LIFE CYCLE ASSESSMENT

Lowering emissions in the cement industry

CRe

As the first European venture capital fund, Planet A relies on its own scientific team to assess the environmental and climate impact of an innovation. Prior to an investment, a life cycle assessment, like this one, is conducted and integral part of the investment decision. All assessments as well as the methodology is published for maximum transparency.

Terminology and abbreviations

AI	Artificial intelligence
CED_f	Cumulative fossil energy demand
CO_2-eq.	Carbon dioxide equivalents
EU	European Union
Functional unit	Quantified performance of a product system for use as a reference unit
GHG	Greenhouse gas
LCA	Life Cycle Assessment
ML	Machine learning
RoW	Rest of the World
USA	United States of America

About CarbonRe

CarbonRe uses artificial intelligence (AI) and machine learning (ML) algorithms to reduce the energy demand of carbon and energy intensive industries. Building a digital twin of plants, they simulate plant operations. CarbonRe software identifies energy reduction potentials and advises their customers how to optimize energy efficiency. As a first product, CarbonRe developed a tool that optimizes fuel efficiency in cement production.

Summary

This Life Cycle Assessment (LCA) evaluates potential changes in greenhouse gas (GHG) emissions and cumulative fossil energy demand of fuel consumption in the cement production. Cement production is an energy intensive industry. Currently, the kiln is the largest energy consumer within the whole process. Its **fuel-derived emissions account for around 40 % of total GHG emissions of clinker production.**

Commonly used Portland cement is made of 95 % clinker. With the help of an AI based software for the cement industry, Carbon Re can reduce the fuel consumption of the clinker production, saving **up to 12% of a cement plant's fuel demand**.

Globally, 81 % carbon-intensive fossil fuels are used. **Petroleum coke and hard coal are the most carbon-intensive of all commonly used fossil fuels, while biomass waste and alternative fuels have a significant positive impact on the performance of the fuel mix regarding GHG intensity.**

CarbonRe AI can **reduce cumulative emissions of 110 Mt CO_2-eq per year** (total addressable market (world without China)). This reduction potential corresponds to **4 % of global emissions from cement production** in 2020.

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1 About this study

Cement is a widely used and important construction material, which is predominately used in the buildings sector. The **cement industry is responsible for about 3% of the European Union's** (Emele, Graichen, and Mendelevitch 2022) **and about 7 % of global greenhouse gas (GHG) emissions** (Crippa, M. et al. 2021; Vass et al. 2021)**.** These high emissions originate first, in chemical reactions from the manufacturing process itself. And second, cement production requires a large amount of thermal energy, which is currently produced with large amounts of fossil fuels.

The kiln (and if applicable the calciner for pre-heating) is essential to produce the pre-product clinker. **It is the largest energy consumer** within the whole cement production process. Its **fuel derived emissions account for around 40 % of total emissions** from cement production, while the process related emissions of the calcination reaction comprise about 50 % (Fischedick et al. 2014). The fuel derived emissions can be improved without any changes in the current cement making process, while the process related emissions require an increase in material efficiency or a change in the whole cement recipe (Fischedick et al. 2014).

Due to the high impact of energy consumption within the clinker production, CarbonRe initially focuses on improving this process step. With the help of an **AI based software for the cement industry**, Carbon Re wants to significantly reduce the fuel consumption of clinker production. This Life Cycle Assessment (LCA) **evaluates the potential changes in resource use and GHG emissions arising from reduced fuel consumption for cement production** that can be achieved by using the CarbonRe AI tool.

2 System description

The CarbonRe AI modifies parameters related to fuel consumption at the kiln, where the clinker is produced at temperatures of around 1450° C (Fischedick et al. 2014). Commonly used Portland cement is made of 95 % clinker.

Figure 1 gives an overview of the cement production process (most of the gray steps) and the influence of the CarbonRe software: The cement production starts with the extraction of raw materials - mostly limestone. These are transported to the mill, where they are ground and dried. The so-called 'raw meal' is then either directly fed into the kiln or goes into a preheater or precalciner first, where fuel is injected to provide the energy required. At a precalciner, decarbonisation of the limestone starts and then continues in the kiln. Afterwards, the clinker is cooled down and mixed with a small amount of gypsum. Finally, it has to be grounded in the cement mill to produce the final product, cement powder (Summerbell 2017).

The **process steps** of Figure 1 highlighted in green depict the fuel production and consumption process at the kiln (and precalciner). This process comprises the **system boundaries of this LCA**. It starts with the extraction and transport of raw materials. Production of fuel, if necessary, and then burning of the fuels in the kiln (and preheater or precalciner), releases the respective process emissions. The CarbonRe software influences the amount of fuel burned which, in turn, affects the amount of GHG emissions.

We assess the CarbonRe impact on a **system level using a consequential LCA approach**. Hence, we calculate systemic emission reduction potentials from reductions in fuel use at a cement plant. Orange process steps (Figure 2) depict reductions from reduced fuel use. All kinds of fuel reductions at a cement plant influence the amount of fossil fuels used in the whole system. Certain fuels used in kilns are wastes which need to be treated. The thermal energy recovery (in cement kilns) is the only feasible way to handle these wastes. A reduction in energy demand might also reduce the demand for such fuels. However, since these wastes will be incinerated anyways elsewhere, they are likely to be used elsewhere to provide energy: they thus substitute the use of fossil fuels elsewhere.

CarbonRe's software does not affect the clinker and cement production process aside from a reduction in energy demand. This assessment evaluates the impact of reducing the energy demand. Hence, other process-related impacts are not part of the assessment (gray processes in Figure 1).

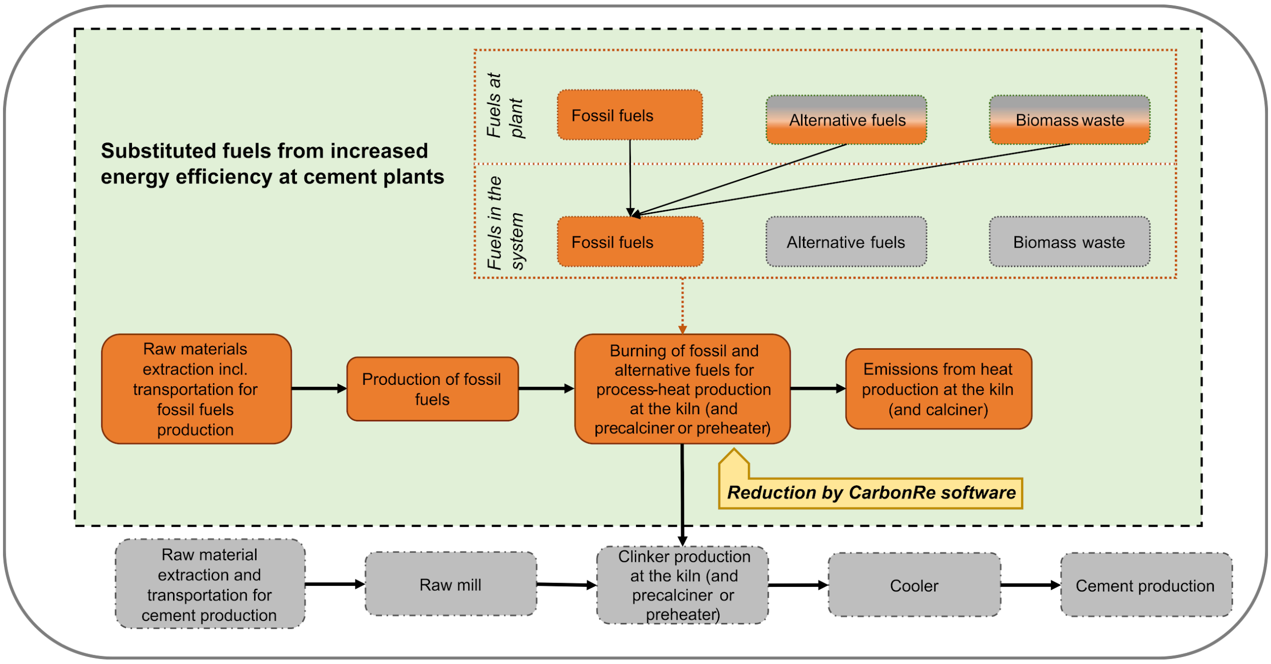

Figure 1 *Depiction of system boundaries. The* ***gray*** *process steps do not change, e.g. the whole cement production process while* ***orange*** *processes depict reductions due to increased energy efficiency.*

2.1 Functional unit and assessed indicators

The functional unit chosen is ***one tonne of clinker*** improved with CarbonRe's software.

The system is assessed using the following indicators

- **GHG emissions/climate change** (Intergovernmental Panel on Climate Change (IPCC) 2014)
- **Cumulative fossil energy demand** - CED_f (Verein Deutscher Ingenieure (VDI) (ed.) 2012).

2.2 Data availability and quality

CarbonRe provided data about potential energy savings from one pilot plant. Market data about geographically specific fuel mix and plant configuration stem from literature research. To assess potential emission savings, we gathered data on specific Scope 1 emissions and heating values in scientific literature, while Scope 3 emissions come from the ecoinvent Database v. 3.8 (see paragraph 3.1 for detailed Scope description).

2.3 Cement production plants and technologies

Two types of cement production plants exist on the market: Integrated plants, which cover the whole production process described above (see chapter 2, Figure 1), and grinding plants, which cover only the last process step of grinding the clinker into the final product cement. Due to efficiency increases, most plant operators nowadays focus on integrated plant construction and operation. **In Europe, 90 % and**

globally already over 91 % of all cement plants are integrated according to total production capacity (Cembureau 2018; Global Cement 2015; IEA 2020).

Furthermore, plants can operate with four different kiln technologies that differ in total energy consumption. Here, theoretically achievable values differ from actual energy consumption of currently implemented technologies. The theoretically achievable values range from 1.76 GJ/t clinker to 6.34 GJ/t clinker (Summerbell, Barlow, and Cullen 2016).

Table 1 gives an overview of the average energy consumption of technologies currently implemented and of the thermal energy consumptions of cement factories in different regions. It is important to mention that long wet kilns are an outdated technology, which is only used in old cement plants (about 2 % of the whole market) and not targeted by CarbonRe. **The average energy consumption of the remaining three kiln technologies is 3.9 GJ/t clinker**.

Table 1 Average *energy consumption of different kiln technologies (Summerbell 2017) in different regions in 2019 (gcca 2022a).*

Technology	Average energy consumption in GJ/t clinker	Country/Region	Average energy consumption in GJ/t clinker
Long wet kiln	6.34	Europe	3.65
Long dry kiln	4.49	India	3.10
Dry kiln with preheater	3.70	North America	3.83
Dry kiln with precalciner	3.38	Northeast Asia	3.14
		World average	3.46

2.4 Life Cycle Inventory

This chapter comprises an overview of the cement market as well as country shares of the worldwide production volume of cement. Furtheron, different fuel mix composition will be explained.

2.4.1 Overview of the cement market

China, with 52 %, is the largest cement producer in the world, followed by India, the European Union (EU) and the United States (USA) (Cembureau 2020; gcca 2022b). See Figure 2. for an overview of the market shares of the world's largest cement producing countries.

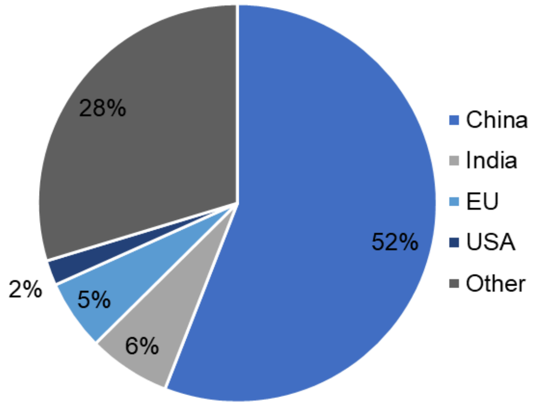

Figure 2 *Market share in global cement production (gcca 2022).*

2.4.2 Fuel mix in the cement market

The fuel mix, used to provide the thermal energy required by the kiln, is essential to estimate emissions and corresponding emission reduction potentials from increased energy efficiency. In the cement industry **fossil fuels are the primary energy source** of the kiln. In cement kilns, the following fuels are used:

- **Primary fossil fuels** are mainly based on coal and petroleum coke; oil, natural gas or other fossil sources like blast furnace or converter gas can also be used (gcca 2022a; Zitscher et al. 2020). While the average EU fuel mix already consists of about 40 % alternative fuels and biomass waste, other countries like India still primarily use fossil fuels to provide thermal energy for the kiln (Cembureau 2018; gcca 2022a; Global Cement 2021).
- **Alternative fuels** usually consist of different kinds of industrial and non-industrial waste. They can be of fossil origin as well.
- **Biomass waste** comes from renewable residues.

The actual fuel mix varies across different geographical regions. In this LCA, we **compared and evaluated the fuel mixes of the largest cement producing countries:**

1. **World**[1]

   The fuel mix contains 81 % fossil fuels, approximately 13 % alternative fuels and 6 % biomass waste (gcca 2022a). Figure 3 depicts this fuel mix with all contributing fuel sources per fuel type (fossil, alternative fuels, biomass waste).

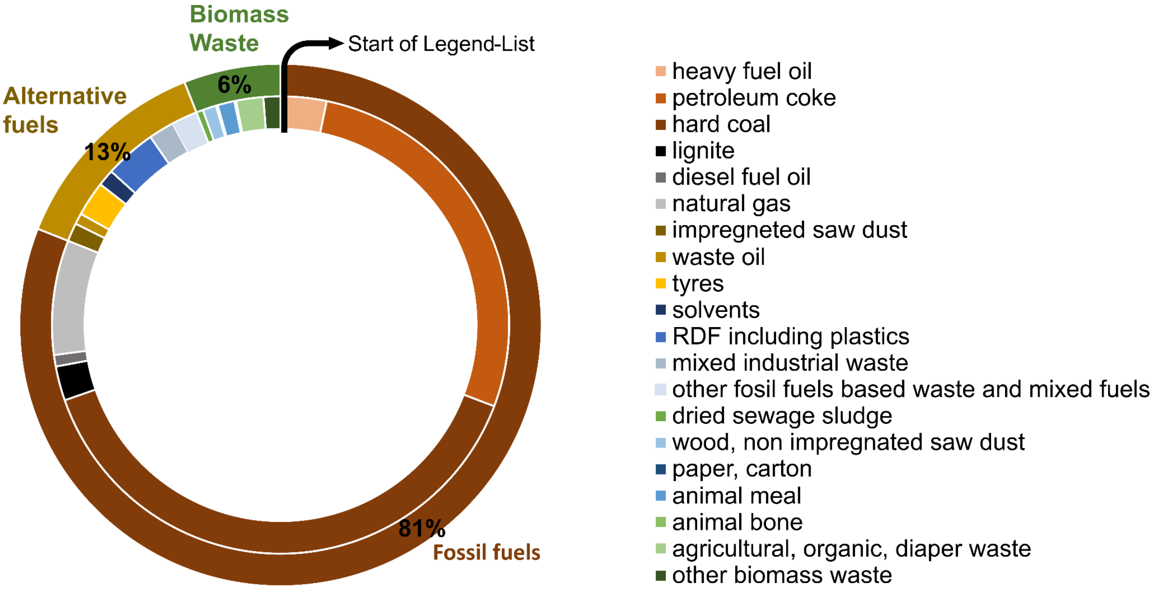

Figure 3 *Global fuel mix for cement production (gcca 2022a). Abbr.: RFD - refuse derived fuels.*

2. **India**

   In India, **coal and petroleum coke** are the major energy providers in clinker production. During the corona pandemic the prices for petroleum coke have risen due to less refinery output. This led to a change in the fuel mix from petroleum coke to coal. The share of waste remained stable.

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[1] The (gcca 2022a) reports collect data regarding cement and concrete manufacturing. The GCCA reports a mix containing only 23 % of Chinese cement manufacturers (year 2019). Due to unavailability of other data, this mix has been taken as the global fuel mix.

The current average Indian fuel mix (year 2021) consists of **53 % petroleum coke, 36 % coal mix and 11 % waste** (Global Cement 2021).

3. European Union

The EU cement fuel mix comprises **30 % alternative fuels and 16 % biomass waste**. The remaining **54 % are fossil fuel** based (Somers 2022). Germany, as the largest cement producing country in the EU, already has a share of 69 % non-fossil primary fuels *(VDZ Technology GmbH 2020)*. Figure 4 shows the sources of the German alternative fuel mix in clinker production.

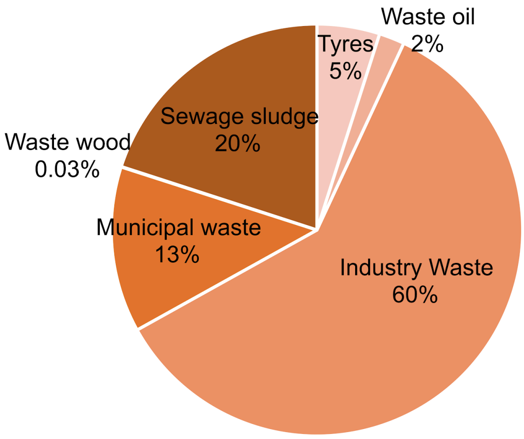

Figure 4 *Alternative fuel mix of German cement production (VDZ Technology GmbH 2020).*

Such high shares of alternative fuels are mainly driven by the EU Emission Trading System (EU-ETS) (Ecofys 2009). The decision on the fuel mix depends on the availability and the prices of fuels (Global Cement 2021).

4. USA

73 % of all American cement plants are currently using alternative fuels. The USA's fuel mix comprises **64 % coal and coke, while 17 % of the fuel is sourced from different kinds of waste**. The rest of the thermal energy is generated from natural gas (17 %) and petroleum products (1.3 %) (Bohan 2019).

5. China

In China, **cement plants use almost exclusively fossil fuels to provide thermal heat** (IEA 2018). Almost all available scientific literature considers **coal as the single source of thermal energy**, cf. (Xu, Xue, and Rehman 2022; Li, Ma, and Chen 2017; Shen et al. 2015). Recently, the use of alternative fuels was promoted.

3 Results

This chapter comprises the results of our LCA. In chapter 3.1, we focus on GHG emissions and resource demand of different fuel types used in the clinker production process. The overall net reductions in GHG emissions and resource utilization that can be achieved by using CarbonRe's optimization tool is discussed in chapter 3.2.

3.1 Life Cycle Assessment of fuel derived emissions from clinker production

3.1.1 Impact on GHG emissions

GHG emission factors for fossil fuels contain direct (Scope 1) emissions, which are released at the plant, and indirect (Scope 3) emissions, which originate from downstream processes before fuel arrives at the cement plant. Alternative fuels (and biomass waste), on the other hand, only comprise Scope 1 emissions, because they would have been incurred in any case and just undergo a different treatment process than before.

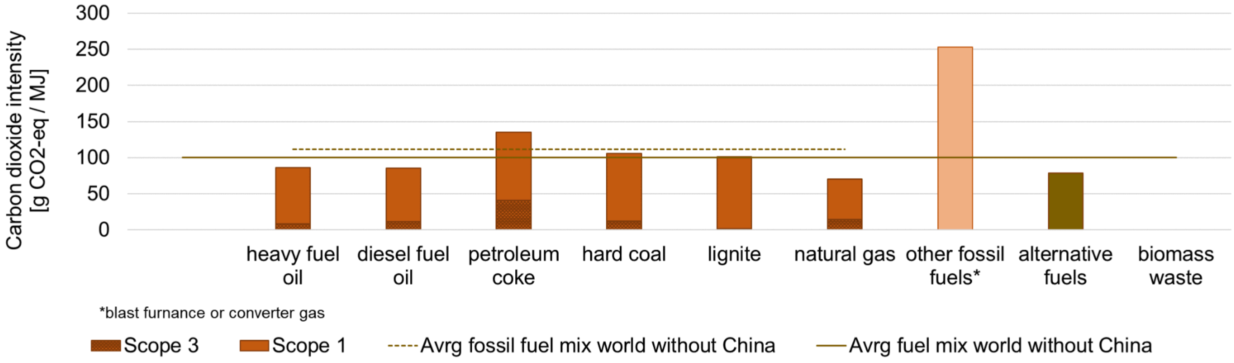

Figure 5 *Carbon dioxide intensity of fuels in the cement industry.*

Figure 5 shows that **petroleum coke is the most carbon intensive of all commonly used fossil fuels**. Petroleum coke, hard coal and fuels contained in the category "*other fossil fuels*" are the only fuels that are above the average fuel intensity of the "world without China" fuel mix. The category "*other fossil fuels*" comprises i.a. blast furnaces and converter gas.

From an environmental perspective these three should thus be the first fuels to be reduced or substituted. It should be noted that petroleum coke and blast furnaces or converter gas are by-products of other industrial processes, which need some kind of treatment. Even if the energy demand in kilns decreases, these by-products will still be provided to the market (inflexible supply). Due to high energy intensity, it is very likely that on a systems level no emission reductions from either of these three fuels can be achieved. Even if they will not be burned in a cement plant, they will be used as an energy source elsewhere. Germany is the only country reporting the use of furnace and converter gas.

Biogenic CO_2 emissions released from the combustion of biomass waste are treated as carbon neutral as these emissions have already been captured by plants (Smith, P. et al. 2014). Therefore, biomass waste is the best and most preferred option to reduce GHG emissions of the fuel mix. Detailed emission factors and sources can be taken from Tables A.1 and A.2 in the Annex.

Looking at the global fuel mix as a whole (Figure 6), hard coal and petroleum coke contribute most to the total fuel mix emissions. Total emissions can be reduced substantially by using biomass.

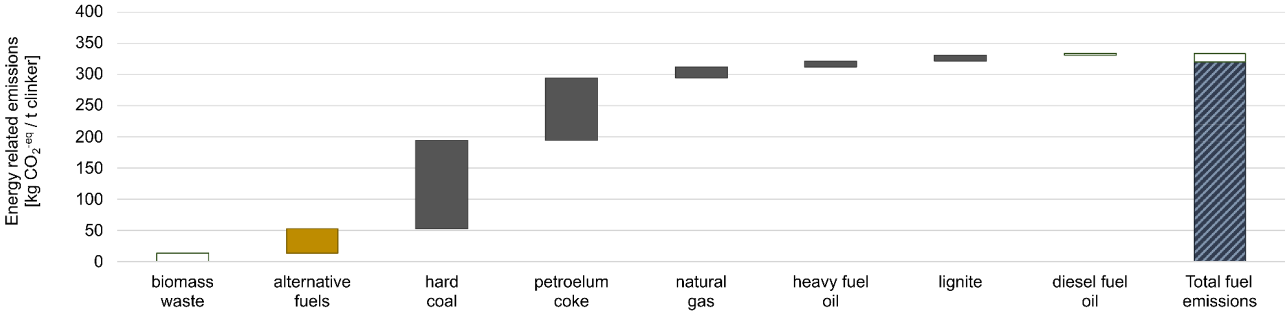

Figure 6 *Contribution of fuels to overall fuel mix GHG emissions (world without China).*

3.1.2 Impact on fossil resource demand

The indicator "fossil resource demand" is only affected by Scope 3 - the downstream processes. As mentioned above, alternative fuels or biomass waste do not cause any fossil energy demand (MJ). **Here, petroleum coke performs the worst**. In contrast, **on a systemic level hard coal performs best of all fossil fuels** (Figure 7). In this category, the variety in impact across all fossil fuels is small.

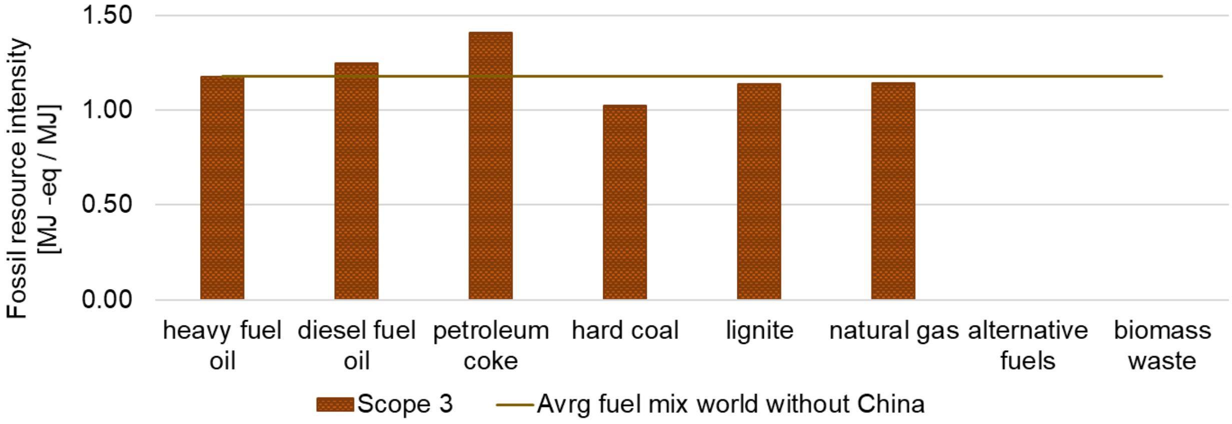

Figure 7 *Fossil resource intensity of fuels in the cement industry.*

3.2 Emission reduction potential from CarbonRe AI in the cement sector

So far, CarbonRe has tested their software on one pilot plant. The achieved energy reductions after a four month operation period are aligned with the findings of (Summerbell, Barlow, and Cullen 2016). Hence, our assessment focuses on the energy reduction achieved at this first cement plant.

CarbonRe can reduce 30.4 kg CO_2-eq. / t clinker, considering a reduction in the global fossil fuel mix and the fuel efficiency achieved at a pilot plant. Table 2 contains all possible emission reductions that can be achieved by reducing the fuel demand accordingly. In terms of climate mitigation, **21 to 40 kg CO_2-eq. / t clinker** can be avoided with this efficiency gain depending on which energy carrier is displaced.

Table 2 *Emission reduction per fuel type. The results refer to the fuel efficiency achieved at a first pilot plant after a four month operation period. The values stated in the table are derived by calculating the net savings if the energy carrier(s) stated in the first column is fully reduced by the extent demonstrated by CarbonRe.*

Fuel Type	**Climate change [kg CO2 / t clinker]**	**Fossil depletion [MJ e / t clinker]**
heavy fuel oil	-25.30	-0.35
diesel fuel oil	-25.12	-0.37
petroleum coke	-39.90	-0.41
hard coal	-31.16	-0.30
lignite	-29.73	-0.34
natural gas	-20.71	-0.34
average global fossil fuel mix	-26.93	-0.33

In 2020, the global cement amounted to 4.3 Gt (IEA 2020). Taking into account the market assumptions above (95 % clinker share in cement), **CarbonRe AI can lead to emission reductions in the total scale of 110 Mt CO_2-eq. per year** (total addressable market). This **reduction potential corresponds to 4.3 % of the global GHG emissions from cement production in 2021.**

The energy requirements and fuel types used in different important world markets vary (section 2.4). Our assessment comprises a reduction in all fossil fuel types that are not produced as a by-product of other processes (only flexible fuel supply will be reduced if energy demand decreases). Among assessed fossil fuels, natural gas has the lowest GHG reduction potential, while the reduction potential of petroleum coke is the highest (cf. Figure 5). It must be kept in mind that petroleum coke is a by-product of oil refineries, so it is very likely that this product will be treated as waste and burned anyway somewhere in the whole system. Because it is not clear which type of fuel will be reduced, several displacement scenarios are evaluated.

1. **Fuel mix:**
   Taking a systems approach, we assume that alternative fuels (that is, mostly waste) and biomass waste will be burned anyway (elsewhere). In other words, even if fuel usage will be reduced at a cement plant, the avoided use of alternative fuels and biomass waste will substitute the use of fossil fuels elsewhere.
   As explained in chapter 3.1.1, emissions from petroleum coke will not be reduced on a system level either. Therefore, a reduction of the energy demand will lead to a reduction of emissions from the fossil fuel mix without petroleum coke.

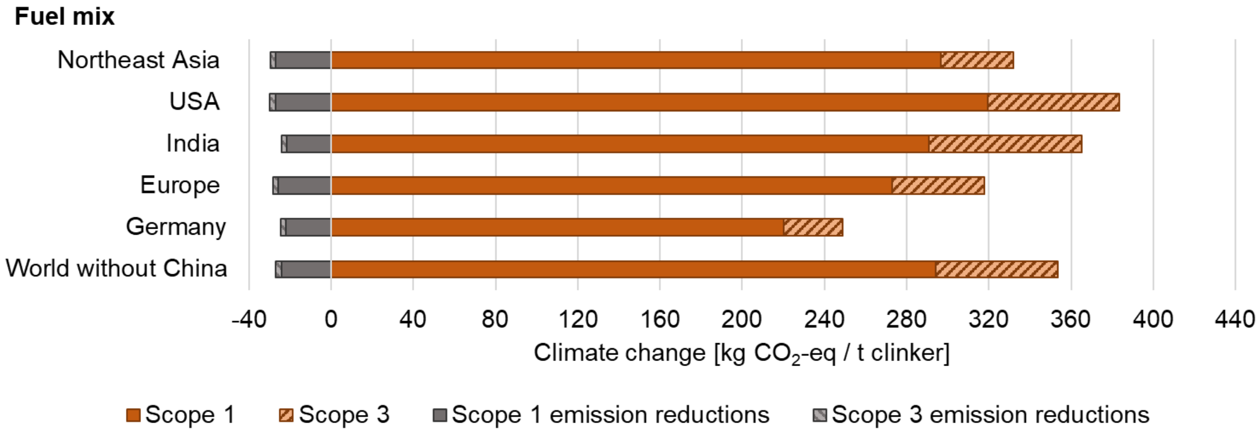

***Figure 8** Impact of fuel mix reduction on GHG emissions. The results refer to the fuel efficiency achieved at a first pilot plant after a four month operation period.*

Little data on country specific fossil fuel mix' are available. For this reason, we used the global fossil fuel mix excluding petroleum coke (see absolute value in Table 2, chapter 3.2.1 - 26.9 kg CO_2-eq. / t clinker) and calculated the emission reduction potential from fuel mix reductions. Comparing these reductions to the country specific fuel mix', the relative reduction potential varies across the regions. In Germany, the emission reduction potential is the highest with 10 %, while it is the lowest in India with 6 % of the total energy related fuel emissions (Figure 8).

2. **Coal:**

   As coal has a high carbon intensity - it is very likely that this fuel will be reduced if legislation and emission reduction mechanisms (such as the EU ETS) propell the phase out of coal energy.

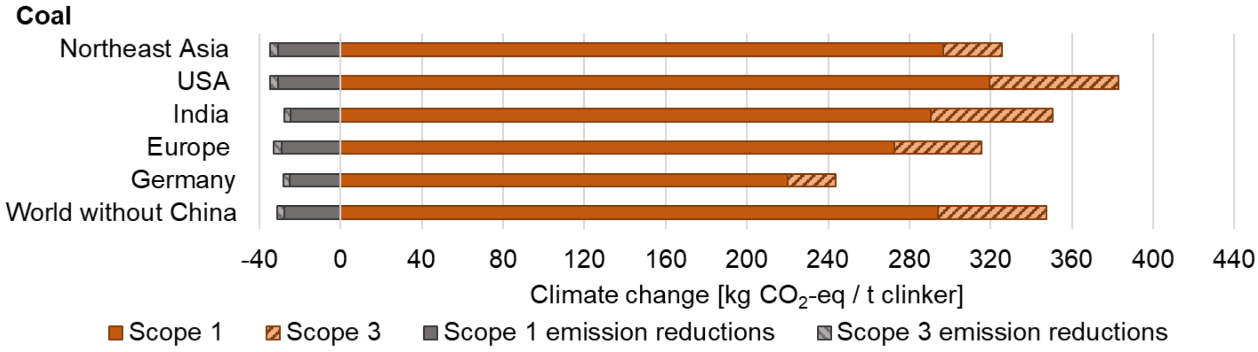

***Figure 9** Impact of hard coal reduction on GHG emissions. The results refer to the fuel efficiency achieved at a first pilot plant after a four month operation period.*

Even for coal, the relative emission reduction potential is highest in Germany (12 %) (Figure 9). Here, too, the relative emission reduction potential is the lowest compared to the Indian total energy related fuel emissions per t clinker production. In absolute terms, the emission reduction potential from hard coal is higher than for the average fossil fuel mix (without petroleum coke) (see also Table 2, chapter 3.2.1).

3. **Natural gas:**

   Due to rising gas prices we assume that the use of gas may be reduced. Here, **the highest considered relative emission reduction potential is again in Germany with 8 % and the**

lowest in India with 5 % (Figure 10). The energy related emission reduction potential from natural gas for the world without China accounts for 6 %.

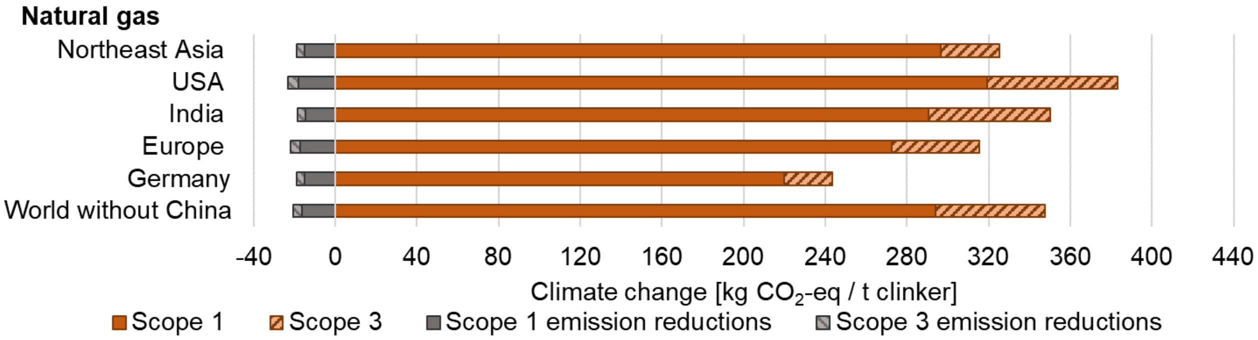

Figure 10 *Impact of natural gas reduction on GHG emissions. The results refer to the fuel efficiency achieved at a first pilot plant after a four month operation period.*

Results of a sensitivity analysis assessing the influence of the achieved energy reduction and the fuel that is substituted is presented in Table A.3 in the Annex. Apart from a pure reduction in energy demand (directly translating into a reduction in GHG emissions), **carbonRe's AI targets fuel switching**, too. Fuel switching presents another key lever to reduce emissions substantially aside from a direct reduction in energy consumption (Miller et al. 2021; Rehfeldt et al. 2020). **Scientific literature states that energy related emissions can be reduced by as much as 39%** (Rehfeldt et al. 2020). When this study was conducted, not enough data was available, to include the fuel switching promoted by carbonRe's AI. It will be included in the assessment once data is available.

3.3 Limitations of the study

Interpreting the results of this study one has to keep in mind that the fuel mix varies substantially. While the European fuel mix already contains a lot of alternative fuels, others are mainly fossil based. As the fuel mix can change between years the average fossil fuel mix will be affected and may change as well. The relative impact of a reduction in fossil fuel types, presented in Table 2, remains constant. If CarbonRe manages to reduce fuel consumption even further, these factors have to be adjusted accordingly.

Furthermore, our calculations are restricted to the findings of (Summerbell, Barlow, and Cullen 2016) and the results of one CarbonRe pilot plant, which we have balanced with a sensitivity analysis.

NOTE: This LCA is not intended to recommend an ideal fuel mix. The use of alternative fuels requires deep process knowledge, and process as well as plant configurations must be taken into consideration. Fossil and alternative fuels or biomass waste have different characteristics, which is challenging for fuel mix configuration (Moses 2011). These challenges have neither been considered nor been addressed in the results of this report.

4 Conclusion

Cement production is an energy intensive industry. Currently, the kiln is the largest energy consumer within the whole process. **Its fuel-derived emissions account for around 40 % of total GHG emissions of clinker production. Therefore, the cement sector offers a high leverage for emission reduction potential.** Compared to other technologies aiming at reducing emissions of energy intensive industries, the AI developed by CarbonRe is easy to implement and can be applied to almost the total cement sector. Under the limitations of this study, even in a worst case scenario the impact reduction potential of CarbonRe AI is high. **This leads to the overall conclusion that CarbonRe reveals a high potential to significantly lower the overall environmental impact of the global cement production.**

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A. Annex

Table A.1 *Emission factors of fuels (gcca 2022a; Wernet et al. 2016; Zitscher et al. 2020).*

	Scope 1	**Scope 3**	
	Climate change [g CO_2 / MJ]	**Climate change [g CO_2-eq. / MJ]**	**Fossil depletion [MJ -eq/MJ]**
Fossil fuels			
heavy fuel oil	77.4	8.6	1.2
diesel fuel oil	74.1	11.3	1.2
petroleum coke	94.8	40.9	1.4
hard coal	93.9	12.1	1.0
lignite	99.3	1.8	1.1
natural gas	55.9	14.5	1.1
alternative fuels			
impregnated sawdust	75		
waste oil	74		
tyres	85		
solvents	74		
RDF including plastics	75		
mixed industrial waste	83		
other fossil fuels based waste and mixed fuels	80		
biomass waste	0		

Table A.2 *Ecoinvent v 3.8 (2021) datasets for Scope 3 emission factors* (Wernet et al. 2016)

	Ecoinvent dataset
heavy fuel oil	market for heavy fuel oil, Europe without Switzerland
diesel fuel oil	market for light fuel oil, Europe without Switzerland
petroleum coke	market for petroleum coke, GLO
hard coal	market for hard coal, Europe without Russia and Turkey
lignite	market for lignite, RER
natural gas	market for natural gas, low pressure, RoW

Table A.3 *GHG reduction potential depending on the region and reduced fuel. Abbr,; C - coal, FM - fuel mix, NG - natural gas.*

	5%			6%			7%			8%			9%			10%		
Region	**FM**	**C**	**NG**	**FM**	**C**	**NG**	**FM**	**C**	**NG**	**FM**	**C**	**NG**	**FM**	**C**	**NG**	**FM**	**C**	**NG**
Global	-4%	-5%	-4%	-5%	-6%	-4%	-6%	-7%	-5%	-7%	-8%	-6%	-8%	-9%	-6%	-9%	-11%	-7%
Germany	-6%	-7%	-5%	-7%	-8%	-5%	-8%	-10%	-6%	-9%	-11%	-7%	-10%	-12%	-8%	-12%	-14%	-9%
Europe	-5%	-6%	-4%	-6%	-7%	-5%	-7%	-9%	-6%	-8%	-10%	-7%	-9%	-11%	-7%	-11%	-12%	-8%
India	-4%	-5%	-3%	-5%	-6%	-4%	-5%	-7%	-4%	-6%	-7%	-5%	-7%	-8%	-6%	-8%	-9%	-6%
USA	-5%	-5%	-4%	-5%	-6%	-4%	-6%	-7%	-5%	-7%	-8%	-6%	-8%	-10%	-6%	-9%	-11%	-7%
Northeast Asia	-4%	-5%	-3%	-5%	-6%	-4%	-6%	-7%	-5%	-7%	-8%	-5%	-8%	-9%	-6%	-9%	-10%	-7%

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