



# ISSUE BRIEF



## DECARBONIZING THE CEMENT AND CONCRETE SECTOR

## COUNCIL OF ENGINEERS FOR THE ENERGY TRANSITION

An independent advisory council to the  
United Nations Secretary-General

### KEY MESSAGES

#### 1: Infrastructure Demand

75% of the global urban infrastructure that will exist in 2050 is yet to be built, and it will almost all be built in developing countries. Furthermore, more than 90% of the world's cement demand will come from the global south, particularly in India and Africa.

#### 2: Realities of Cement Production

Cement-based materials do not have an intrinsically high carbon footprint, but demand remains high and there is no alternative to cement at scale. Cement is responsible for 8% of global emissions because of the quantity of its demand and use.

#### 3: Emissions and Material Efficiency

Emissions reductions can be made at all levels of cement production through a prioritization of material efficiency in production, use, and design. While changes to the current structural codes and standards are desirable, huge reductions are possible now. Substituting part of the clinker in cement, using cement efficiently through industrialization, and optimizing building design can reduce emissions by 70-80%, even without revising codes and standards or using CCS.

#### 4: Alternative Materials and Fuels

An important way to reduce emissions and costs throughout production is to replace certain materials, like clinker and fuel, with alternatives. Cement clinker, which emits carbon mostly through limestone breakdown, can be substituted in part by [calcined kaolinitic] clays, which are less carbon-intensive and more abundant than limestone in the developing countries that demand cement. Additionally, alternative fuels, primarily made from waste fossil sources, provide an effective route for the safe disposal of many waste streams.

#### 5: Carbon Capture and Storage

Due to the chemistry and process of cement production, Carbon Capture and Storage (CCS) will be necessary to achieve net-zero emissions, but because of challenges in engineering, capital investments, and storage sites, it should be the last resort of decarbonization for the industry. Technological, financial, and spatial constraints are especially difficult for developing countries, so to realistically achieve net-zero goals, other means of emissions reduction, which can be achieved in the short term by working through the value chain, must be prioritized.

As economies grow, urban and residential areas are rapidly expanding across the globe, particularly in developing countries, where 75% of the global urban infrastructure that will exist in 2050 is yet to be built. Therefore, in order to reduce the carbon footprint of buildings and infrastructure by mid-century, tackling the production as well as the usage of concrete in developing countries is of utmost importance.

Carbon emissions are released from all built assets, including buildings and infrastructure, not only during their operational life, but throughout their entire lifecycles—the raw material extraction, manufacturing, transportation, construction, and end-of-life phases of building materials (see Figure 1). These emissions, known as “embodied carbon,” have been historically overlooked. Cement, which accounts for 7-8% of global emissions and makes up a significant portion of concrete, the second most consumed material in the world after water, must be decarbonized to achieve building emissions reductions goals.

This briefing note examines the situation of cement and concrete in light of the urgency to reduce global warming in the following eight sections. The three most important aspects for the attention of policy makers are summarised below:

1. 90% or more of cement will be used in the Global South in the coming decades to 2050. Most importantly, use will shift from China (presently >50%) to other countries and regions of the Global South, most notably Africa, where the amount of cement used is forecasted to increase nearly five-fold (See Figure 2).
2. It is impossible to reduce the emissions associated with cement and concrete to zero without employing some degree of carbon capture and storage (CCS). However, installation of sufficient capacity will be technically challenging and expensive, increasing the cost of production by two to four times.<sup>i</sup> In developing regions, large-scale deployment before 2050 will be challenging. In contrast, it is possible to realize very substantial reductions in emissions (by 76%<sup>ii</sup>) by working through the value chain: minimizing the amount of clinker in cement, minimizing the amount of cement in concrete, and minimizing the amount of concrete in buildings. The importance of working on all stages of the value chain is ignored in many policy documents, which look only at cement production in isolation.<sup>iii</sup> This results in an overemphasis on CCS and does not incentivize savings that could be made quickly, especially in developing regions.
3. Limestone, the essential raw material to produce clinker, is scarcely available in many parts of the developing world (e.g., parts of Africa, India, and Bangladesh). These regions must import clinker, effectively importing CO<sub>2</sub>e. The need for imports can be substantially reduced (up to 50%) by the use of local kaolinitic clays<sup>iv</sup> which also mitigates the need for foreign currency and creates local employment opportunities. While the use of kaolinitic clays will reduce CO<sub>2</sub>e emissions on a global level, it can lead to an increase in individual country emissions of CO<sub>2</sub>e, and this should be taken into account. (See limestone and clay maps Figures 6 and 7).



**Figure 1.** Schematic of CO<sub>2</sub>e emissions through the construction cycle. Source: Image created by SDSN.

## 1. THE CHANGING GEOGRAPHY OF CEMENT USE: REGIONAL NEEDS<sup>v</sup>

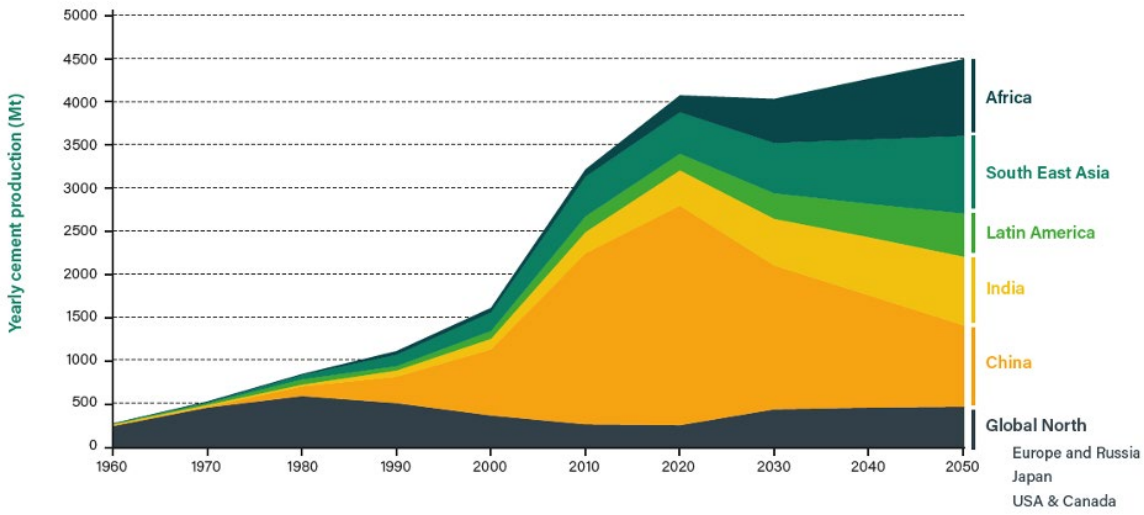
It is important to consider the changing geography of cement use first, as it impacts where and how the most important interventions need to be made. It is also the aspect that is overlooked in most recent policy documents. Figure 2 shows how the use of cement has evolved since 1960. In 1970, the world production was around 500 million tons, with 90% in the Global North. By 2020, the world production had increased seven-fold, with China accounting for more than 50% of production.

So, how will things evolve leading up to 2050? Demand in China is already decreasing, and this trend is forecasted to continue, with China likely to account for only 20% of cement output in 2050.<sup>vi</sup> Demand in all the other countries and regions of the Global South, including India, Latin America, and the rest of Asia and Africa, is anticipated to increase to more than 60% of the total projected world demand of approximately four billion tons in 2050. The strongest growth will be in Africa, where a five-fold increase in demand is predicted between 2020 and 2050.

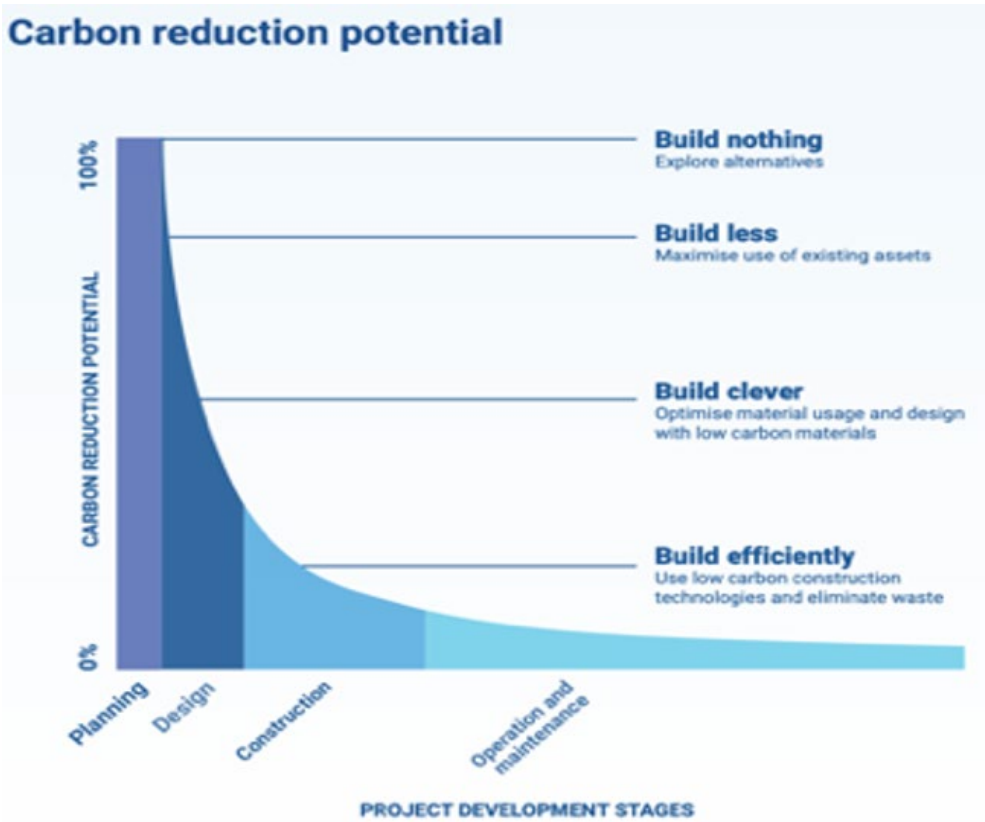
The production of cement and concrete accounts for about three billion tons of CO<sub>2</sub>e<sup>vii</sup> per annum:<sup>viii</sup> around 7-8% of anthropogenic GHG emissions. This is not because they are intrinsically high-carbon materials, but because of the enormous quantities used (See Figure 5). Worldwide, there are around four billion tons of cement produced annually, which are used to produce around 30 billion tons of cement-based products. Roughly half is concrete, and the other half is a combination of mortars mixed on-site and factory-produced products, such as pavers, blocks, and roof tiles.

The potential for reduction of cement and concrete GHG emissions is large if measures are taken throughout the value chain: clinker in cement, cement in concrete, concrete in the construction, and the circular economy.<sup>ix</sup> This point is not well appreciated by many when only cement in isolation is considered. Figure 3 shows schematically the magnitude of CO<sub>2</sub>e reduction potential through the different stages of the project development from planning to operation.

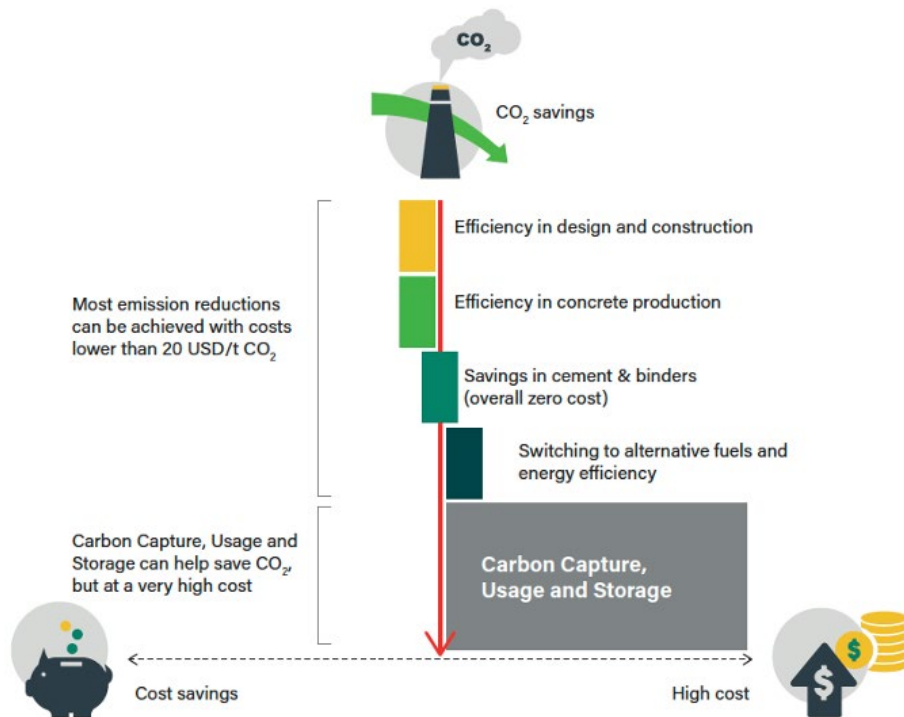
### Historical and forecast cement supply per region



**Figure 2.** Historical and forecast cement supply per region. Graph redone by the author. Source: IEA, *Cement Technology Roadmap: Carbon Emissions Reductions up to 2050*, (Paris, IEA, 2009).



**Figure 3.** Carbon reduction potential. Source: HM Treasury (2013) and Green Construction Board (2013), reproduced under the terms of the Open Government Licence (Crown Copyright 2013).



**Figure 4:** Schematic of different levers to reduce CO<sub>2</sub>e emission, showing their relative potential to reduce emissions (vertical scale not quantitative) and their relative cost (horizontal scale). Source: The author from documents including the GCCA roadmap10.

The Global Cement and Concrete Association (GCCA), which represents 80% of producers outside of China, as well as several of the major Chinese producers, has committed to reaching net zero by 2050.<sup>1</sup> However, in their roadmap, 36% of this reduction would come from CCUS. There is reason to believe that higher reductions (even up to 80%) could come from other means if all parts of the sector take on the challenge of implementing strategies for reduction across the whole value chain. Such non-CCUS strategies are much more realistic for developing countries, as they do not increase costs and may even reduce them (see Figure 4).

## 2. HOW CAN REDUCTIONS BE MADE: OPTIMIZING PROCESSES OR EXPLORING ALTERNATIVES?

Just eight elements make up more than 98% of the earth’s crust. This limits the range of materials that can be used in the quantities required for construction. Two of the most widely available minerals, limestone and clay, form the basis of “Portland” cement, which is used to produce around 30 billion tons of construction materials a year.

Despite the media interest they attract, many niche technologies entering the market—such as, alkali-activated materials and cement from algae—are impractical, costly, unscalable, or will take too long to mature, leaving little to no possibility of delivering any significant impact before 2050.

1. GCC Association, “GCC Association.”

Furthermore, even when these materials are available on a commercial scale, the process of codifying new materials for use in construction is very protracted, due to the critical aspects of structural safety and the longevity (50 years or more) expected from structures.

Bio-based materials, such as timber and bamboo, may have lower emissions than concrete if produced sustainably, but can only supply a small fraction of the materials needed for construction. For example, replacing just one-quarter of the concrete we use today with timber would require planting new forests one and a half times the size of India and waiting a few decades for them to grow.<sup>2</sup>

Therefore, replacing cement altogether is not an option, and there are no “miracle” solutions. However, as detailed below, very substantial savings in emissions at low or even negative costs can be achieved based on known technologies if the whole value chain of construction is considered.

### **1. At the cement level by substituting the more carbon-intensive clinker with other materials.<sup>x</sup>**

Traditionally, blast furnace slag (GGBFS, a by-product of pig iron production) and fly ash (from burning coal) have been the main substitute materials, but the supply of these already only accounts for around 15% of cement production and is expected to decline in the future, as these are both by-products of carbon-intensive processes.<sup>2</sup> This limitation can be overcome by using kaolinitic clays calcined at around 800°C together with limestone (LC<sup>3</sup> technology<sup>3</sup>). The International Energy Agency (IEA) recognized in their latest report<sup>4</sup> that limestone and calcined clay are the main alternative materials which will be used in blended cements by 2050.

The IEA estimates that savings of at least 20% by 2030 and 40% by 2050 could be possible by reducing the clinker/cement ratio.

### **2. Minimising cement content in concrete.**

Several studies show that the amount of cement used to produce concrete of the *same strength class* may vary by a factor of 3-4.<sup>5</sup> One way to reduce cement overconsumption in concrete is to move from on-site mixing to ready mix production, where mixes can be better optimized. There are several other important factors that reduce the amount of cement in concrete. These include: 1) abolition of minimum cement contents, which are an anachronism from the times when admixtures were not efficient; 2) choice of a good size distribution of aggregates; and 3) use of fluidity-enhancing admixtures.<sup>6</sup> Around 20% to 30% of CO<sub>2</sub>e could be saved by these measures.

### **3. Minimising concrete use in a building.**

Early planning and early supplier engagement to tailor materials for the lowest carbon outcome is important. First, the amount of concrete specified must not exceed that needed to satisfy the building code—often 10-20% extra is added out of a tendency to be “on the safe side.” Then, the layout of the building should be considered, as overly complex layouts may require up to 100% more concrete than simple building layouts.<sup>7</sup> Additionally, demands on the speed of construction should be reviewed, as it may be more difficult to obtain the specified one or two-day strength with low carbon.<sup>xi</sup>

2. Energy Transitions Commission, “Mission Possible: Reaching Net Zero Emissions from Hard-to-Abate Sectors by Mid-Century.”

3. LC3, “Limestone Calcined Clay Cement.”

4. IEA, “IEA – Cement.”

5. Bruno Damineli et al., “Measuring the Eco-efficiency of Cement Use,” 555-562.

6. Josephine Cheung, Lawrence Roberts, and Jiaping Liu, “Admixtures and Sustainability,” 79-89.

7. Hannes Gauch et al., “Carbon vs. Cost Option Mapping: A Tool for Improving Early-Stage Design Decisions.”

### 3. INVESTMENT CYCLES / RETROFIT POTENTIAL

The capital cost of a new cement plant producing clinker is above US\$150 million per million tons of annual capacity.<sup>8</sup> A clinker capacity of one million tons per year is now considered a fairly modest-sized plant. The payback period on a new plant is long, and a profitable operation depends on a reliable source of limestone to supply raw material for more than 30 years. On the other hand, retrofitting cement kilns is very standard, and a typical plant is likely to receive some investment every five to ten years.

New technologies that save money may be implemented rapidly. For example, alternative fuels were introduced rapidly in Europe where many plants operated with replacement fuels above 80%<sup>xii</sup>. Another example is the introduction of clay calcination, which can substantially increase the replacement level of (CO<sub>2</sub> intensive) clinker in cement. This can be implemented in a plant in as little as two years.

There are also options for retrofitting existing equipment, with varying cost implications. For example, it is possible to retrofit a disused clinker kiln which exists in many areas and requires a low capital investment (Capex for this may be as little as few percent of new clinker capacity). At the other extreme is the cost of retrofitting plants for CCS, which is likely to be two to three times the cost of new clinker capacity.

### 4. MAJOR MISUNDERSTANDINGS

The overall impact of the cement and concrete sector in global CO<sub>2</sub> emissions and the lack of understanding of how clinker, cement and concrete are made leads to several misunderstandings by the general public and even by users.

We list the key misunderstandings below to help policy makers prioritize real solutions to reduce emissions, while managing costs in an industry with an already narrow profit margin.

#### **False: Cement-based materials have an intrinsically high carbon footprint.**

It is a common misunderstanding that concrete is a “high-carbon material.” In fact, the emissions per ton are much lower than almost all alternatives. The overall carbon footprint is due to the enormous quantities used (See Figure 5).

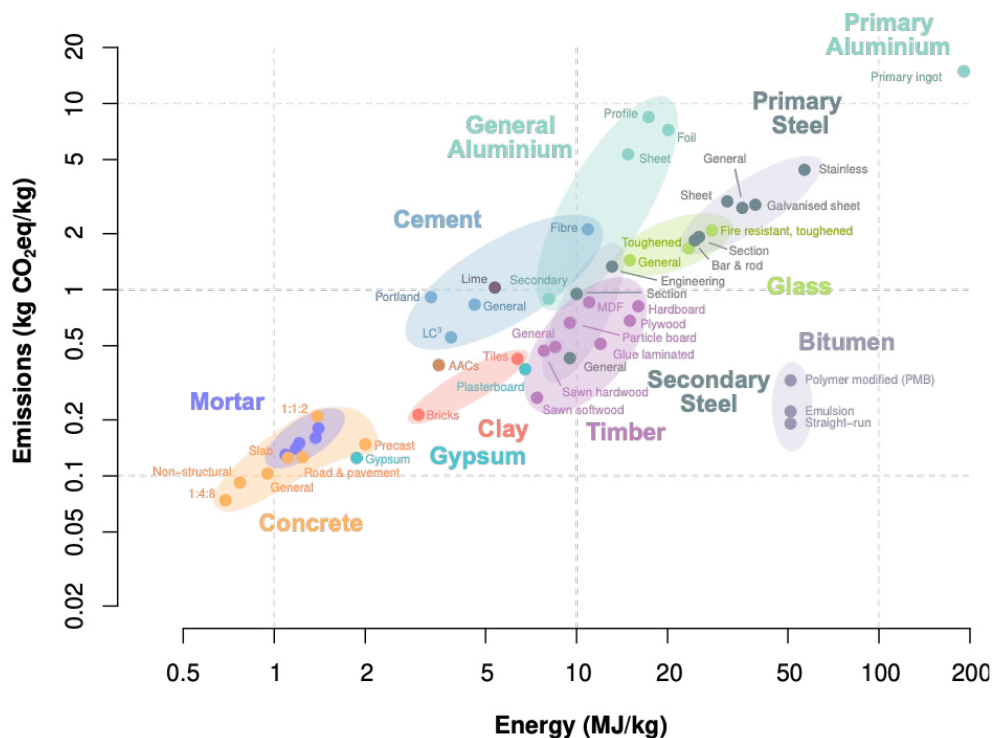
#### **False: There is an alternative to cement at scale.**

No materials can replace cement to any significant extent due to the resource issue explained above (Section 2: How Reductions Can Be Made). The main issue of using alternative materials is scalability to have a meaningful impact in terms of emissions reductions. Another issue is cost, because the present cost of cement and concrete is low compared to other materials. Alternative production routes which have been proposed would increase costs 10-100 times. As discussed above some emissions will have to be dealt with by CCS, which will increase the production cost 2-4, so options costing more than this are not commercially viable.

#### **False: Renewable energy alone can solve the problem.**

Around 60% of CO<sub>2</sub>e emissions (~525 kg/t) do not come from the fuels used to produce clinker, but from the breakdown (decarbonization) of limestone (CaCO<sub>3</sub> > CaO + CO<sub>2</sub>). Switching to renewable energies will not avoid this, and the basic chemistry of clinker cannot be changed, as it is an inevitable consequence of the chemistry and geology of the Earth.<sup>xiii</sup>

8. ESFC Investment Group, “Construction Cost of a Cement Plant.”



**Figure 5:** CO<sub>2</sub> and Energy per kg, by material type.<sup>xiv</sup> Source: ICE Database, “Embodied Carbon.” Graph drawn by Dr. Cyrille Dunant, University of Cambridge.

The remaining 40% of emissions come from the fuel used (~340 kg/t), to attain the high temperature (1450°C) needed for clinker production. The best available technology is very energy efficient, approaching 80% of the thermodynamic limit, so, although there can be some future savings through updating of old plants and by further deployment of waste heat recovering, these will be fairly minor, accounting for only around a few percent.

There is active research to electrify part of this process. There are promising avenues to electrify the step where the limestone is decarbonated to calcium oxide (e.g., the Leilac project,<sup>9</sup> which also produces a highly concentrated CO<sub>2</sub> gas, another significant advantage). However, the last part of the process (800-1450°C) is very challenging. While hydrogen as a fuel is also being investigated, supplies of renewable energy and green hydrogen are limited, and cement production needs to be a

continuous process. A recent study has shown that the likely cost of electrification is comparable to that of CCS,<sup>10</sup> leading to an increase in production costs of two to four times.

In light of the technical challenges, costs, and limitations of renewable energy and hydrogen, it may be strategically desirable to promote the use of alternative fuels, instead. These are primarily waste fossil sources, such as waste oils, waste (non-recyclable) plastics, industrial waste, but also biomass, agricultural wastes, and refuse.<sup>xv</sup> While the waste fossil sources do still emit CO<sub>2</sub>e, they provide an effective route for the safe disposal of many waste streams, which also recuperates their calorific value, while avoiding the need for virgin fossil fuels and the problems of disposing of these wastes in landfills where they may generate other GHGs, such as methane.

9. Cemnet, “HeidelbergCement and Caliz Reach LEILAC-2 milestone.”

10. ESFC Investment Group, “Construction Cost of a Cement Plant.”



This also provides an alternative to incineration, and ultimately contributes to the overall reduction of CO<sub>2</sub>e.

Alternative fuels (both waste fossil fuels and biomass) have been used for decades in Europe. And one should note that cement kilns have been recognized by the Stockholm Convention on Persistent Organic Pollutants (POPs) as a safe environment for the destruction of these wastes.<sup>11</sup>

**False: There is very little calcium available on Earth which is not already carbonated or very expensive to extract.**

As the fifth most abundant element in the Earth's crust, calcium is a significant component of many common rock types (e.g., around 10% in basalt). Natural weathering processes over millions of years lead to the breakdown of igneous rocks. The calcium component reacts with atmospheric CO<sub>2</sub> to produce limestone. This concentration of calcium in limestone provides an ideal raw material for cement production. Yet, trying to accelerate this natural concentration process is very costly. For example, the dissolution of basalt by acid and precipitation of the calcium contained, or the production of limestone from seawater with a calcium concentration of 400 ppm, will likely cost more than ten times the cost of clinker production—much higher than the already expensive cost of CCS.

**False: Ground Granulated Blast Furnace Slag (GGBFS) is the solution.**

GGBFS is a by-product of iron production from iron ore in blast furnaces. As it has a similar chemistry to Portland cement clinker, it can be substituted in cement in high amounts (blends with 70% slag are common). However, the main issue is the limited amounts of GGBFS available compared to the demand for cement, though the blast furnace route for steel production is the most commonly

used. Currently, the production of GGBFS is around 7-10% of cement production, of which 90-95% is already used in cement or concrete. Slag is already transported long distances, adding considerably to the cost and increasing its carbon footprint. In light of this, specifying high levels of slag replacement in one project or region just takes it away from another project or region with no net global CO<sub>2</sub>e reduction.<sup>12</sup> Similarly, clinker-free materials based on slag activated by alkalis are overhyped, as these will only *increase* emissions globally due to the carbon footprint of the activators.

## 5. BOTTLENECKS

The major bottlenecks are the fragmentation of the industry and the lack of incentives for reducing CO<sub>2</sub>e downstream (at the concrete and building levels). Additional bottlenecks include the perception of risk and the high burden of individual responsibility for safety and low knowledge and skill levels in many stages of the process.

By demanding transparency in project and material emissions and making carbon reduction a top priority during partner selection and design, project buyers from both the public and private sectors can effectively motivate architects, structural engineers, construction firms, and cement manufacturers to act toward reducing carbon emissions.

Standards and codes are also bottlenecks, particularly as these work at three different levels (cement, concrete, and building), which relates back to the issue of fragmentation. However, it must be emphasized that there is considerable scope for reduction even within the existing codes, as it relates to how structures are “over engineered.”

Finally, given the chemical processes in this sector, net zero carbon will always necessitate some degree of CCS.

11. Stockholm Convention, “Guidelines on best available techniques and provisional guidance on best environmental practices relevant to Article 5 and Annex C of the Stockholm Convention on Persistent Organic Pollutants.”

12. Will Arnold et. al., “The efficient use of GGBS in reducing global emissions.”

Technologies will be available in the medium-term for CO<sub>2</sub> capture, the issue is more what to do with the CO<sub>2</sub> once it is captured. The amount of CO<sub>2</sub> that needs to be captured far outweighs most potential uses. Long-term storage will need to be considered more on a country-level than on the level of an individual plant. This will be a challenge, especially in the Global South.<sup>xvi</sup>

## 6. BANKABILITY

In general, making cement is a reasonably profitable business, and sources of finance are available for new installations, including the production of calcined clay. However, the cost of loans is still considerably higher in developing countries where there is most demand. In these countries, the most interesting investment will be in facilities to calcine clay, as these can increase capacity at a much lower cost.

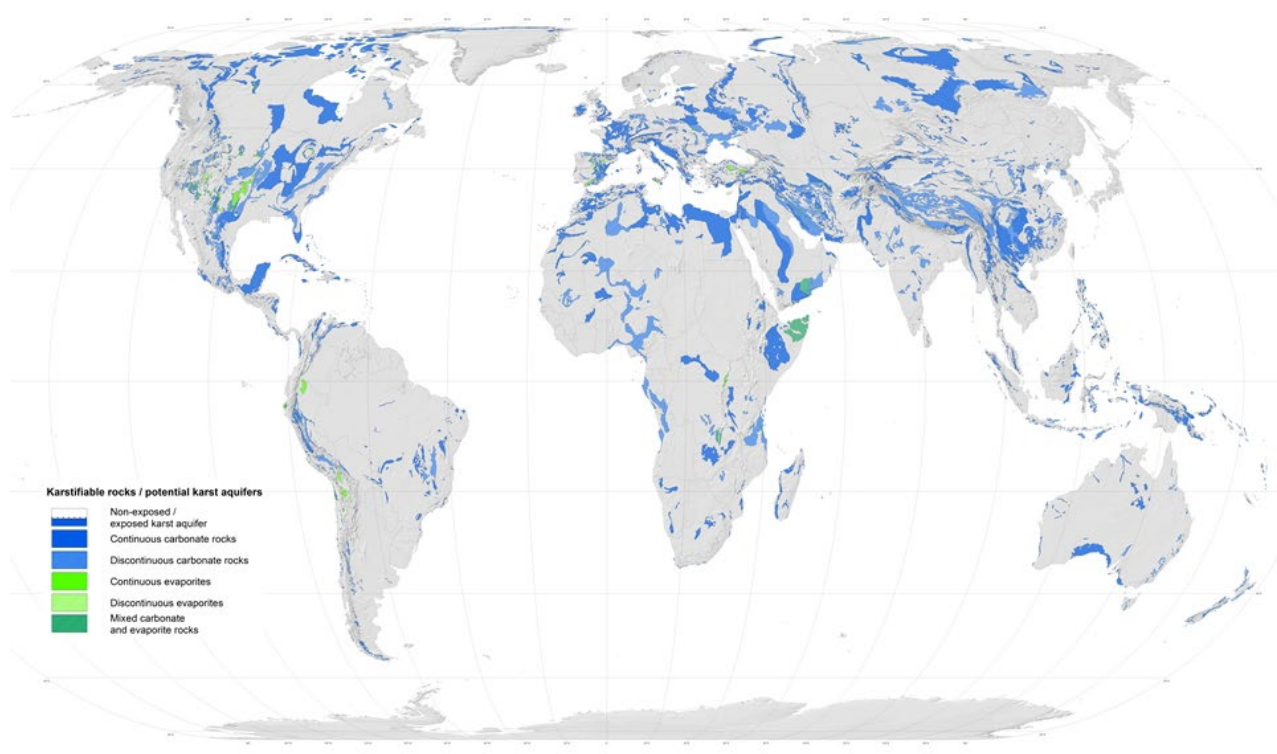
On the other hand, the needed investment in carbon capture and storage will be much more costly from 2030 to 2050. To meet the net zero target by 2050, it will be necessary to install CCUS at a rate of one plant a week.<sup>xvii</sup> The large potential reduction at the downstream level is currently not incentivized. Studies need to be undertaken to look at ways to do this.

## 7. EXAMPLES OF BEST PRACTICES

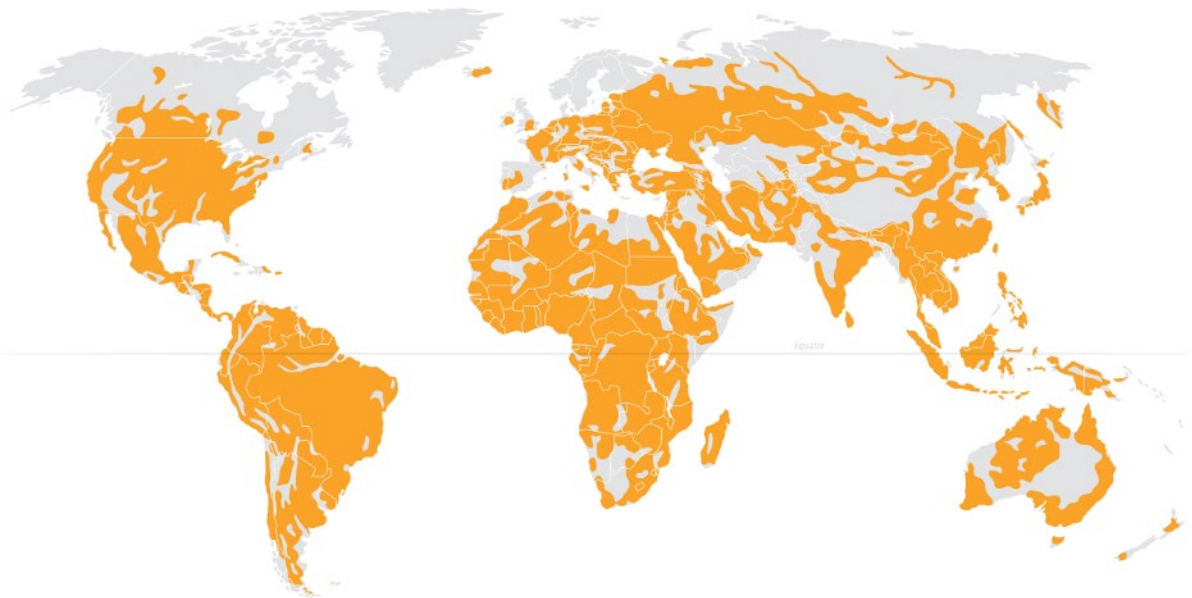
Again, it is important to stress that all levels of the value chain need to be considered.

- At the level of clinker production, the most important practice is the use of alternative fuels. While this is above 80% in many plants in Europe, it is less than 5% in most developing countries. Increasing the use of alternative fuels also depends on policies for waste collection and disposal.
- At the level of cement production, the level of clinker substitution needs to be increased. As described above, this is now possible with calcined clay together with fine limestone. Based on my knowledge of the industry, I estimate that the global clinker factor of around 75% clinker/cement) could be reduced to 60% by 2030 and 45% by 2050 with avoided CO<sub>2</sub> emissions of 400 million tons of CO<sub>2</sub> per year and 800 million tons of CO<sub>2</sub> per year, respectively.
- At the level of concrete production, more widespread use of ready-mix concrete, good aggregate grading, and the use of admixtures can have a major impact to lower cement content and thus CO<sub>2</sub>.
- At the level of buildings, the concrete “intensity” of buildings (m<sup>3</sup>/m<sup>2</sup>) needs to be assessed at an early stage in the design process. New software tools to explore different options for design, such as “Panda” from Cambridge University,<sup>13</sup> are available.

13. UK Fires, “Panda Softwares.”



**Figure 6:** Global limestone distribution. Source: Zhao Chen et. al., “The World Karst Aquifer Mapping Project – Concept, Mapping Procedure, and Map of Europe.” (Hydrogeology Journal, 2017) 771-785.



**Figure 7:** World distribution of Kaolinitic clays. Map redone by author. Source: Akihiko Ito and Rota Wagai, *Global distribution of clay-size minerals on land surface for biogeochemical and climatological studies* [map]. Scale not given. Scientific Data. Volume 4, Article number: 170103 (2017).

## A NOTE ON THE CIRCULAR ECONOMY

The reuse and recycling of concrete in a circular economy approach should be encouraged from a resource perspective, but it is not likely to be a route to reducing CO<sub>2</sub>e emissions *on a major scale* today or in the next decade. In the table below, I have tried to summarize key considerations for major recycling strategies and provide some perspectives on their potential and limitations. The indicators are very rough based on personal knowledge collected in recent years. In terms of recycling, it is important to bear in mind that concrete has a low embodied CO<sub>2</sub>e per unit mass to start with, so operations like crushing and transportation quickly cancel out potential savings.

The more important aspect is that concrete needs to exist before it can be reused or recycled. This is the case in the Global North where levels of demolition are commensurate with levels of construction, but the Global North only accounts for 10% of cement use. In the developing regions of the world, the buildings generally do not exist or are of poor or uncertain quality. The population is growing, and urbanization with changing patterns of land use is rapid. 75% of the urban infrastructure that will exist in 2050 has yet to be built, and this will happen in those developing nations. In this situation, there is more limited potential for these circular approaches, although significant recycling or reuse likely occurs at the informal level.

**Table 1:** Circular Economy Strategies: Impact, Extent and Barriers

Strategy	CO <sub>2</sub> savings	Extent of Deployment	Comments on Barriers
Reuse whole building	Very large	Small	<ul style="list-style-type: none"> <li>• Building needs to be suitable for future use. Often, especially in rapidly evolving societies, there is a need to increase building density.</li> <li>• Difficulty to evaluate state of building with respect to safety / longevity difficult to find insurers to take risk.</li> </ul>
Cut up and use component parts	Large	Miniscule for concrete and significant for steel structures	<ul style="list-style-type: none"> <li>• Usually much more expensive than new building.</li> <li>• Very difficult to match stock of components to new needs.</li> <li>• Difficult to assess present and future performance, which makes it difficult to insure.</li> </ul>
Demolish: Extract steel	Medium to large	Large	<ul style="list-style-type: none"> <li>• Well-established routes for steel collection and recycling.</li> </ul>
Demolish: Crush concrete aggregate	Very low or negative	Large	<ul style="list-style-type: none"> <li>• Widely deployed, especially in Europe. Aggregate can be used to replace virgin aggregates in road base or in new concrete, but in new concrete, the need for cement usually increases and CO<sub>2</sub>e emissions increase.</li> </ul>
Demolish: crush concrete fines	Small, but could be increased	Active research area	<ul style="list-style-type: none"> <li>• At present, most of the fines from concrete crushing are sent to the landfill. Here, they may absorb some CO<sub>2</sub> by reaction of the cement paste with atmospheric CO<sub>2</sub>. There is significant ongoing research to look at reusing these fines either to make new clinker or as an addition to concrete.</li> </ul>

## NOTES

- i The current marginal cost of production of clinker (the main component of cement) is around \$30-\$50 per ton. Investment costs are not usually included, due to the fact that most cement plants are several decades old. A ton of clinker produces on average 850 kg of CO<sub>2</sub>e. The cost of carbon capture is at present in the range of \$100 per ton and in the long term is estimated to decrease to around \$40. Transport and storage will add around another \$50-100 per ton. So, the cost of CCS per ton of clinker is around \$70-130 per ton of clinker produced. This is an increase in the cost of clinker production by 2-4 times. It is better to calculate costs in terms of clinker production as this is the component which produces almost all the CO<sub>2</sub>e and cost. The world average figure given of 600 kg emissions per ton of cement comes from the fact that almost all cements today contain some other component in addition to clinker. (Refs 50-80 €/t (Skagestad et al. 2019), 50-148 €/t (Dena 2021).
- ii A recently published article estimates a potential to reduce GHG emissions by 76% compared to 2015 levels by a similar combination of strategies outlined in this brief. Reference: Olsson, J A, Miller, S A, Alexander M G “Near-term Pathways for Decarbonizing Global Concrete Production” Nature communications (2023) 14:4574: <https://doi.org/10.1038/s41467-023-40302-0>.
- iii For example, “Achieving Net Zero Heavy Industry Sectors in G7 Members,” IEA, May 2022. <https://www.iea.org/reports/achieving-net-zero-heavy-industry-sectors-in-g7-members>
- iv According to the IEA, Cement Sub Sector Report, 2022—the global clinker-to-cement ratio has increased in recent years—with higher use of clinker substitutes and innovative technologies needed to get on track with the Net Zero Scenario, largely “...owing to greater use of blended cements and clinker substitutes. In the long run, clinker replacements made from widely available materials—such as calcinated clay in combination with limestone—will become more important, as decarbonization of other sectors reduces the availability of industrial by-products currently used as alternatives, such as fly ash from coal power plants and ground granulated blast furnace slag from the steel sector.” Link: <https://www.iea.org/reports/cement>
- v Historic data is from USGS. Future predictions come from data published by IEA in 2009, which is somewhat outdated. More recent data does not seem to be publicly available.
- vi The decrease in China is related to the extremely high consumption per capita, above 1,500 kg, which is about three times the global average (around 500kg).
- vii The term CO<sub>2</sub>e or CO<sub>2</sub> equivalent is used. The overwhelming this majority of emissions are CO<sub>2</sub>, but there are small amounts of CH<sub>4</sub> and N<sub>2</sub>O produced.
- viii There has been a reduction in carbon intensity of 22% per ton of cement since 1990.
- ix Recycling and other aspects of the circular economy are very important from the perspective of conserving resources. However, they do not have much impact on CO<sub>2</sub>e emissions. For example, using recycled aggregate may even increase the amount of cement needed in concrete, which increase CO<sub>2</sub>e emissions. Furthermore, only in the developed world are the amounts of materials from demolition available on the same scale as new construction.
- x The relation between clinker to cement content and performance is complex. A CEM II or CEM III cement (according to the EN 197 -5) does not necessarily have a lower 28-day strength than a CEM I. It depends on the type and amount of materials used to substitute the clinker. For example, a CEM II C-M(Q-LL) containing only 50% clinker and a combined addition of calcined clay and limestone can have the same strength even at two days as a CEM I containing 90% clinker and with 40% higher CO<sub>2</sub> emissions. On the other hand, a CEM II B LL containing at least 65% clinker, but with only limestone as a substitute would have significantly lower 28-day strength. And these figures only refer to strengths in test mortar. When these cements are used to make concrete, the performance can be adjusted by controlling the amount of water added.
- xi It is these early strengths which determine the rate at which construction can proceed such as remoulding or starting to work on the next floor. If you slow down the construction rate you strongly increase the cost related to labour, hiring cranes, etc
- xii In an individual plant use of alternative fuels can be implemented in about 6 months. The speed of change in Europe can be exemplified by Poland where it was 45% in 2011 and in 2017 was above 60% with some plants using up to 85%, this was made possible by a combination of the strong commitment of the cement sector; ongoing enforcement of waste regulations particularly related to landfilling and a favourable economic context comprising smart national and international investments, taxation on landfilling and some alternative fuel opportunities supported by European subsidies. (<https://documents1.worldbank.org/curated/en/563771502949993280/pdf/118737-REVISED-Alternative-Fuels-08-04.pdf>)
- xiii Cement plants already incorporate a high degree of heat recovery. They use air from the clinker cooling to heat the incoming materials, etc. There is also on-going research to increase the level of heat recovery by the use of organic Rankine Cycles (ORC). However, the levels of further energy saving will be marginal order. Some savings will also come from modernizing old plants.
- xiv The data shown in this graph regarding timber has been disputed. The graph comes from a reputable source. Experts I have consulted say that the estimate is reasonable considering the carbon and energy from drying and glues and burning half the wood from the tree, which can't be used for anything else, as well as the release from bacteria in the disturbed ground. It seems the carbon impact of timber varies widely depending on how the forest is managed. For instance, are trees replanted, and how is the cut wood then processed? As all the data is from the same source, I do not want to arbitrarily change one value. The recent study on benchmark-



ing CO<sub>2</sub> in buildings (Röck M, Sorensen A, Tozan B, Steimann J, Le DEn X, Horup L H, Birgdottir H, “Towards EU Embodied Carbon Benchmarks for Buildings - Setting the Baseline: A Bottom-Up Approach, 2022, <https://doi.org/10.5281/zenodo.5895051>) shows the massive timber buildings only had an average CO<sub>2</sub>/m<sup>2</sup> about 10% lower than concrete ones, and many of the concrete buildings had lower CO<sub>2</sub>/m<sup>2</sup> than the massive timber ones. But in any case, the main reason that timber and other bio-based materials cannot make a further contribution to lowering CO<sub>2</sub>e from construction is the shortage of sustainably-produced supplies of these materials. For example, it was estimated that to replace even 25% of concrete would require planting a new sustainable forest 1.5 times the size of India.

- xv It is true that wastes and biomass will be increasing in demand for manufacturing transport fuels, but cement plants do not generally compete with the relatively homogeneous sources needed to produce these fuels, but can use a wide range of very heterogeneous and impure sources.
- xvi As far as I can find, outside South Africa, potential sites for CCS in Africa have not yet been identified.
- xvii At their 2023 annual meeting, the GCCA said there would be a need to retrofit one plant a week for CCS. The *capital* cost of retrofitting CCS is difficult to find as most estimates merge installation and running costs together at around \$40-80 per ton of CO<sub>2</sub> captured. The study of “CCS knowledge” on a pilot plant installation in Canada is available here: [https://ccsknowledge.com/pub/Publications/2021Nov\\_Summary\\_for\\_decision%20makers-CCS-LEHIGH-FINAL%20\(2022-05-11\).pdf](https://ccsknowledge.com/pub/Publications/2021Nov_Summary_for_decision%20makers-CCS-LEHIGH-FINAL%20(2022-05-11).pdf). The study reports installation cost at approximately \$500 million USD for a million-ton plant, which is more than three times the cost of building a new plant, but this figure is likely to decrease as the technology becomes more widespread. See also endnote i.

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#### CEET SUBJECT MATTER EXPERT

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