 2020; IEA, n.d.; Ukrainian Biofuel Portal, 2021)
cement production labour, maintenance, insurance, and taxes	x	x	x	x	x	(Gardarsdottir et al., 2019; CBS Statline, 2021)
CO_2 capture materials		x	x	x	x	(AMIS, 2021; Gardarsdottir et al., 2019)
CO_2 capture and compression fuel and electricity		x	x	x	x	(European Commission, 2020; Ukrainian Biofuel Portal, 2021)
CO_2 capture system labour, maintenance, insurance, and taxes		x	x	x	x	(Gardarsdottir et al., 2019; CBS Statline, 2021)
Annualized capital expenses of CO_2 capture system			x	x	x	(Gardarsdottir et al., 2019)
CO_2 transport and storage energy use				x	x	European Commission (2020)
CO_2 transport and storage labour, maintenance, insurance, and taxes				x	x	European Technology Platform for Zero Emission Fossil Fuel Power Plants (2011)
Annualised capital expenses of CO_2 pipeline and injection					x	(European Technology Platform for Zero Emission Fossil Fuel Power Plants, 2011; Knoope et al., 2014)

2.3.3.1. *Variable Costs.* The variable costs included the cost of materials, fuels, and utilities needed for the production of cement and operation of CO_2 capture, transport, and storage. The costs and data sources used are presented in Table 6.

- **Labour**. The cement plant was assumed to employ 100 workers and the operation of the CO_2 capture system was assumed to require 20 additional personnel (Gardarsdottir et al., 2019). Labour costs were assumed to be 62000/person/year (CBS Statline, 2021) based on the Dutch manufacturing sector average, with an additional 30% of operational labour costs for administrative labour.

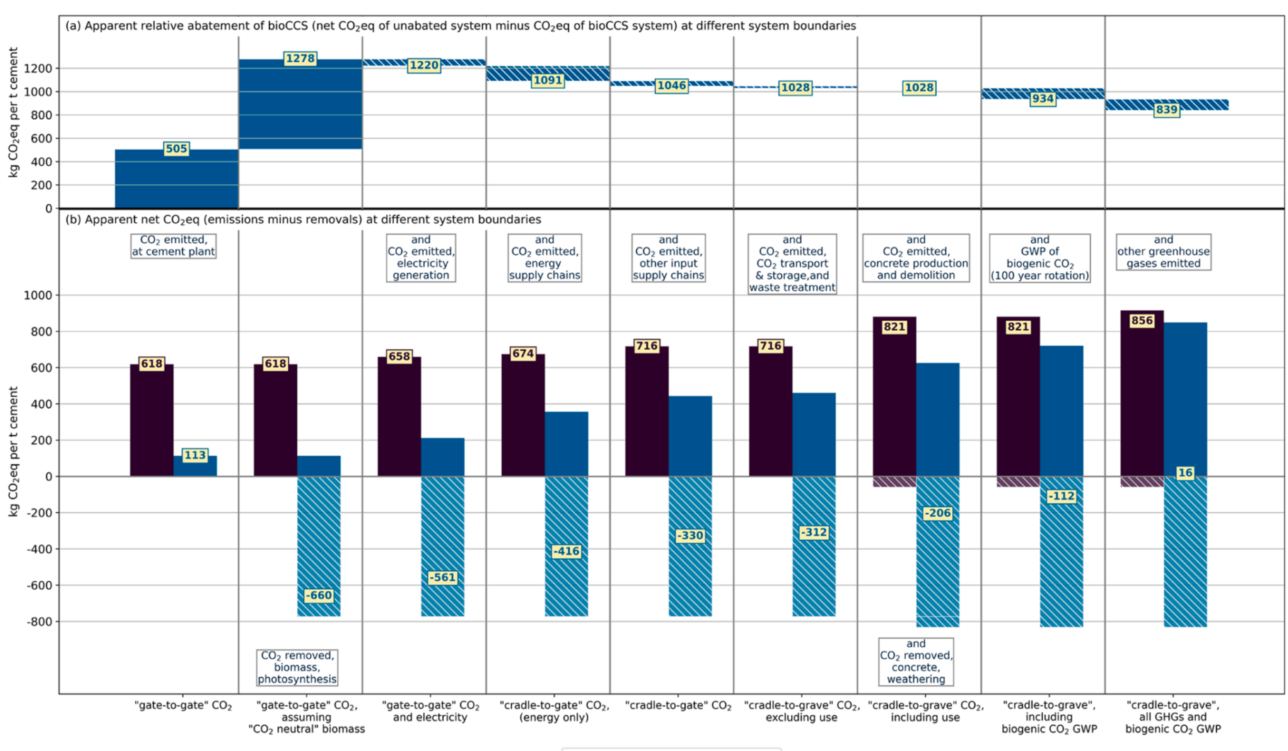

Fig. 3. (a) Relative abatement, the metric used in CO_2 avoidance cost, is the difference in emissions from unabated cement production to cement production with bioCCS. (b) Net CO_2(eq) is the net total of modelled emissions and (permanent) removals of greenhouse gases in the atmosphere.

- **Maintenance** costs were based on the installed cost of equipment, as indicated in Table 4.
- Insurance and taxes were assumed to be 2% of total capital costs per year(Gardarsdottir et al., 2019).

2.3.4. System Boundaries Considered

Cost estimates of bioCCS in literature encompass different components of the CCS system, and therefore different boundaries of cost estimates were considered in this paper (Table 7), both from the perspective of "first of a kind" and "Nth of a kind" cost scaling assumptions.

2.4. CO₂(eq) Avoidance Cost

The CO_2(eq) avoidance cost is the cost per unit reduction in net CO_2(eq) emissions from one system configuration and another, calculated as in Equation 3. In this paper, it is the cost in €$_{2017}$/t CO_2(eq) of reducing the greenhouse gas emissions of cement by retrofitting bioCCS into the system of production. As the cost of CO_2(eq) avoidance depends on both the estimated net emissions and estimated costs, it is presented for each combination of cost and emission system boundaries.

$$\mathrm{CO_2(eq)\ avoidance\ cost} = \frac{\mathrm{Cost\ of\ production\ with\ abatement} - \mathrm{Cost\ of\ unabated\ production}}{\mathrm{CO_2(eq)\ of\ unabated\ production} - \mathrm{CO_2(eq)\ of\ production\ with\ abatement}} \quad (3)$$

3. Results and Discussion

3.1. Accounting for costs

The first component of avoidance cost estimates is the cost of production relative to the unabated system, in this case, the cost of cement with bioCCS in comparison to without. In our model, the cost of unabated cement production was 33€$_{2017}$/t cement (based primarily on Gardarsdottir et al., 2019). While the production of charcoal and monoethanolamine-based capture systems are themselves commercialised technologies, they are not commercialised in the cement industry. Therefore, we considered two cost scaling options: "First of a kind" (FOAK) cost scaling (Fig. 3(a)), which assumes greater contingencies and equipment redundancies for a near-term installation where technological learning is still needed; and "Nth of a kind" (NOAK) cost scaling (Fig. 3(b)), which assumes that bioCCS is available as a fully commercialised technology. Most available studies on bioCCS use NOAK scaling, focusing on the question of what bioCCS *could* cost, once it is fully developed (Roussanaly et al., 2021). FOAK estimates instead consider the question of what bioCCS *would* cost if implemented in the near term.

In our model, the cost of bioCCS costs were dominated by "on-site" costs of fuel switching and CO_2 capture. The most expensive element is the marginal cost of capture (75€$_{2017}$ (63 NOAK) / t CO_2 captured), of which half is the purchase of wood pellets to supply the energy needed for the capture unit, 20% is electricity, and the remaining is chemicals, labour, maintenance, and other operating costs. The difference in operating costs between the FOAK and NOAK cases is explained by the difference in estimated capital costs, as the FOAK capital cost estimate is double that of the NOAK estimate. This, in turn, leads to a 51% higher total "cost of capture" at 133 vs 88€$_{2017}$/t CO_2 captured for FOAK and NOAK, respectively.

Cost of transport and storage was a smaller factor in this model, which assumed 100 km of dedicated pipeline transport, at 24€$_{2017}$ (22 NOAK)/t CO_2 transported and stored, of which half are capital expenses. However, transport costs accounted for the majority of variability in the studies reviewed in (Tanzer et al., 2021b), ranging from 5-368€$_{2017}$/t CO_2, depending on distance and mode of transport. In our model, doubling transport distance to 200 km increased costs by 11€$_{2017}$ (8 NOAK)/t CO_2, primarily from additional pipeline construction, but also 1.5€$_{2017}$ from additional electricity needed for recompression and pumping.

3.2. Accounting for abatement

The other component of avoidance cost estimates is the change in net emissions from the unabated case. In this case, the estimated abatement potential is the net emissions of a present-day cement plant minus the net emissions of that cement plant with bioCCS, which is the "relative abatement" presented in Fig. 4(a) at different system boundaries. Here, the change in apparent relative abatement as system boundaries expand is the difference in how much the apparent net CO_2eq of each case changes as additional parts of their life cycle system are accounted for. As the emissions of cement use are the same for both systems, the relative abatement does not change in that instance, even though both their net CO_2eq increases. Beneath, Fig. 4(b) presents the apparent net emissions and removals, and the resulting net CO_2eq, of both the unabated and bioCCS cement plants for each system boundary. The only thing that changes between the different instances is what emissions and removals are accounted for; the model itself is static. Biogenic CO_2 is assumed to have a 100-year GWP of 0.44 kg CO_2eq/kg Co$_2$bio (Guest et al., 2013) and other greenhouse gases are also characterised by their 100-year CO_2eq GWP (Myhre et al., 2013).

In the unabated case, CO_2 emitted at the cement plant accounts for over 80% of the total CO_2 emissions estimated for production, supply chains, and cement use and disposal. Upstream supply chains account for 99 kg CO_2/t cement, of which 41 kg is from electricity and 15 kg is from coal.

Studies that focus on the technological cost of bioCCS often only account for CO_2 emitted at the industrial plant itself. At this "gate-to-gate" boundary, bioCCS results in an 80% decrease in estimated CO_2 emitted. If the model also assumed that the biomass is "CO_2 neutral", without accounting for other impacts, the bioCCS case appears to be deeply "CO_2 negative". However, in the bioCCS case most emissions occur outside the cement production gates. Besides the 84 kg CO_2 from supply chains of the material and electricity demand of cement production, the biofuel supply chains emit 243 kg CO_2/t cement and the electricity demand of CO_2 capture and compression is also responsible an additional 64 kg CO_2. Downstream, emissions from the transport and storage of CO_2 are less significant in this model, accounting for less than 15 kg CO_2/t cement, though this may not be true for systems that use more carbon-intensive truck transport, as in Silva et al. (2018); Pilorgé et al. (2020).

From a "cradle to grave" perspective that incorporates upstream and downstream emissions of CO_2 in the bioCCS and cement production chains, bioCCS has an apparent avoidance potential of 1028 kg CO_2/t cement, or 144%. However, this metric of relative avoidance does not provide information about the absolute magnitude of net emissions. In bioCCS systems, the combination of emissions and removals also means that the "net CO_2" metric also obscures this information. Furthermore, the total carbon intensity of the system is further obscured if the amount of stored CO_2—here 907 kg/t cement—is not reported. Despite its lower net CO_2 emissions, the bioCCS system *produces* 652 kg/t cement more CO_2 than the unabated system. If the fate of CO_2 was not permanent

Table 8
Avoidance costs by system boundaries of cost and net emission estimates, €$_{2017}$/t CO_2 abated. The future scenarios considered in (c) and (d) are based on those used in Tanzer et al. (2021a). Graphs of the net CO_2(eq) and relative abatement for the future scenarios are available in the appendix (Fig. S2).

	Increase in cement production cost (EUR$_{2017}$/t cement)	gate-to-gate CO_2	gate-to-gate CO_2 assuming "CO_2 neutral" biomass	gate-to-gate CO_2 and electricity	cradle-to-gate CO_2, energy supply chains only	cradle-to-gate CO_2	cradle-to-grave CO_2	cradle-to-grave CO_2eq, including biogenic CO_2 GWP	cradle-to-grave CO_2eq, all GHGs and biogenic CO_2 GWP
(a) using "First of a kind" cost scaling and baseline model parameters									
Apparent abatement of bioCCS system (kg CO_2eq/t cement)		*505*	*1279*	*1220*	*1091*	*1047*	*1029*	*934*	*839*
Kiln fuel switching and CO_2 capture opex	*87*	172	68	71	80	83	85	93	104
...and CO_2 capture capex (annualized)	*140*	277	109	115	128	134	136	150	167
...and CO_2 pipeline transport and storage opex	*149*	295	117	122	137	142	145	160	178
...and CO_2 pipeline transport and storage capex (annualized)	*162*	321	127	133	149	155	158	174	193
(b) using "Nth of a kind" cost scaling, and baseline model parameters									
Apparent abatement of bioCCS system (kg CO_2eq/t cement)		*505*	*1279*	*1220*	*1091*	*1047*	*1029*	*934*	*839*
Kiln fuel switching and CO_2 capture opex	*76*	150	59	62	69	72	74	81	90
...and CO_2 capture capex (annualized)	*98*	195	77	81	90	94	96	105	117
...and CO_2 pipeline transport and storage opex	*107*	212	84	88	98	102	104	115	128
...and CO_2 pipeline transport and storage capex (annualized)	*117*	232	91	96	107	112	114	125	139
(c) using "Nth of a kind" cost scaling and assuming modest improvement in kiln and CO_2 capture efficiencies, and 60% decarbonization of transport and electricity									
Apparent abatement of bioCCS system (kg CO_2eq/t cement)		*494*	*1182*	*1180*	*1066*	*1039*	*1026*	*942*	*903*
Kiln fuel switching and CO_2 capture opex	61	124	52	52	58	59	60	65	68
...and CO_2 capture capex (annualized)	83	167	70	70	77	79	80	88	91
...and CO_2 pipeline transport and storage opex	90	183	76	77	85	87	88	96	100
...and CO_2 pipeline transport and storage capex (annualized)	99	200	84	84	93	95	96	105	110
(d) using "Nth of a kind" cost scaling and assuming optimistic improvement in kiln and CO_2 capture efficiencies, and 100% decarbonization of transport and electricity									
Apparent abatement of bioCCS system (kg CO_2eq/t cement)		*494*	*1064*	*1064*	*971*	*952*	*940*	*872*	*855*
Kiln fuel switching and CO_2 capture opex	51	103	48	48	53	54	54	59	60
...and CO_2 capture capex (annualized)	70	141	65	65	72	73	74	80	81

(*continued on next page*)

Table 8 (*continued*)

	Increase in cement production cost (EUR₂₀₁₇/t cement)	gate-to-gate CO_2	gate-to-gate CO_2 assuming "CO_2 neutral" biomass	gate-to-gate CO_2 and electricity	cradle-to-gate CO_2, energy supply chains only	cradle-to-gate CO_2	cradle-to-grave CO_2	cradle-to-grave CO_2eq, including biogenic CO_2 GWP	cradle-to-grave CO_2eq, all GHGs and biogenic CO_2 GWP
…and CO_2 pipeline transport and storage opex	77	155	72	72	79	81	82	88	90
…and CO_2 pipeline transport and storage capex (annualized)	85	172	80	80	88	89	91	98	100

storage, but instead reuse in short-term products or otherwise re-emitted, the net CO_2 of the bioCCS system would be 595 kg CO_2/t concrete, just 120kg lower than the unabated case.

If bioCCS is to allow for "CO_2 neutral" (or negative) cement production, then it must also produce enough "negative emissions" to compensate for emissions for use and end-of-life of the cement, as well as direct and upstream emissions. Expanding the system to also include downstream emissions of cement use in concrete increases net CO_2 by 115 kg/t cement. Since this is the same for both systems, relative abatement, the metric considered in avoidance cost, remains unchanged.

In studies considering "CO_2 neutral biomass", CO_2 reuptake by biomass is assumed to perfectly offset biogenic CO_2 emissions. However, emitted biogenic CO_2 contributes to global warming during its temporary residence in the atmosphere. For long rotation biomass, this impact can be significant in the short term, with a bioCCS system contributing more CO_2 to the atmosphere than its fossil counterpart in the first third of rotation period (Tanzer et al., 2021a). In this model, we assumed that the timber for charcoal and pellet production has a 100-year rotation period. Accounting for this by using a 100-year global warming potential factor of 0.44 kg CO_2eq/kg biogenic CO_2 (Guest et al., 2013) increases the net CO_2eq of the bioCCS case by 89 kg CO_2eq/t cement.

BioCCS can also have substantial non-CO_2 greenhouse gas emissions. In the unabated system, other greenhouse gases increase the net CO_2eq estimate by 34 kg CO_2eq/t cement—half being fugitive methane from fossil fuel supply chains. In contrast, the net emissions of the bioCCS system increase by 128 kg CO_2eq, of which 60% is CH_4 from charcoal production and 25% is from electricity supply chains.

There are many variables in process configuration, optimisation, and uncertainty that impact the greenhouse gas emissions of a cement system with or without bioCCS, including fuel choice, clinker proportion, electricity source, capture technology, and these are commonly explored in studies about bioCCS in cement(e.g., Obrist 2021, Schackel et al 2018, Tanzer et al 2021). These were not explored here to avoid obscuring the focus of this study, that is, the impact of system boundary selection,

At the broadest system boundaries considered in this paper, bioCCS in cement production is no longer "CO_2eq negative", though emissions are reduced by over 95%. That is, the removal and storage of biogenic CO_2 is insufficient to compensate for the life cycle greenhouse gas emissions of cement production and use, bioenergy production, and CCS. At 16 kg CO_2eq/t cement, the net CO_2eq of this more complete system is 676 kg/t cement higher than estimating only the net emissions from "gate to gate CO_2 with carbon neutral biomass". The estimated relative abatement changed less, decreasing by 439 kg CO_2, as the net CO_2eq of the unabated system also increased with the expanding boundaries, by 238 kg CO_2eq/t cement. Nothing in the cement or bioCCS system has changed, only how comprehensively the emissions and removals were estimated.

3.3. The avoidance cost possibility space

Combining the different system boundaries of near term FOAK cost estimates with those of the "present day" avoidance potential estimates results in avoidance cost "possibility space" in Table 8(a) ranging from 68-321€$_{2017}$/t CO_2(eq) avoided. For each abatement boundary considered, expanding the costs considered from marginal cost of fuel switching and CO_2 capture to the full operating and capital expenses of bioCCS leads to a doubling in the cost of avoidance. In our model capital costs of capture and compression account for 30% of avoidance costs and transport and storage 15%.

The highest avoidance cost estimates are seen when only gate-to-gate abatement is considered. These are higher than the "cost of capture" and "cost of CCS" seen in section 3.1, as more CO_2 is captured (619 kg/t cement) than is abated (505 kg/t cement), as steam provision for CO_2 capture also generates CO_2 that is captured. In contrast, expanding the system boundary to also consider CO_2 removed by biomass—without considering any other impacts outside the cement plant— results in the lowest avoidance cost estimates, 60% lower than the gate-to-gate estimates.

Expanding the system boundaries from "gate to gate with CO_2 neutral biomass" to "cradle-to-grave, CO_2 only" increases avoidance costs by 24%, though CO_2 emissions accounted for in the bioCCS system quadrupled, from 113 kg to 460 kg CO_2/t cement. In contrast, including the global warming potential of biogenic CO_2 and other greenhouse gases also increases cradle-to-grave avoidance costs by 24% from the CO_2-only metric even though the estimated net CO_2eq of the bioCCS system increases by only half as much, 223 kg CO_2eq/t cement from the CO_2 only metric. This apparent incongruity is because the change in CO_2 avoidance cost is not linked with absolute net CO_2(eq) but with the difference between the abated and unabated system. Thus, it does not necessarily reflect the magnitude of changes in accounted absolute emissions or removals.

The avoidance costs discussed above consider near-term estimates for both costs and abatement potential. The few other literature estimates for avoidance costs bioCCS-in-industry typically consider Nth-of-a-kind costs paired with abatement potential estimates that consider present-day efficiencies and background systems (e.g., Onarheim et al., 2017; Santos et al., 2021; Yang et al., 2021). This creates a "tomorrow's technology today" scenario, which is not necessarily intuitive to interpret, as it can both underestimate the avoidance cost of near-term implementation and overestimate the avoidance cost of future implementation.

Table 8(b) shows the avoidance cost estimates using NOAK costs and near-term abatement potential, which are 13-30% lower than the corresponding FOAK estimates, depending on which costs are included. As the cost scaling primarily effects capital costs, the impact is lower for cases that do not fully include annualised capital costs. In contrast, these estimates are 13-27% and 20-40% higher than those shown in Table 8(c) and (d) respectively. These contain avoidance cost estimates using NOAK costs and abatement potentials that include projections of increased efficiencies of cement production and CO_2 capture and decarbonisation of electricity and transport, based on a conservative and optimistic scenario of future technological development. Graphs of the net CO2(eq) of the modest and optimistic scenarios embodied in Table 8

(c) and (d) are provided in the supplementary information.

Though the net CO_2(eq) of the optimistic scenario is lower than those of the conservative scenario, the estimated CO_2(eq) abated is also lower. Partly, this is because the unabated system also has lower estimated net CO_2 in the optimistic scenario. It is also due to the phenomenon of "inefficient bioCCS"; since the clinker kiln optimistic scenario was assumed to be more efficient and therefore require less (bio)fuel, it resulted in less CO_2 being removed from the atmosphere from biomass production (Mac Dowell and Fajardy, 2017). While the optimistic scenario has lower overall resource use, this is not embodied in either the metric of net CO_2(eq) or CO_2(eq) avoidance cost.

The model in this paper only accounted for direct, physical emissions and removals of greenhouse gases in the modelled bioCCS system. However, estimates of abatement potential and avoidance cost sometimes also incorporated "avoided emissions", such as those that are assumed to be displaced by the use of a (by)product from the system, (e.g., Berghout et al., 2019; Giuliano et al., 2020; Hailey et al., 2016; Meerman and Larson, 2017; Schakel et al., 2018; Yang et al., 2021). A common example is to assume that electricity cogenerated by at the industrial production site replaces electricity produced by the grid, and therefore the grid-average emissions of that amount of electricity is deducted from that system's net CO_2.

Avoided emissions are typically accounted for by subtracting them from the net CO_2 in the same manner as for physical removal of atmospheric CO_2. However, avoided emissions do not represent a physical reduction in atmospheric CO_2, but rather a rather an assumed reduction in CO_2 emitted. When avoided emissions are accounted for in the same metric as physical flows, it can lead to a "negative" net CO_2(eq) estimate without physical removals of CO_2 exceeding physical emissions (Tanzer and Ramírez, 2019). This can be particularly confusing for technologies such as bioCCS, as it can lead to apparent negative emissions without physical negative emissions occurring. Therefore, we advocate that avoided emissions should always be separated from the net CO_2(eq) metric for physical emissions and removals.

When avoided emissions result from the sale of a byproduct, it also adds complication to CO_2(eq) avoidance cost, as it changes both the estimate of abatement potential and net cost. Care is needed to align the assumptions used for calculating avoided emissions and byproduct prices. Returning to the example of excess cogenerated electricity, if it is assumed to displace grid-average generation, then grid-average pricing should be assumed. If it is assumed to be sold at a premium, or receive a credit, for being low-carbon, then it should also be assumed to displace comparable low-carbon electricity. Similarly, for electricity in particular, it should be considered whether the profile of the cogenerated electricity would be more likely to replace constant base load or variable peaking electricity generation, and apply the costs and emission factors appropriate for that type of generation. Otherwise, inconsistent assumptions can further decrease the accuracy of the avoidance cost estimates.

4. Conclusions

BioCCS is a complex carbon-intensive technology system whose primary goal of bioCCS is "negative emissions", a net decrease in atmospheric CO_2. The use of bioCCS in carbon-intensive industries has the potential to allow for "CO_2(eq) neutral" or "CO_2(eq) negative" production, if the negative emissions produced via bioCCS are sufficient to compensate for CO_2 emitted in the life cycle of the industrial product. Clear and comprehensive metrics of the abatement potential and cost of bioCCS are needed to make informed decisions of when bioCCS is an effective abatement option and when can it result in negative emissions.

In this paper, we evaluated the case of bioCCS integration into cement production under different system boundaries to understand the impact of these modelling choices on estimates of net greenhouse gas emissions and costs. Depending on the system boundaries considered, estimates for net greenhouse gas emissions for a near-term retrofit of bioCCS into a cement plant ranged from -660 to 16 kg CO_2eq/t cement; cost estimates ranged from 87 to 162€$_{2017}$/t cement; and CO_2(eq) avoidance cost from 68 to 321€$_{2017}$/t CO_2(eq) abated.

In the case of unabated coal-based cement production, 72% of all emitted greenhouse gases occurred at the cement plant itself. However, for the bioCCS case, 82% of emissions—and all CO_2 removals—occur outside of the cement plant gates. If CO_2 removals are considered without also considering the emissions from supply chains of biomass and other inputs, the net CO_2 estimate can be dramatically underestimated. Additionally, as the net CO_2(eq) metric contains both emissions and removals and does not consider CO_2 stored, it obscures that the bioCCS case is more carbon intensive than the unabated case. Similarly, small changes in avoidance cost can hide large changes in estimated emissions, as only the relative difference in net CO_2(eq) between the unabated and bioCCS systems is considered. Avoidance cost can also obscure misalignment between cost and abatement estimates, such as when "Nth of a kind" cost estimates are paired with a "present day" abatement estimate, leading to an underestimate of near-term avoidance cost or an overestimate of future avoidance cost.

To increase the comparability and usefulness of bioCCS avoidance cost estimates, we propose the following guidelines to ensure that estimates maintain a minimum level of completeness and transparency and align with the nature of bioCCS as a potential negative emission technology:

1. Estimates of abatement potential should include emissions throughout both the chain of biomass production and CO_2 transport and storage. As the crux of bioCCS the removal and permanent storage of atmospheric CO_2, the full impacts of both these processes must be included.
2. Only physical emissions and removals of greenhouse gases should be included in the "net CO_2(eq)" metric of bioCCS; virtual abatement, such as avoided emissions from byproduct sales, should always be accounted for separately. This prevents the potential appearance of "net negative CO_2(eq)" without physical net removal of CO_2.
3. The fate of the captured CO_2 should always be explicitly stated and estimates of bioCCS costs must include the transport of CO_2 to permanent storage, as this is a fundamental component of bioCCS's abatement potential.
4. Emissions of other greenhouse gases, and the global warming potential of long-rotation biomass should always be explicitly treated. If they are excluded from the study, this should always be mentioned, and the conclusions should be limited accordingly.
5. The temporality of the study should be explicitly stated, with costs and abatement potentials both aligned to the timeframe considered.
6. Assessment of "carbon neutral" industrial production should also include the full life cycle emissions of the industrial product considered.

Applying these guidelines to the bioCCS case in this paper, the range of avoidance cost estimates would shrink from 48-321€$_{2017}$/t CO_2(eq) avoided to 157-193€$_{2017}$/t for near-term estimates, depending on which greenhouse gases are considered, and to 89-107€$_{2017}$/t for longer-term estimates depending on the greenhouse gas and future technology scenario considered.

Furthermore, given the limitations of single-point metrics of net CO_2(eq) and CO_2(eq) avoidance cost, we propose that studies on costs or abatement of bioCCS always also provide clearly decomposed metrics. For costs, we recommend that the cost of CO_2 capture, transport, and storage be presented separately—as is also recommended by Roussanaly et al. (2021)—as well as the cost of fuel switching, if relevant. These should be presented prior to the inclusion of any assumed taxes, subsidy, credit, or byproduct sales to clarify the technological cost from assumptions of broader economic circumstances. For emissions, we recommend the independent presentation of on-site and off-site CO_2(eq) emissions; CO_2 removals by biomass; CO_2 permanently stored; and

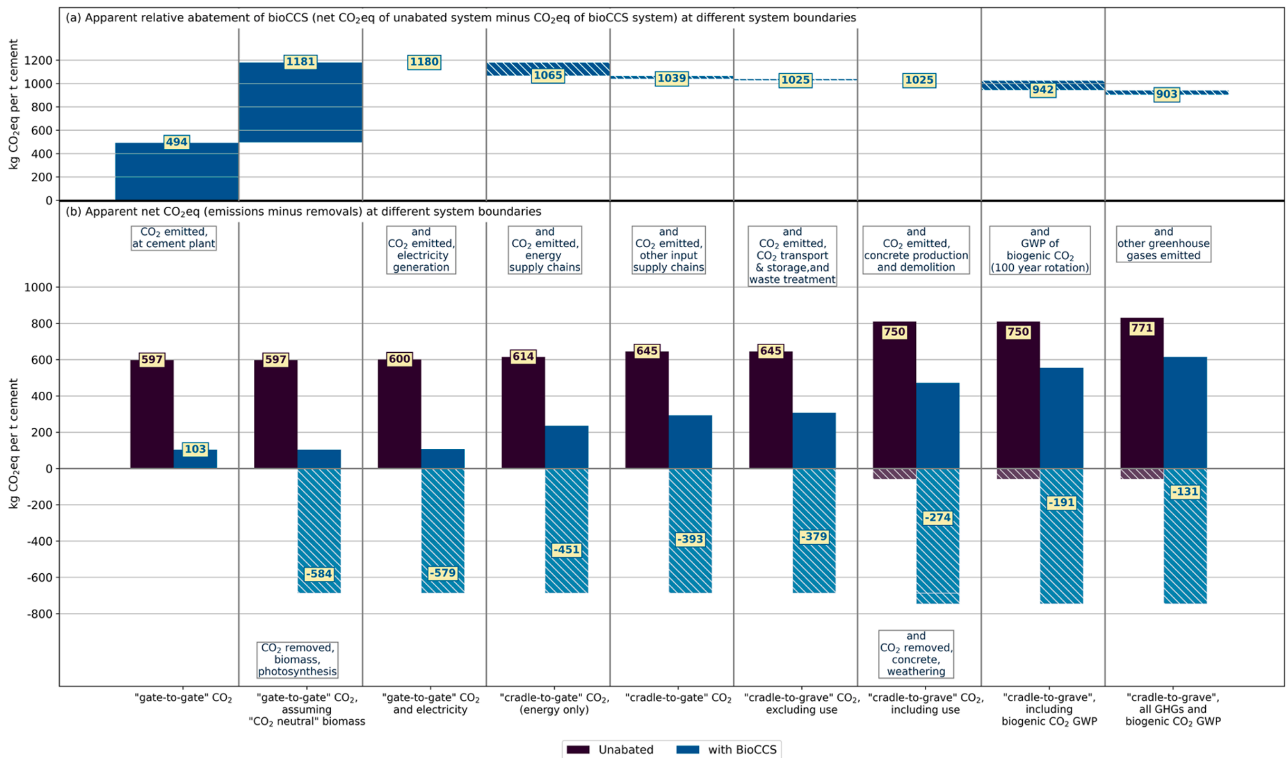

Fig. S1. Net CO_2 of future cement production from different system boundaries, conservative scenario (Tanzer et al., 2021).

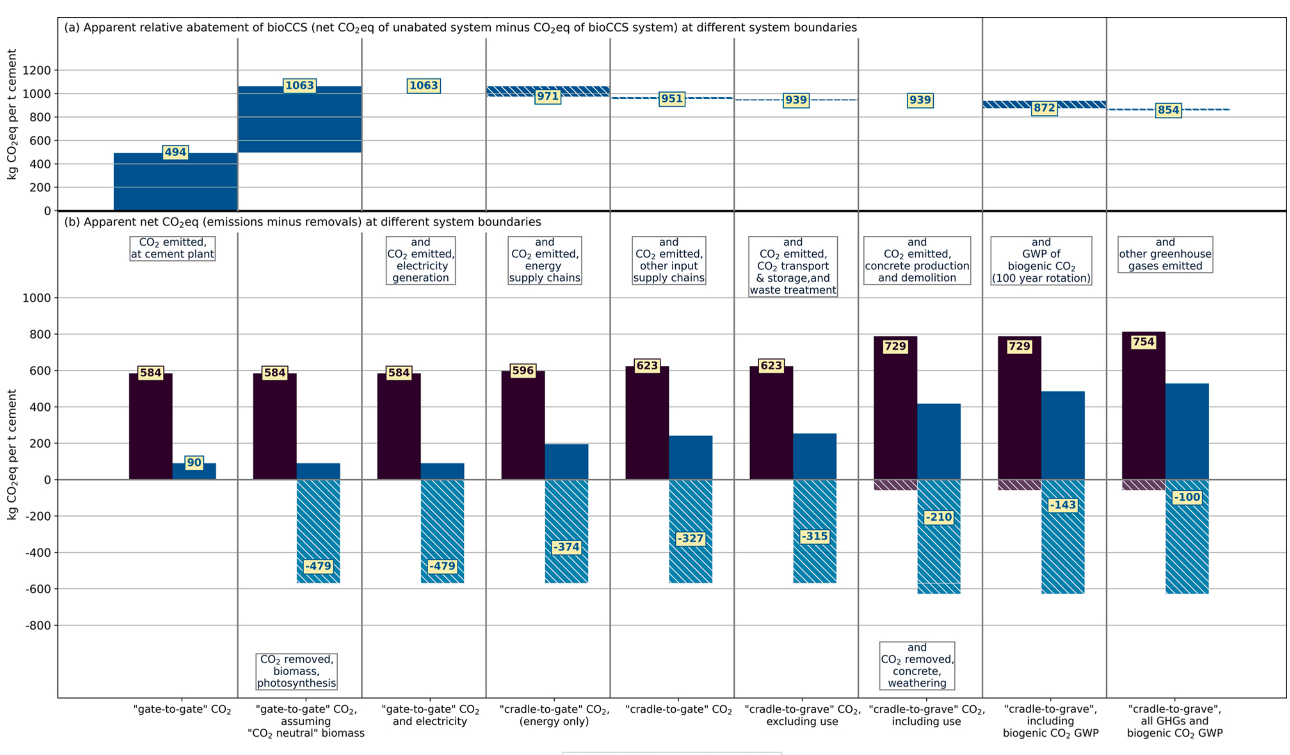

Fig. S2. Net CO_2 of future cement production from different system boundaries, optimistic scenario (Tanzer et al., 2021).

virtual abatement of CO_2(eq). This will allow for easier comparison between studies as well as a clearer assessment of the carbon intensity of bioCCS systems, which is obscured in the net CO_2(eq) metric.

Strategic choices in system configuration—the type of biomass use, the method and distance of transport, the efficiency of CO_2 capture or the industrial production, the system of electricity generation—can decrease the net emissions of a bioCCS system. Similarly, technological choices and technological learning will reduce costs of implementation. However, without comprehensive, transparent, and comparable estimation, it is not possible to understand the significance of those choices.

Table 9
Process Model Parameters.

Parameter	Qty	Unit	Data Source
Meal Grinding, Ball Mill			
Limestone	745	kg/t meal	Schakel et al. (2018)
Clay	135	kg/t meal	Schakel et al. (2018)
Iron ore	23	kg/t meal	Schakel et al. (2018)
Bauxite	33	kg/t meal	Schakel et al. (2018)
Clay	3	kg/t meal	Assumed (to close mass balance)
Electricity	12	kWh/t meal	Worrell et al. (2007)
Transport of raw materials, by train	200	km	Assumed
Clinker Production, Short Dry Kiln with Precalciner and Preheater			
Raw meal	1.57	t/t clinker	
Calcination efficiency	100	%	Assumed
Thermal energy demand	3.3	GJ/t clinker	European Commission (2013)
Electricity demand	23	kWh/t clinker	Worrell et al. (2007)
Cement Mixing, Roller Mill			
Clinker	737	kg/t cement	Gardarsdottir et al. (2019)
Gypsum	50	kg/t cement	Assumed
Fly ash	213	kg/t cement	Assumed
Electricity demand	16	kWh/t clinker	Worrell et al. (2007)
CO_2 Capture, monoethanolamine solvent absorption			
Capture efficiency	90	% of CO_2 in	
Electricity demand	38	kWh / t CO_2 captured	Gardarsdottir et al. (2019); IEAGHG (2013)
Heat demand	3.2	GJ / t CO_2 captured	Assumed, based on literature review of MEA capture
Solvent makeup demand	1	kg / t CO_2 captured	Assumed, based on literature review of MEA capture
H_2O demand	473	kg / t CO_2 captured	Gardarsdottir et al. (2019)
CO_2 Compression, to 110 bar			
Compression losses	0	%	assumed
Electricity demand	106	kWh / t CO_2 compressed	Gardarsdottir et al. (2019)
Heat demand	2.6	MJ / t CO_2 compresssed	Gardarsdottir et al. (2019)
Steam Boiler			
Efficiency	90	%	
Electricity demand	5	kWh / GJ steam	Tanzer et al. (2020)
Flue Gas Cleaning			
Electricity demand	11.4	kWh / t CO_2 in flue gas	IEAGHG (2008)
Water demand	9.2	kg / t CO_2 in flue gas	IEAGHG (2008)
NH_3 demand	6	kg / t CO_2 in flue gas	IEAGHG (2008)
NaOH demand	0.1	kg / t CO_2 in flue gas	IEAGHG (2008)
$CaCO_3$ demand	1	kg / t CO_2 in flue gas	IEAGHG (2008)
CO_2 transport by pipeline and injection to geologic storage			
Losses	1	% of CO_2 stored	assumed, based on Schakel et al. (2018) and IPCC (2005)
Transport distance, onshore	100	km	assumed
Transport distance, offshore	10	km	assumed
Electricity demand, transport	3	kWh / t CO_2 transported	Knoope et al. (2014)
Electricity demand, storage	7	kWh / t CO_2 stored	Khoo and Tan (2006)
Charcoal Production, Missouri-style kiln			
Timber demand	2.7	t timber (dry mass) / t charcoal	Pennise et al. (2001)
CO_2 emissions	540	kg CO_2 / t charcoal	Pennise et al. (2001)
CH_4 emissions	1022	kg CO_2eq / t charcoal	Pennise et al. (2001)
Carbon efficiency	69	% of C in wood in charcoal	Pennise et al. (2001)
Natural carbonation			
Service life	50	years	assumption
Exposure conditions	Outdoors, Exposed to rain; Indoors, Covered		assumption
Ks	1.76, 4.84	mm/$\sqrt{}$year	European Committee for Standardization (2017), Annex BB.1
Surface area	5, 5	m^2	assumption
Degree of carbonation	0.85, 0.4	%	European Committee for Standardization (2017), Annex BB.1

CRediT authorship contribution statement

Samantha Eleanor Tanzer: Conceptualization, Software, Visualization, Writing – original draft, Writing – review & editing. **Kornelis Blok:** Supervision, Writing – review & editing. **Andrea Ramírez Ramírez:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Table 10
Upstream CO_2 parameters used in life cycle greenhouse gas accounting.

Upstream CO_2	CO_2 only	Total GHGs (CO_2eq, 100year GWP)	unit	Data source
Aggregate	5.1	5.2	kg CO_2eq / t	Gravel, round {CH},market for gravel, round, Wernet et al. (2016)
Ammonia	2535	2723	kg CO_2eq / t	Ammonia, anhydrous, liquid {RER},market for ammonia, anhydrous, liquid, Wernet et al. (2016)
Bauxite	25.7	26.7	kg CO_2eq / t	Bauxite {GLO},market for bauxite, Wernet et al. (2016)
Clay	9.6	10	kg CO_2eq / t	Clay {CH},market for clay, Wernet et al. (2016)
Coal	168	358	kg CO_2eq / t	Hard coal {Europe, without Russia and Turkey},market for hard coal, Wernet et al. (2016)
Concrete, production	132	145	kg CO_2eq / t	Concrete, normal {CH},unreinforced concrete production, with cement CEM II/B (excluding cement production)
Concrete, demolition	8.3	8.3	kg CO_2eq / t	Waste concrete {Europe without Switzerland},market for waste concrete, Wernet et al. (2016)
Electricity, direct	390	n.a.	kg CO_2eq / MWh	European Commission (2020)
Electricity, upstream	26	57	kg CO_2eq / MWh	market group for electricity, medium voltage RER, Wernet et al. (2016), minus direct CO_2 intensity of NL 2017
Gypsum	7.2	7.6	kg CO_2eq / t	Gypsum, mineral {RER},market for gypsum, mineral, Wernet et al. (2016)
Iron ore	47	49	kg CO_2eq / t	market for iron ore, crude ore, 46% Fe GLO, and Iron ore, crude ore, 63% Fe {GLO}, market for iron ore, crude ore, 63% Fe, Wernet et al. (2016) (50/50 split)
Limestone	4.8	5.1	kg CO_2eq / t	Limestone, crushed, washed {CH},market for limestone, crushed, washed, Wernet et al. (2016)
Monoethanolamine	2878	3254	kg CO_2eq / t	Monoethanolamine {GLO},market for, Wernet et al. (2016)
Monoethanolamine, disposal	1956	1975	kg CO_2eq / t	Spent solvent mixture {Europe without Switzerland},treatment of spent solvent mixture, hazardous waste incineration, Wernet et al. (2016)
Natural gas	285	458	kg CO_2eq / t	Natural gas, high pressure {Europe without Switzerland},market group for, Wernet et al. (2016)
Sand	10.9	11.4	kg CO_2eq / t	Sand {RoW},market for sand, Wernet et al. (2016)
Sodium hydroxide	1212	1337	kg CO_2eq / t	Sodium hydroxide, without water, in 50% solution state {GLO},market for, Wernet et al. (2016)
Timber, for charcoal	44	47	kg CO_2eq / t	Cleft timber, measured as dry mass {Europe without Switzerland},market for, Wernet et al. (2016)
Transport, lorry	0.1	0.1	kg CO_2eq / tkm	Transport, freight, lorry >32 metric ton, euro6 {RER},market for transport, freight, lorry >32 metric ton, EURO6, Wernet et al. (2016)
Transport, pipeline, onshore	0.05	0.06	kg CO_2eq / tkm	Transport, pipeline, onshore, long distance, natural gas {RER},market for transport, pipeline, onshore, long distance, natural gas, Wernet et al. (2016)
Transport, pipeline, onshore	0.05	0.06	kg CO_2eq / tkm	Transport, pipeline, offshore, long distance, natural gas {RER},market for transport, pipeline, offshore, long distance, natural gas, Wernet et al. (2016)
Transport, rail	0.05	0.05	kg CO_2eq / tkm	Transport, freight train {Europe without Switzerland},market for, Wernet et al. (2016)
Water	0.3	0.4	kg CO_2eq / t	Tap water {RER},market group for, Wernet et al. (2016)
Waste water, disposal	0.3	0.4	kg CO_2eq / t	Wastewater from concrete production {CH},market for wastewater from concrete production, Wernet et al. (2016)
Wood pellets	695	709	kg CO_2eq / t (dry)	Wood pellet, measured as dry mass {RER},wood pellet production, Wernet et al. (2016)
Infrastructure Use - charcoal kiln	5.1		kg CO_2eq/ t	extracted fro Charcoal {GLO} Wernet et al. (2016)
Infrastructure Use - wood pellet	2.4	2.5	kg CO_2eq/ t	extracted from Wood pellet, measured as dry mass {RER}, wood pellet production
Infrastructure Use - Cement production	3.2	3.2	kg CO_2eq/ t	extracted from Cement, alternative constituents 6-20% {Europe without Switzerland}, production
Infrastructure Use - CO_2 Capture	<0.001	<0.001	kg CO_2eq/ t	Koornneef et al. (2008)
Infrastructure Use - Selective Catalytic Reduction	<0.001	<0.001	kg CO_2eq/ t	Koornneef et al. (2008) (assumed to be the same as for CO2 capture)
Infrastructure Use - Steam Boiler	0.5	0.5	kg CO_2eq/ GJ	extracted from heat, district or industrial, other than natural gas {CH} heat production, softwood chips from forest, at furnace 1000kW

Appendix

1. Abatement potential of future cement product scenarios

2. Model Parameters

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